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An isotopically enriched mantle component in the source of Rodrigues, Réunion volcanic hotspot

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ABSTRACT

The Mascarene Islands in the western Indian Ocean, encompassing La Réunion, Mauritius, and Rodrigues, are the recent (<10 Ma) surface expressions of the Réunion hotspot. Ocean island basalts (OIB) from these islands exhibit a remarkably homogeneous long-lived radiogenic isotopic composition, coinciding with the convergence field of many global OIB trends in the mantle array. Réunion plume-related OIB therefore provide one of Earth's most pristine representations of this "focal zone" component, which may have a primordial heritage. Besides this signature, Mascarene lavas have been suggested to retain contributions from sources with distinct compositions, including: (1) Archaean-aged zircons assimilated from continental crust within the oceanic lithosphere by trachytic magmas from Mauritius; (2) more deeply recycled continental crust components preserved by elevated $^{87}Sr/^{86}Sr$ and $^{208}Pb/^{206}Pb$ in lavas from the Piton des Neiges volcano of Réunion; and (3) an isotopically depleted mantle component resulting from interaction with Central Indian Ridge material.

In this study we use Sr-Nd-Pb isotope systematics, along with major and trace element compositions of basaltic lavas from all three Mascarene Islands to investigate the relationship of their sources to well-characterized mantle endmembers. Among the Mascarene Islands, Rodrigues lavas are the most enriched in highly incompatible elements, likely reflecting shallower and lower degrees of partial melting than Réunion or Mauritius. Combined Sr-Nd-Pb isotope compositions indicate that lavas from the Older Series of Mauritius resemble those from Réunion, whereas lavas from the Younger and Intermediate Series, together with Rodrigues, are consistent with contributions from an isotopically depleted component. In addition, the Pb isotopic compositions of Rodrigues samples require an additional contribution from a component with a long-term enrichment in its Th/U ratio. Based on isotope mixing models, direct assimilation of continental crust embedded within the oceanic lithosphere is unlikely to account for the Pb isotopic variation of Rodrigues. A metasomatized mantle component, previously envisaged as a "fossil" Réunion plume near the Central Indian Ridge, is partially able to reproduce the trace element signature, but not the observed Sr-Nd-Pb isotopic compositions of Rodrigues. Instead, small proportions (<5%) of an EM1-like component provide a preferred endmember. The composition and origin of this component, which is exclusively reflected within Rodrigues lavas, may constitute a new geochemical feature of the Mascarene Islands and is consistent with geodynamical predictions that small-scale enriched mantle domains may be widespread in the source regions of hotspot volcanoes.

1. Introduction

Earth's mantle is suggested to host various reservoirs with different elemental and isotopic signatures that reflect the secular evolution of the mantle and its dynamic interaction with the crust. A major source for investigating the geochemical characteristics of these mantle reservoirs are oceanic basalts, including ocean island basalts (OIB; e.g., Zindler and Hart, 1986; Hofmann, 1988, 1997, 2014; Stracke, 2012). Most OIB are typically assumed to derive from mantle domains deeper than the source of mid-ocean ridge basalts (MORB; e.g., Hofmann and Hart, 1978), meaning that OIB and MORB may sample fundamentally different mantle domains. Although the compositional fields of global MORB and OIB overlap to some extent, the latter display a broader range in Sr-Nd-Pb isotope compositions compared to MORB (e.g., Hofmann, 2014). This implies that the mantle source reservoirs for OIB are either more heterogeneous or consist of multiple distinct reservoirs with distinct

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histories. The different isotopic signatures of various ocean islands led to the introduction of compositional endmembers by Zindler and Hart (1986), which can account for the majority of the Sr-Nd-Pb isotopic array displayed by OIB. These components are the depleted MORB mantle (DMM), the prevalent mantle (PREMA; often and here referred to as FOZO for "Focal Zone"), high-μ (HIMU; $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$), and enriched mantle (EM), which is sometimes described as two discrete endmembers (EM1 and EM2; e.g., Hart et al., 1992) or as a continuum of endmembers (e.g., Class et al., 2009; Willbold and Stracke 2010). Each of these components is thought to have been generated through distinct processes, the understanding of which is fundamental to unraveling the history and evolution of the silicate Earth.

Ocean island basalts from the Mascarene Islands, consisting of La Réunion, Mauritius, and Rodrigues (Fig. 1), show limited variations in isotopic compositions compared to other ocean islands. These variations were attributed to the interaction of a remarkably homogeneous Réunion mantle plume (e.g., Fisk et al. 1988; Albarède et al., 1997; Vlastélic et al., 2005) with contributions from at least three different mantle components (e.g., Paul et al., 2005; Bosch et al., 2008; Nauret et al., 2019). The first and dominant geochemical component of Réunion hotspot OIB is akin to FOZO (e.g., Bosch et al., 2008; Moore et al., 2011). It is generally described as a common geochemical component to most – if not all mantle plumes (Hart et al., 1992). The second component is DMM, which was previously discussed as a potential source reservoir for lavas from Réunion and Mauritius (Nohda et al., 2005; Paul et al., 2005; Bosch et al., 2008; Moore et al., 2011; Nauret et al., 2019). Finally, small proportions of an isotopically enriched component was proposed to contribute to the Réunion plume composition, which could be of EM1 "flavor" (Bosch et al., 2008). The origins of EM1 endmember compositions are disputed, with most studies proposing the incorporation of continental material (e.g., Milner and le Roex, 1996; Eisele et al., 2002; Willbold and Stracke, 2006; 2010; Delavault et al., 2016; Boyet et al., 2019).

Alternatively, isotopically enriched components could derive from a Precambrian continental crust fragment beneath Mauritius. The presence of a continental crust fragment could explain anomalously thick crust extending from Mauritius to the Seychelles and the discovery of Proterozoic zircons in basaltic beach sands of Mauritius (Torsvik et al., 2013), although these interpretations are controversial (e.g., Singh et al., 2016). More recent support for this theory stems from the recovery of Archaean-aged zircons in Mauritian trachytes (Ashwal et al., 2017). A crustal fragment in the mantle lithosphere may be a remnant of the Gondwana break-up in the early Cretaceous (Torsvik et al., 2013; Ashwal et al., 2017). Alternatively, isotopic signatures with continental crust affinities could represent more deeply recycled continental crust with a geochemical affinity to crust from Madagascar and the Seychelles, as proposed for Réunion and speculated for Mauritius OIB (Nauret et al., 2019). Both hypotheses for the introduction of a continental crust signature into an OIB source have not been evaluated in parallel for the Réunion hotspot.

In general, most research on the Réunion volcanic hotspot system has focused on either Réunion or Mauritius, which both lie on the main hotspot track. From this, it is well known that OIB from Réunion and the Older Series lavas of Mauritius display similar geochemical and isotopic signatures that are considered characteristic of the Réunion plume (Nohda et al., 2005; Paul et al., 2005; Moore et al., 2011). In contrast, Rodrigues is situated off the hotspot track but is assumed to be connected to it and to the Central Indian Ridge (CIR) via en-échelon volcanic ridges (Dyment et al., 1999; Fig. 1), making it unique among global hotspot systems. There may also be significant differences in the geochemical and isotopic signatures between Rodrigues and Réunion and/or Mauritius. However, there are few geochemical and petrological studies on Rodrigues (McDougall and Compston, 1965; McDougall et al., 1965; Upton et al., 1967; Baxter et al., 1985). Adding new constraints on the geochemical and isotopic character of OIB from Rodrigues to the framework of the understanding of the Réunion hotspot may help to further assess whether isotopically enriched components are common features of hotspot systems like Réunion. Here, we report new Sr-Nd-Pb isotope compositions, as well as major and trace element abundance data for OIB from all three Mascarene Islands to characterize the persistence of Réunion plume-like and enriched signatures across the Mascarene Islands chain.

2. Samples and methods

The investigated samples were collected in a 2007 field campaign and represent unweathered basaltic lava flows deriving from all three Mascarene Islands (Réunion, Mauritius, and Rodrigues). The sampling locations (Table S.1) cover all inferred volcanostratigraphic units on each island (e.g., McDougall, 1971; Gillot and Nativel, 1982 for Réunion; McDougall and Chamalaun, 1969; Baxter, 1972; 1975 for Mauritius; Upton et al, 1967 for Rodrigues). Simplified geological maps

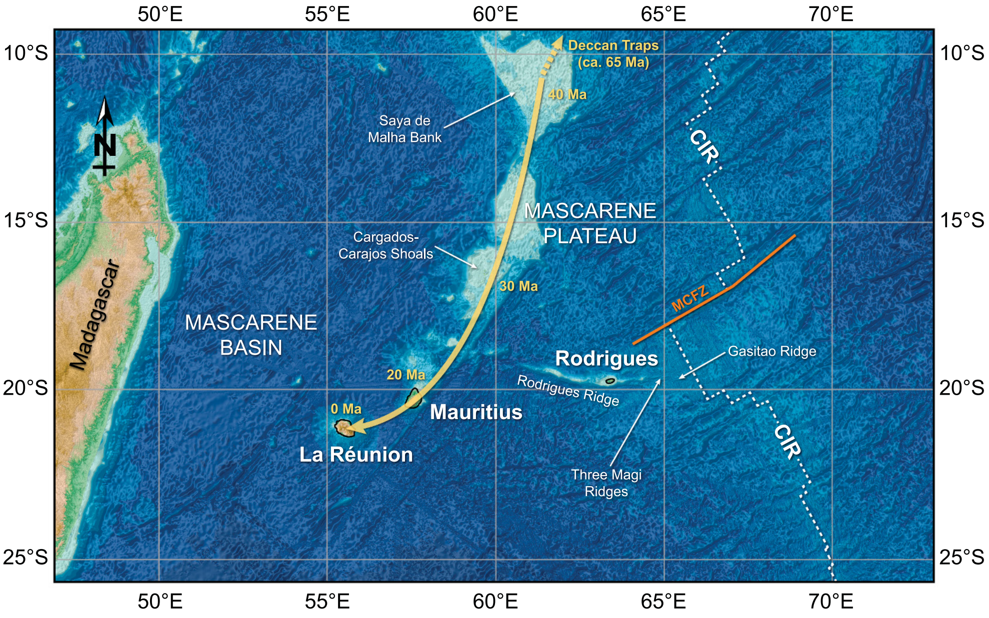

Fig. 1. Location map of the Mascarene Islands in the western Indian Ocean. The path of the Central Indian Ridge (CIR) is roughly traced. The islands of La Réunion and Mauritius are located on the Réunion hotspot track (indicated by the yellow arrow), which extends from the Deccan Traps (ca. 65 Ma), via the Maldives, Chagos, and the Mascarene Plateau, to its modern surface expression La Réunion. Rodrigues lies on the eastern end of the Rodrigues Ridge, away from the hotspot track, but is connected to it and to the CIR via en-échelon volcanic ridges (i.e., the Rodrigues Ridge, the Three Magi Ridges, and the Gasitao Ridge; Dyment et al., 1999). The base map is the General Bathymetric Chart of the Oceans (GEBCO_2021 Grid; GEBCO Bathymetric Compilation Group, 2021). MCFZ: Marie Celeste Fracture Zone.

of the Mascarene Islands including the sampling locations are shown in Fig. S.1. The collected rocks represent a range of bulk geochemical compositions from picrobasalt to trachybasalt, with Rodrigues lavas being more differentiated than those from Réunion and Mauritius. Most of the rocks are olivine- and/or clinopyroxene-phyric.

Before crushing, weathered rock surfaces were removed using a diamond lap saw. Afterwards, any metal remnants were abraded with corundum paper. The samples were then crushed in an alumina-paneled jaw crusher, followed by pulverization in an alumina vessel using a Spex ShatterBox®. Bulk rock major and select trace element compositions were acquired using a PANalytical PW2404 X-ray fluorescence analysis (XRF) vacuum spectrometer at Franklin & Marshall University (fandm.edu/earth-environment/laboratory-facilities/xrf-and-xrd-lab; Boyd and Mertzman, 1987), along with measurement of loss on ignition (LOI) and ferrous Fe abundance by titration. Other trace element data were collected using a Thermo Scientific™ iCAP™ q-C quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at the Scripps Isotope Geochemistry Laboratory (cf. Peters et al., 2016 for more detail). This dataset was already published for the majority of Réunion samples (Peters et al, 2016, 2019) and are now complemented with data from Mauritius ($n = 8$) and Rodrigues ($n = 12$). For data analysis and modeling, only the trace element data measured with ICP-MS were used.

In terms of isotopes, Nd isotopic compositions for all investigated Réunion samples (Peters et al., 2018), as well as Os (Peters et al, 2016), Hf, and W isotopic compositions (Peters et al., 2021) for a subset of the Réunion samples were previously determined. In addition, a subset of samples from all three Mascarene Islands were analyzed for He isotopes (Füri et al., 2011). In this study, selected samples from Réunion ($n = 15$), Mauritius ($n = 6$), and Rodrigues ($n = 8$) were measured for Sr, Nd, and/or Pb isotopic compositions. The chosen samples represent the whole compositional range displayed within the trace element data, including average and extreme compositions, although the limited size of the sample set nevertheless holds the potential to miss some compositional variation.

The rock powder samples were dissolved and Sr, Nd, and Pb were separated from the rock matrix according to the methods provided in the Supplementary Material (Table S.2). Following recent practice for young OIB (e.g., Truong et al., 2018; Nauret et al., 2019), the samples were not leached prior to the Sr-Nd-Pb separation chemistry because their unweathered appearance, generally low loss on ignition (<2.5 wt% except for three samples), and the presence of fresh olivine phenocrysts renders significant post-eruptive alteration unlikely. Moreover, isotope ratios are generally suggested to be robust to alteration processes and measuring unleached samples enables comparison with previously obtained data of unleached Réunion OIB that preserve evidence for an isotopically enriched component (e.g., Nauret et al. 2019). To confirm these observations, leaching experiments were conducted on selected samples from Mauritius and Rodrigues (see Supplementary Material) to evaluate the potential Sr and Pb isotopic contributions from alteration products, which may result in a more radiogenic signature (e.g., Nobre Silva et al., 2009, 2010). These experiments did not reveal significant differences in Sr-Pb isotope compositions large enough to change the major conclusions of the study with respect to mantle source compositions (Figs. S.2–S.4; Table S.3). The effect of acid leaching on Nd isotope compositions was not determined because of the limited mobility of Nd in water (e.g., Nobre Silva et al., 2010).

The measurement procedures for Sr-Nd-Pb isotopes are described in detail in the Supplementary Material. All isotope data were collected in the mass spectrometry laboratories of the Institute of Geochemistry and Petrology (IGP) at ETH Zürich. Sample Sr isotopic compositions were normalized to the NIST® SRM987 Sr-carbonate standard given a measured value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710238 \pm 0.000013$ (2 SD; $n = 90$) and a preferred value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.710245$ (GeoReM; Jochum et al., 2005). Repeated measurements of the NIST® SRM981 common Pb standard ($n = 117$) resulted in average Pb isotope ratios of $^{206}\text{Pb}/^{204}\text{Pb} = 16.9422 \pm 0.0009$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4999 \pm 0.0012$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.725 \pm 0.003$ (all errors are 2 SD) and sample data were normalized to the preferred values of Baker et al. (2004). The average $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of measured JNdi standards was 0.512113 ± 0.000009 (2 SD; $n = 79$) and the external reproducibility of Nd isotopic measurements was estimated as $\pm$ 0.2 ε^{143}Nd units. Average measured blanks were (in pg) 276 for Sr, 21 for Nd, and 3 for Pb.

3. Results

3.1. Major and trace element compositions

Major and trace element data of the Mascarene Islands samples are presented in Table S.3. Rocks from Réunion have the lowest total alkali and silica contents, whereas those from Mauritius and especially Rodrigues are relatively differentiated (Fig. 2). One sample from Rodrigues, RG0702, is a basalt containing plagioclase glomerocrysts and was collected in an area where gabbroic crustal xenoliths are present in other basalt flows. It is therefore possible that the composition of this sample was modified by addition of xenocrystic material with the same origin as the gabbro xenoliths. The MgO contents of all samples considered in this study range from 7.2 to 35.1 wt% for Réunion, 7.2 to 12.0 wt% for Mauritius, and 4.5 to 9.4 wt% for Rodrigues.

The LOI values for Réunion samples are typically below 1 wt%. However, three samples have LOI values >2 wt% and the LOI for sample RU0715 is about 5 wt%. Mauritius rocks display LOI values in the range of about 1.0–4.7 wt%. Lavas from Rodrigues exhibit the lowest LOI, varying from approximately 0.6–2.5 wt%. Consistent with these generally low LOI values (<2.5 wt%) of most Mascarene Islands samples, these rocks were considered fresh upon collection, without observed affection by post-magmatic alteration.

Primitive mantle normalized trace element abundance patterns (spidergrams) for the Mascarene Islands samples are displayed in Fig. 3. Overall, steep, sub-parallel rare earth element (REE) patterns are observed for samples from Réunion (Fig. 3a), which show La/Sm$_N$ (primitive mantle-normalized; McDonough and Sun, 1995) ratios of 1.7–2.4 and Dy/Yb$_N$ ratios of 1.5–1.7. These ratios correspond to systematic depletions of the heavy relative to the light REE, whereas the sub-parallel patterns of different samples are consistent with heterogeneous accumulation and fractionation of olivine as the magma ascends to the surface.

Mauritius exhibits the highest variability in trace element compositions (Fig. 3b), with different trends associated with the distinct lava series recognized for Mauritius. Basalts from Mauritius were grouped

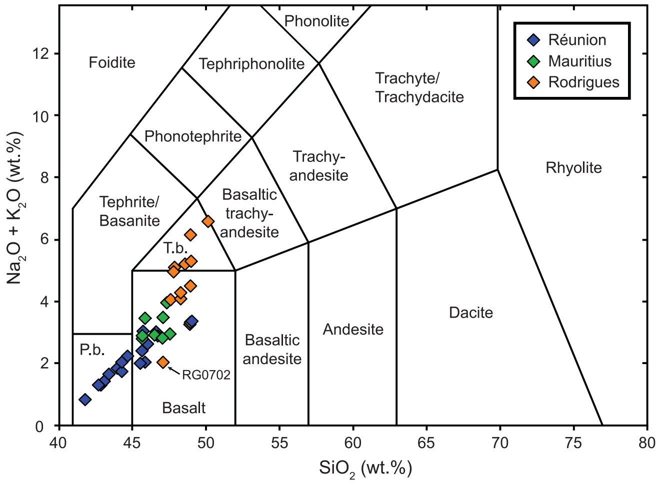

Fig. 2. Total alkali versus silica diagram for volcanic rocks after Le Bas et al. (1986), showing all analyzed Mascarene Islands samples. All lavas have either picrobasaltic, basaltic, or trachybasaltic compositions. Abbreviations: P.b. = Picrobasalt, T.b. = Trachybasalt.

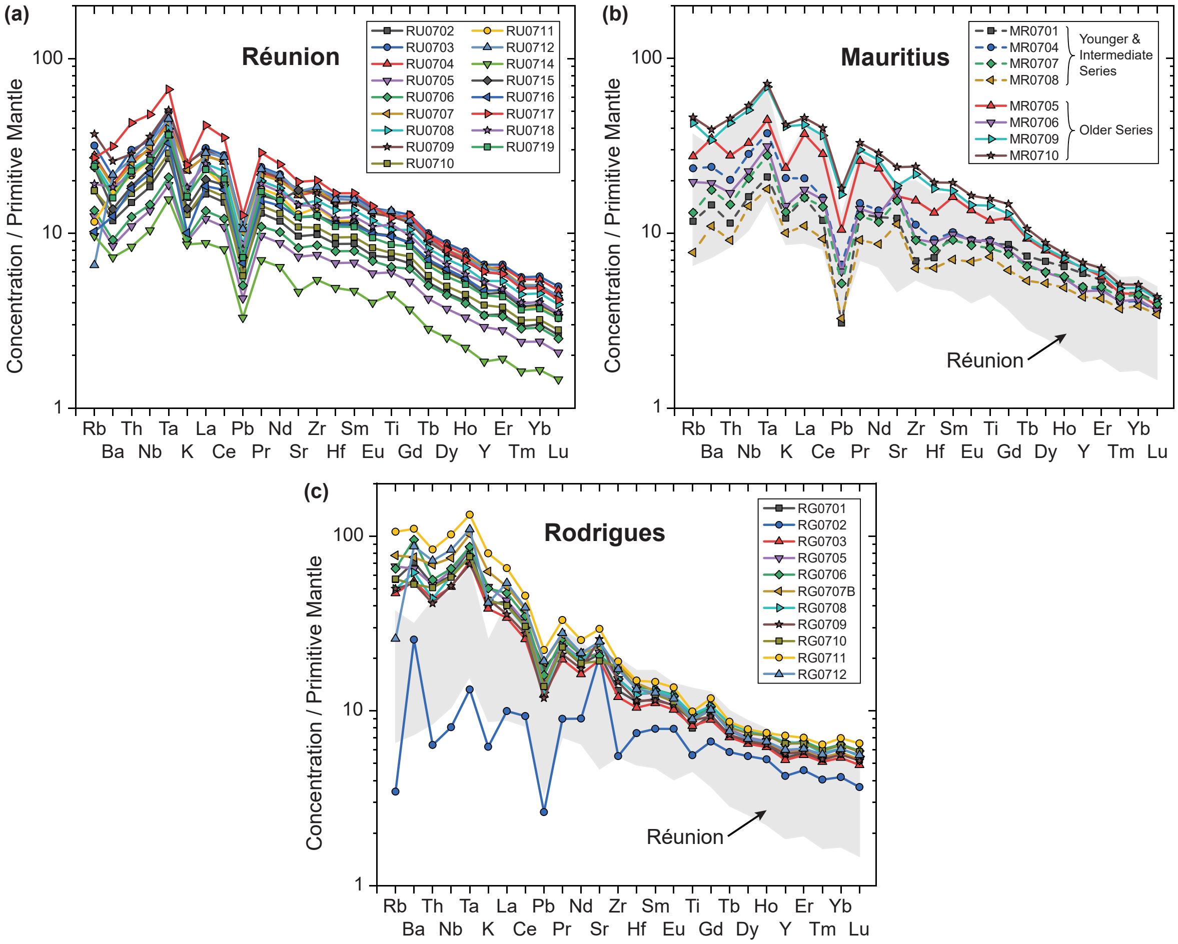

Fig. 3. Trace element variation diagrams of the analyzed samples from (a) Réunion, (b) Mauritius, and (c) Rodrigues. Trace element concentrations are normalized to the primitive mantle composition proposed by McDonough and Sun (1995). The field of abundances for Réunion lavas (gray array) is displayed in panels b and c for comparison.

into lavas from the incompatible element enriched Older Series, which is associated with the shield-building phase, and those from the Younger and Intermediate Series, associated with phases of rejuvenated volcanism (Baxter, 1972; Moore et al., 2011). The slopes of the REE among Older Series lavas are similar to lavas from Réunion, whereas those from the Younger and Intermediate Series are flatter. This corresponds to an enrichment in incompatible trace element abundances for the Older Series ($La/Sm_N = 1.8–2.4$) compared to the Younger and Intermediate Series ($La/Sm_N = 1.6–2.0$). The heavy REE compositions, on the other hand, are more similar throughout the different series (Dy/Yb_N ratios of 1.3 to 1.8 across both series). These patterns for Mauritius lavas are consistent with previous studies (Paul et al., 2005; Moore et al., 2011).

Rodrigues displays the highest abundance in the highly incompatible elements ($La/Sm_N = 3.1–4.5$; except for RG0702 with a ratio of 1.3), evolving to a flatter pattern than Réunion for the heavy REE ($Dy/Yb_N = 1.1–1.3$; Fig. 3c). Sample RG0702 is significantly more REE-depleted compared to the others, consistent with the previously mentioned possibility that it may contain gabbroic xenoliths. This sample further shows a pronounced relative enrichment in Sr abundance, reflecting the presence of accumulated plagioclase, as observed in the hand sample.

The Réunion incompatible trace element patterns show relative depletions in Ba, K, and Pb (Ce/Pb = 26.5–31.7). These depletions are commonly observed in rocks that were not influenced by recycled crust or sediments (cf. Hofmann, 1988), except for EM derived lavas (e.g., Eisele et al., 2002; Workman et al., 2004). Relative depletions in Pb are similarly present for Mauritius and Rodrigues (Ce/Pb = 24.3–43.1 and 19.6–26.1, respectively), but with a somewhat lower magnitude for the latter. However, negative K and Ba spikes are less pronounced or absent in their patterns.

3.2. *Strontium-Nd-Pb isotope data*

The obtained Sr-Nd-Pb isotope data for the Mascarene Islands samples are illustrated in Tables 1 and S.4. In general, Mauritius rocks display the highest variation in isotopic ratios, reflecting the compositional differences of the inferred eruption phases on the island. The Older Series lavas resemble those from Réunion, whereas the Younger and Intermediate Series rocks are more similar to basalts from Rodrigues.

The highest $^{87}Sr/^{86}Sr$ ratios are displayed by lavas from Réunion and the Mauritius Older Series (Fig. 4a). Réunion rocks yield $^{87}Sr/^{86}Sr$ ratios between 0.70404 and 0.70426, whereas the Older Series range from 0.70418 to 0.70429. Samples from the Mauritius Younger/Intermediate Series, together with Rodrigues lavas, are more depleted. Their $^{87}Sr/^{86}Sr$ ratio ranges are 0.70368–0.70391 and 0.70359–0.70378, respectively. The Sr isotope data of all islands are within the range reported in previous works. The literature data of the Mascarene Islands considered in this study derives from a GEOROC database query (georoc.mpch-mainz.gwdg.de) and is filtered as described in the Supplementary Material. Most MORB have lower $^{87}Sr/^{86}Sr$ ratios compared to those of the Mascarene Islands, whereas some OIB show significantly higher ratios (e.g., Society, Samoa, and Tristan; cf. Stracke, 2012; Hofmann, 2014).

Neodymium isotope ratios (Fig. 4b) of the Mauritius Older Series are also Réunion-like, ranging from 0.512849 to 0.512868. The Mauritius

Table 1
Sr-Nd-Pb isotope data for selected samples from the Mascarene Islands and USGS standard reference materials.

Sample	^{87}Sr/^{86}Sr	2 SE/SD	*n*	^{206}Pb/^{204}Pb	2 SD	^{207}Pb/^{204}Pb	2 SD	^{208}Pb/^{204}Pb	2 SD	(^{208}Pb/^{206}Pb)*	*n*	^{143}Nd/^{144}Nd	2 SD	ε^{143}Nd	2 SD	*n*
Réunion:																
RU0702[a]	0.704174	0.000009	4									0.512847	0.000001	4.24	0.01	2
RU0703[a]	0.704162	0.000003	1									0.512852	0.000002	4.34	0.02	4
RU0705[a]	0.704167	0.000003	1									0.512854	0.000027	4.37	0.27	2
RU0706[a]	0.704124	0.000003	1									0.512862	0.000013	4.52	0.13	2
RU0707[a]	0.704174	0.000001	2	18.827	0.003	15.607	0.003	38.933	0.010	0.9934	4	0.512852	0.000001	4.32	0.01	1
RU0708[a]	0.704125	0.000003	1	18.914	0.004	15.606	0.003	39.024	0.011	0.9939	4	0.512858	0.000002	4.46	0.02	3
RU0709[a]	0.704200	0.000015	2	18.935	0.003	15.608	0.003	39.061	0.009	0.9955	4	0.512851	0.000008	4.32	0.08	3
RU0710[a]	0.704195	0.000003	1									0.512849	0.000016	4.28	0.06	2
RU0711[a]	0.704246	0.000009	3									0.512838	0.000005	4.05	0.05	3
RU0712[a]	0.704259	0.000003	1	18.938	0.003	15.613	0.003	39.013	0.010	0.9902	4	0.512827	0.000001	3.85	0.01	2
RU0715[a]	0.704130	0.000003	1									0.512856	0.000001	4.42	0.01	2
RU0716[a]	0.704039	0.000002	1	18.955	0.003	15.607	0.003	39.052	0.011	0.9926	4	0.512872	0.000002	4.73	0.02	4
RU0717[a]	0.704218	0.000003	1									0.512831	0.000001	3.93	0.01	1
RU0718[a]	0.704108	0.000006	2									0.512854	0.000001	4.37	0.01	1
RU0719[a]	0.704225	0.000003	1									0.512841	0.000004	4.11	0.04	3
Mauritius																
Younger and Intermediate Series:																
MR0701	0.703908	0.000008	6	18.8764	0.0006	15.5953	0.0004	38.932	0.002	0.9882	4	0.512912	0.000009	5.50	0.17	3
MR0704	0.703678	0.000010	6	18.7986	0.0007	15.5785	0.0010	38.807	0.003	0.9831	3	0.512929	0.000007	5.84	0.13	3
MR0708	0.703679	0.000006	8	18.8128	0.0005	15.5822	0.0005	38.851	0.002	0.9862	4	0.512908	0.000001	5.42	0.01	3
Older Series:																
MR0705	0.704292	0.000010	6	18.8373	0.0011	15.6090	0.0013	38.932	0.003	0.9922	9	0.512863	0.000001	4.55	0.02	3
MR0709	0.704179	0.000005	6	19.0257	0.0012	15.6199	0.0012	39.147	0.003	0.9951	9	0.512868	0.000002	4.64	0.04	3
MR0710[b]	0.704293	0.000015	8	19.0068	0.0011	15.6180	0.0006	39.159	0.002	0.9982	4	0.512849	0.000009	4.28	0.17	3
MR0710 rep	0.704288	0.000007	6	19.0065	0.0011	15.6179	0.0010	39.156	0.002	0.9980	9					
Rodrigues:																
RG0703	0.703666	0.000006	7	19.1577	0.0006	15.6059	0.0010	39.192	0.003	0.9863	5	0.512875	0.000014	4.78	0.28	3
RG0705	0.703591	0.000006	6	18.9972	0.0007	15.5974	0.0004	39.121	0.001	0.9953	6	0.512848	0.000010	4.25	0.19	3
RG0706	0.703779	0.000013	6	19.0158	0.0008	15.5932	0.0006	39.114	0.003	0.9927	6	0.512894	0.000006	5.15	0.12	3
RG0707B	0.703621	0.000012	6	18.8324	0.0009	15.6058	0.0005	38.813	0.002	0.9802	6	0.512899	0.000017	5.25	0.33	3
RG0708	0.703692	0.000005	6	19.1299	0.0012	15.6105	0.0010	39.154	0.002	0.9852	9	0.512902	0.000012	5.31	0.23	3
RG0710	0.703692	0.000008	6	19.0386	0.0013	15.6006	0.0009	39.072	0.002	0.9861	9	0.512891	0.000003	5.09	0.06	3
RG0711	0.703679	0.000007	4	19.1425	0.0005	15.6042	0.0011	39.241	0.005	0.9928	3	0.512883	0.000007	4.93	0.13	3
RG0712	0.703618	0.000006	4	19.1210	0.0012	15.6046	0.0009	39.217	0.001	0.9926	3	0.512882	0.000010	4.91	0.19	3
USGS reference materials:																
BHVO-2	0.703471	0.000011	16	18.6492	0.0009	15.5420	0.0008	38.2741	0.0025	0.9418	9	0.512983	0.000007	6.89	0.14	11
BCR-2	0.705007	0.000008	6	18.7627	0.0008	15.6306	0.0008	38.7473	0.0021	0.9805	25	0.512636	0.000007	0.11	0.14	11

Notes: For single runs, the reported values are given as run average and 2 SE from the mean of the run. For replicated measurements, the reported values represent the averages and 2 SD of all accepted runs. The variable *n* represents the number of measurements per sample. The (^{208}Pb/^{206}Pb)* ratio was defined as [(^{208}Pb/^{204}Pb)$_{sample}$ − 29.476]/[(^{206}Pb/^{204}Pb)$_{sample}$ − 9.307] by Galer and O'Nions (1985). The ε^{143}Nd values are defined as [(^{143}Nd/^{144}Nd)$_{sample}$ / (^{143}Nd/^{144}Nd)$_{CHUR}$ − 1]·10^4, with CHUR being the chondritic uniform reservoir.

[a] Nd isotope data from Peters et al. (2018).

[b] For interpretation and modeling, the values for sample MR0710 were averaged from the two separate digestions, which display excellent agreement.

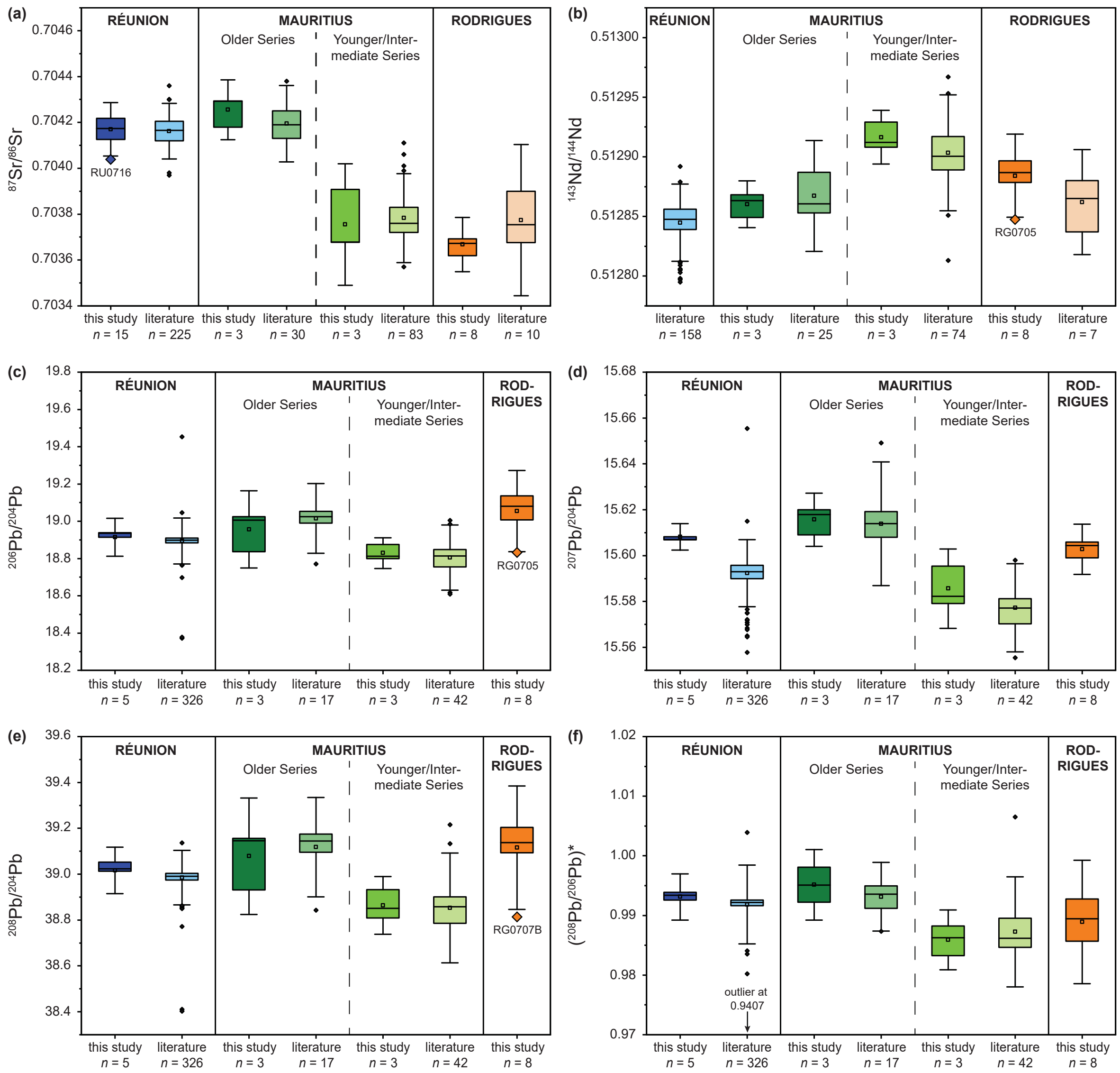

Fig. 4. Box-and-whisker diagrams of the measured (a) $^{87}Sr/^{86}Sr$, (b) $^{143}Nd/^{144}Nd$, (c) $^{206}Pb/^{204}Pb$, (d) $^{207}Pb/^{204}Pb$, (e) $^{208}Pb/^{204}Pb$, and (f) calculated $(^{208}Pb/^{206}Pb)^*$ ratios of the investigated Mascarene Islands samples (strong colors) and literature data (weak colors). Samples from Mauritius were grouped into lavas from the Older Series and those from the Younger/Intermediate Series. The value *n* represents the number of datapoints in each category. The boxes show the inter-quartile range and the whiskers represent 2 SD of the data about the medians, which are displayed inside the boxes as empty squares. Statistical outliers are plotted as individual datapoints (diamonds) but were not excluded from the discussion and modeling on this basis (RG0705, RG0707B). Literature data was selected and filtered as described in the Supplementary Material. The data for Réunion derives from Graham et al. (1990), Albarède and Tamagnan (1988), Albarède et al. (1997), Fisk et al. (1988), Nauret et al. (2006, 2019), Luais (2004), Bosch et al. (2008), Pietruszka et al. (2009), Vlastélic et al. (2005, 2007, 2009, 2016), Schiano et al. (2012), Di Muro et al. (2014), and Israel et al. (2020); for Mauritius from Peng and Mahoney (1995), Sheth et al. (2003), Nohda et al. (2005), Paul et al. (2005), and Moore et al (2011); and for Rodrigues from McDougall and Compston (1965) and Baxter et al. (1985).

Younger and Intermediate Series show the highest Nd isotope ratios (0.512908–0.512929). Both are consistent with literature data. Rodrigues lavas display ratios from 0.512848 to 0.512902, with the majority falling within the range of the Mauritius groups. Literature values from Rodrigues overlap with our data but are slightly shifted towards lower ratios (Baxter et al., 1985). The obtained Nd isotope data is in accordance with DMM contributions to the lavas from the Younger and Intermediate Series, as well as Rodrigues.

The new Pb isotope ratios of the Mascarene Islands rocks (Fig. 4c–e) are less variable but still distinct between the islands. Réunion samples show $^{206}Pb/^{204}Pb$ ratios from 18.827 to 18.955, $^{207}Pb/^{204}Pb$ ratios from 15.606 to 15.613, and $^{208}Pb/^{204}Pb$ ratios from 38.933 to 39.061. The $^{207}Pb/^{204}Pb$ ratios for Réunion OIB are slightly elevated in contrast to most literature values, whereas the other Pb isotope ratios, as well as all Pb isotope ratios for Mauritius OIB, agree well with literature data. Although post-eruptive alteration cannot be ruled out as cause for the elevated $^{207}Pb/^{204}Pb$ ratios, it is unclear as to why only the ^{207}Pb composition would be uniquely affected by geologically recent alteration processes (e.g., Nobre Silva et al., 2009). The Pb isotope variations for the Mauritius Older Series are comparable to those for Réunion samples but are slightly more radiogenic (18.837–19.026 for $^{206}Pb/^{204}Pb$, 15.609–15.620 for $^{207}Pb/^{204}Pb$, and 38.932–39.157 for $^{208}Pb/^{204}Pb$). The Younger and Intermediate Series exhibit less radiogenic Pb ratios of 18.799–18.876, 15.579–15.595, and 38.807–38.932, respectively. The more radiogenic Pb isotopic signature of the Older Series lavas compared to those from the Younger and Intermediate Series is consistent with previous studies. The analyzed Rodrigues lavas tend towards higher $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios (18.832–19.158 and 38.813–39.241), whereas the $^{207}Pb/^{204}Pb$ ratios (15.593–15.611) are within the range of Réunion and Mauritius Older

Series samples.

In contrast to the other Rodrigues samples, RG0707B displays significantly lower $^{206}Pb/^{204}Pb$ (Fig. 4e) and $^{208}Pb/^{204}Pb$ ratios (Fig. 4c). The isotopic signature of RG0707B is comparable to that of the Younger and Intermediate Series samples from Mauritius. However, this less radiogenic composition is neither reflected by its $^{207}Pb/^{204}Pb$ ratio (Fig. 4d) nor by distinct major and trace element concentrations (Fig. 3). In fact, RG0707B shows major and trace element abundances close to the average values of other Rodrigues samples.

4. Discussion

4.1. Trace element compositions and constraints on partial melting

To interpret the geochemical compositions of mantle sources to the Mascarene Islands, processes during and after melting, which may have affected the compositions of the samples, must be evaluated. Fractional crystallization is one essential mechanism that may alter the composition of melts, including their incompatible trace element ratios. During ascent, a magma may also assimilate minerals in lithospheric storage regions that were fractionally crystallized from previous magma batches, a process termed “cannibalism” by Albarède et al. (1997). The role of mineral fractionation and accumulation among OIB can be assessed by investigating the relationships of incompatible trace element ratios with MgO contents. As opposed to Réunion and Mauritius, the more evolved lavas from Rodrigues show clear trends between MgO contents and La/Sm, Ba/Y, and Nb/Zr ratios, which all increase with decreasing MgO content (see correlation coefficients in Table S.6). These indicate that the incompatible trace element budget of Rodrigues samples has been more strongly modified by fractional crystallization than those of Réunion and Mauritius samples. On Réunion, the mineralogical composition of cumulate xenoliths shows that fractional crystallization of mineral phases other than olivine, including clinopyroxene, play a relatively minor role in Réunion magma chambers (e.g., Salaün et al., 2010). Because olivine nearly perfectly excludes REE during fractional crystallization (e.g., Fujimaki et al., 1984), this suggests that REE ratios will remain relatively unmodified during differentiation of Réunion parental magmas. Such a conclusion is supported by relatively low correlation coefficients between MgO abundances and La/Sm or Gd/Yb ratios among Réunion and Mauritius lavas, whereas Rodrigues lavas have higher correlation coefficients. These ratios are therefore well-suited to assess the compositions of Mascarene parental magmas and the processes that generated these compositions.

Considering this, the REE ratios of Mascarene parental magmas are used to assess the relative degrees and depths of partial melting for each island. The compositions of parental magmas (i.e., their compositions before fractional crystallization) for each island are calculated using plots (not shown) of Al_2O_3 versus MgO to estimate the parental MgO abundance based on olivine and clinopyroxene fractionation. The determined parental MgO contents are 12 wt% for Réunion and Mauritius and 9 wt% for Rodrigues. The parental REE ratios are then estimated by calculating REE concentrations at the parental MgO abundance using regressions of REE versus MgO. In particular, the highest La/Sm ratios (>5) that are observed for Rodrigues OIB are interpreted to partially result from fractional crystallization, although the estimated parental magma composition of Rodrigues likewise shows an elevated La/Sm ratio compared to the estimated Réunion and Mauritius parental magma compositions (Fig. 5). By contrast, the relatively constant Gd/Yb ratio of Rodrigues OIB over a variety of MgO abundances means that there is little calculated effect of fractional crystallization on this ratio. In comparison, the calculated parental magmas for Réunion and the Older Series of Mauritius display higher and somewhat more variable Gd/Yb ratios, whereas lavas from the Younger/Intermediate Series of Mauritius plot closer to the Rodrigues Gd/Yb composition.

To quantitatively investigate the relationship of the islands in terms of their melting conditions, melting curves involving different residual proportions of garnet and partial melting fractions were calculated (Fig. 5). The chosen mantle source compositions are depleted MORB mantle (DMM; Workman and Hart, 2005) and a primitive mantle (PM;

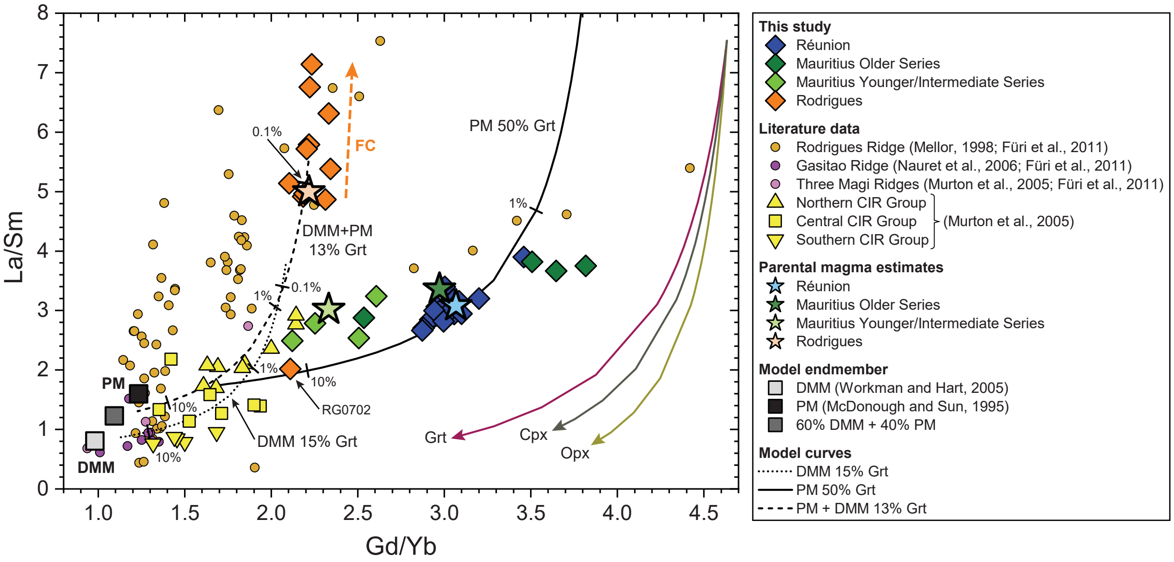

Fig. 5. Gadolinium/Yb versus La/Sm ratios for the Mascarene Islands (this study), together with selected literature data of the adjacent CIR segment (Murton et al., 2005) and the intermediate volcanic ridge systems (Mellor, 1998; Murton et al., 2005; Nauret et al., 2006; Füri et al., 2011) for comparison. The CIR samples are grouped by their geographic location (Northern, Central, and Southern CIR Group) as suggested by Murton et al. (2005). The black lines represent modeled melting curves (up to 20% partial melting) of different solid mantle endmembers with varying proportions of residual garnet: depleted mantle (DMM; light gray square; Workman and Hart, 2005) and 15% residual garnet (dotted line), (2) primitive mantle (PM; black square; McDonough and Sun, 1995) and 50% residual garnet (solid line), and (3) a 60%/40% mixture of DMM and PM (dark gray square) with 13% residual garnet (dashed line). The stars represent estimates of the parental magma compositions of the Mascarene Islands. The vectors on the right demonstrate the effect of garnet (Grt), clinopyroxene (Cpx), and orthopyroxene (Opx) fractionation, and are based on the PM endmember composition and 50% residual garnet. The dashed orange arrow indicates the effect of fractional crystallization (FC) on the compositions of Rodrigues lavas.

McDonough and Sun, 1995), representing the MORB source and a plume-like component, respectively. Contributions from other mantle domains are theoretically possible, including enriched mantle endmembers (cf. Bosch et al., 2008; Nauret et al., 2019). However, the trace element compositions of these endmembers in the solid mantle are not well constrained. The partition coefficients were taken from McKenzie and O'Nions (1991). The calculation of melt compositions assume batch, non-modal melting. Mantle and melt modes are 0.5/0.3/0.1/0.1 and 0.25/0.25/0.25/0.25 for olivine, orthopyroxene, clinopyroxene, and spinel + garnet, respectively (cf. Janney et al., 2002, which similarly considered melting of a PM-like mantle source).

Since interaction between the Réunion hotspot and the nearby CIR was suggested in earlier geochemical and geophysical studies (Morgan, 1978; Murton et al., 2005; Nauret et al., 2006; Füri et al., 2011; Scholz et al., 2018), literature data of samples from the adjacent CIR segment (~18–20°S) from Murton et al. (2005), together with rocks from the intermediate volcanic ridges (Rodrigues Ridge, Three Magi Ridges, and Gasitao Ridge) are included in Fig. 5. Murton et al. (2005) divided the CIR samples into three distinct groups (Northern, Central, and Southern Group), depending on their geographical location within the CIR segment. They observed that the trace element composition of CIR MORB approaches Réunion-like compositions in the Northern Group and becomes more depleted to the south, consistent with the previously proposed pathway of Réunion hotspot-CIR migration (e.g., Morgan, 1978). A reciprocal correlation exists between the Gd/Yb-La/Sm compositions of Réunion and Mauritius Older Series OIB that can be projected through the compositions of many Northern and Central Group CIR MORB (Fig. 5). The Rodrigues Ridge data spans from the Rodrigues to the CIR compositions, whereas the Three Magi Ridges and Gasitao Ridge samples resemble the most incompatible element depleted Southern Group CIR MORB.

A model involving DMM with 15% residual garnet (dotted line in Fig. 5) can reproduce most of the CIR MORB, as well as rocks from the Three Magi Ridges and the Gasitao Ridge. However, due to its depleted composition, even very low degrees of DMM partial melting cannot produce melts with La/Sm or Gd/Yb ratios as high as that of the Rodrigues parental magma. Melting of a PM source with a higher amount of residual garnet (50%; solid line in Fig. 5) can reproduce the Réunion and Mauritius Older Series OIB compositions but this melting curve also does not intersect the Rodrigues parental magma. Thus, models with a mixed DMM + PM source were also considered. A melting curve involving 60% DMM and 40% PM (proportions also implied from the isotopic compositions discussed below), and a residual garnet proportion of 13% (dashed line in Fig. 5) can reproduce the Rodrigues compositions, while also traversing through the Northern and Central CIR Group MORB.

These observations of the model fits permit several comparative observations. First, the compositions of Southern Group CIR MORB are consistent with melting a mantle source that is more trace-element depleted than the sources of the other sample groups. Such a comparison is consistent with observations made in previous studies (Murton et al., 2005; Nauret et al., 2006; Cordier et al., 2010), although these studies argued that the canonical DMM was likely too depleted to explain the trace element compositions of these samples. By contrast, the Rodrigues parental magma may represent melt products of a mantle source with incompatible trace element abundances between those of DMM and PM. Further, the REE ratios of the Rodrigues parental magma indicate that it derives from a melt regime with a lower proportion of garnet versus spinel (i.e., the average depth of melting is shallower) compared to the Réunion and Mauritius Older Series parental magmas. These features are consistent with the general notion of interaction between plume and ridge material (e.g., Murton et al., 2005; Füri et al., 2011; Scholz et al., 2018). In this scenario, the channeling plume material may experience progressive geochemical depletion along the migration path due to continuous melt extraction and preferential melting of enriched compared to depleted plume components, particularly as the plume material is channeled to shallower depths along the base of the lithosphere (e.g., Gibson and Richards, 2018). Thus, the Rodrigues parental magma would then be expected to represent a greater melt proportion of a depleted plume component compared to the Réunion parental magma. Alternatively, the depleted component may be introduced from the ambient depleted mantle into the Rodrigues OIB mantle source. Published trace element compositions for Rodrigues Ridge basalts imply that they may share a mantle source with a similar trace element composition to Rodrigues, but with potentially different melting conditions (depth and/or degree).

Réunion and Mauritius Older Series parental magmas have higher La/Yb and Gd/Yb than CIR MORB (Fig. 5), implying that they derive from lower degrees of partial melting than MORB, whereas the even higher La/Sm ratio of the Rodrigues parental magma indicates even lower degrees of partial melting. This observation comports with more detailed models of plume-ridge interaction, which envisage that volcanic lineaments connecting MOR and hotspot tracks melt only passively compared to regions with vigorous adiabatic melting, such as under the MOR (e.g., Gibson and Richards, 2018). Additionally, the thicker lithosphere underlying Rodrigues compared to the CIR would limit its total extent of melting compared with the latter. However, the existence of Rodrigues as a subaerial island, as well as other volcanic bathymetric features in the same region, requires large magma volumes that are difficult to reconcile with a low fraction of partial melting inferred from trace element compositions. This presents a common paradox for sites of plume-ridge interaction (e.g., Gibson and Richards, 2018). In this context, it is notable that the Mauritius Younger and Intermediate Series parental magma lies close to those of Réunion and the Mauritius Older Series, but with lower Gd/Yb ratios for a given La/Sm ratio (Fig. 5). These compositions imply that the melting characteristics of these lavas reflect conditions intermediate to Réunion and Rodrigues, and that the mantle source to these lavas has a more depleted composition, a lower degree of partial melting, and/or a shallower average depth of melting than the Réunion parental magma.

The presented model has several uncertainties. For example, it utilizes published values for canonical mantle reservoirs such as DMM and PM as assumed mantle sources rather than directly inverting the compositions of the OIB samples (cf., Gibson and Richards, 2018). The participation of distinct endmembers, perhaps more enriched in incompatible trace elements, was not considered here because their trace element compositions are generally unknown. Such an enriched component would relax the unrealistically low degree of melting required to produce the Rodrigues parental magma. Nevertheless, the model provides an opportunity to compare the melting characteristics for each island and compare these to more detailed available models for plume-ridge interaction.

4.2. Isotopic variations of Mascarene lavas

Isotopic compositions are most resistant to magmatic differentiation processes and, therefore, the optimal tools to further investigate the character of the melt source from the Mascarene Islands. The Mauritius Older Series Sr-Nd-Pb isotope compositions (Fig. 6) lie within the array of the Réunion hotspot, showing no indication for a preferred OIB endmember. By contrast, the Younger and Intermediate Series samples tend towards less radiogenic Sr and Pb, and more radiogenic Nd isotopic compositions than Réunion OIB. Rodrigues OIB are less radiogenic than Réunion in terms of Sr and Nd isotopes, but comparable with respect to Pb isotopes (cf. Figs. 4 and 6). The isotopic compositions of Réunion and Mauritius Older Series OIB overlap strongly with the FOZO-like isotopic components of other hotspots, although these other hotspots typically also show trends toward more enriched mantle endmembers, as well as higher $^{3}He/^{4}He$ ratios (Day et al., 2022). The Rodrigues samples define an isotopic trend that is distinct from Réunion and reflect lower time-integrated Rb/Sr and higher time-integrated (U,Th)/Pb and Th/U than Réunion OIB. Such differences are generally consistent with the

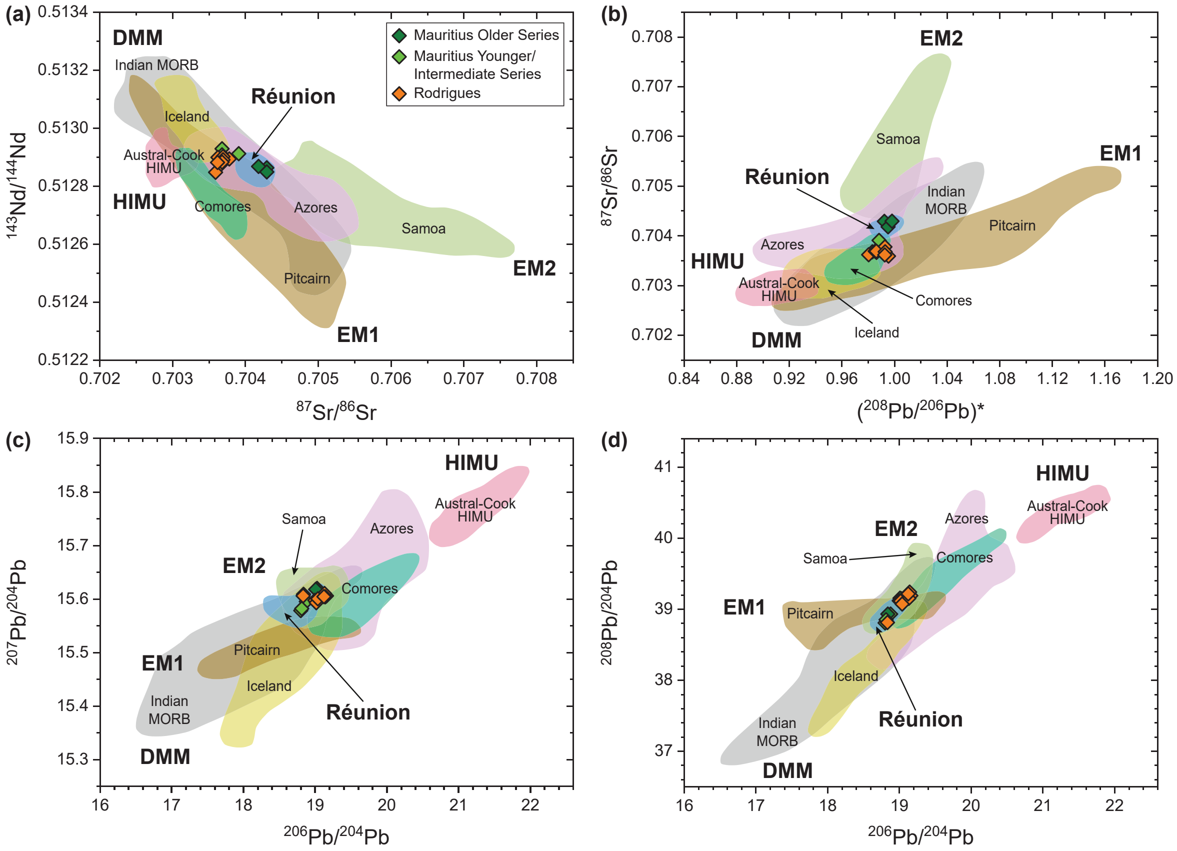

Fig. 6. Isotope data of samples from Mauritius and Rodrigues compared to selected hotspots and Indian MORB from the literature compilation of Stracke (2012) in the (a) $^{87}Sr/^{86}Sr$-$^{143}Nd/^{144}Nd$, (b) $(^{208}Pb/^{206}Pb)^*$-$^{87}Sr/^{86}Sr$, (c) $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$, and (d) $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ space. Literature data for the Réunion fields derive from Dupré and Allègre (1983), Fisk et al. (1988), Vlastélic et al. (2005, 2007, 2009, 2016), Nauret et al. (2006, 2019), Pietruszka et al. (2009), Schiano et al. (2012), and Di Muro et al. (2014). The four typical mantle endmembers from Zindler and Hart (1986) are denoted qualitatively. Note that one Mauritius Younger/Intermediate Series sample in panel a, two in panel b, and several Mauritius samples in panels c and d are covered by Rodrigues data points. Error bars (2 SD) are smaller than the displayed symbols.

compositions of EM-type lavas from, for example, the Comores or Pitcairn, and result in isotopic trends of Rodrigues OIB towards such lavas (e.g., Fig. 9a, b). It is important to note, however, that these trends do not necessarily imply an identical origin of OIB from Rodrigues and these EM hotspots.

The isotopic compositions of the Mascarene Islands samples do not coincide with other hotspots with strongly depleted components, such as Iceland, a hotspot for which an extensive interaction with the MOR has been suggested (e.g., Vogt, 1971, 1976; Schilling, 1973; Cannat et al., 1999). Nevertheless, with respect to Sr and Nd isotopes, OIB from Rodrigues and the Mauritius Younger/Intermediate Series define a distinct trend towards a DMM-like isotopic composition (Fig. 6a). For example, the Réunion basalts, along with those from the enriched Mauritius Older Series display the highest, the Younger/Intermediate Series rocks lower, and the Rodrigues samples the lowest $^{87}Sr/^{86}Sr$ ratios. This pattern is consistent with previously published isotopic data (e.g., Paul et al., 2005; Moore et al., 2011) and supports the proposal of the eastward migration of plume material towards the CIR (Morgan, 1978; Murton et al., 2005; Scholz et al., 2018) and correspondingly greater influence from depleted mantle as one moves eastward from Mauritius to the CIR.

The depletion trend from the hotspot to the CIR has been further investigated in the past by considering the isotopic composition of the Mascarene Islands and the volcanic ridges on the west-east route towards the CIR in dependence of their relative geographical position (Mellor, 1998; Murton et al., 2005; Nauret et al., 2006). Using our new data for the Mascarene Islands, we revisit this relationship with plots similar to those of Mellor (1998), which utilize longitude as representation for the distance from the hotspot (Fig. 7). All three considered isotope ratios confirm the presence of the west-to-east depletion trend observed in previous studies (Mellor, 1998; Murton et al., 2005; Nauret et al., 2006; Füri et al., 2011). While the depletion in the $^{87}Sr/^{86}Sr$ composition is clearly linear (Fig. 7a), the behavior for $(^{208}Pb/^{206}Pb)^*$ (Fig. 7c) and particularly $^{143}Nd/^{144}Nd$ (Fig. 7b) deviates somewhat from linear, likely reflecting differences in the abundance of each element in the respective sources. Samples from the Rodrigues Ridge follow the trend closely, whereas those from the Gasitao Ridge are shifted towards slightly higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios. Nauret et al. (2006) concluded that the isotopically enriched signature of the Gasitao Ridge basalts compared to the CIR MORB at 18–20° S may be attributed to the influence of the Réunion plume. It remains unclear, however, why the Gasitao Ridge samples deviate from the observed depletion trends for Sr and Nd isotopes. The He isotopic compositions of Gasitao Ridge basalts were also shown to be anomalous with respect to the overall eastward depletion trend, with several Gasitao Ridge samples having $^{3}He/^{4}He$ ratios higher than any measured for Mauritius or Rodrigues (Füri et al., 2011).

4.3. Evaluation of the contributing components

4.3.1. DMM and continental crust

To assess the contributing components to the rocks derived from Mauritius and Rodrigues, isotope mixing models were constructed (Fig. 8). The selected endmembers (Table S.5) are a Réunion-like

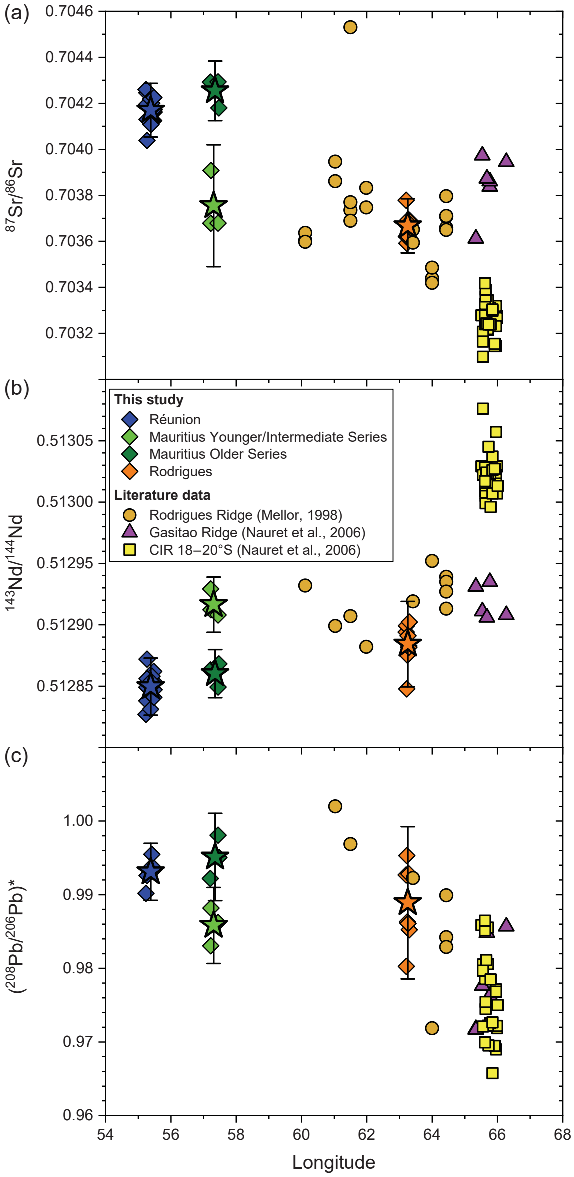

Fig. 7. (a) ^{87}Sr/^{86}Sr, (b) ^{143}Nd/^{144}Nd, and (c) (^{208}Pb/^{206}Pb)* ratios versus the longitude of their sampling/dredging location of samples from the Mascarene Islands (this study) and the intermediate volcanic ridges on the west-east route towards the CIR (Mellor, 1998; Nauret et al., 2006). Stars represent averages and 2 SD of the Mascarene Island compositions.

component, DMM (with trace element abundances represented by a 6% partial melt of a DMM source), and an isotopically enriched component, here represented by various continental crust (CC) components. The latter comprise a regional, Seychelles-Madagascar-like CC component, as suggested by Nauret et al. (2019), as well as generalized upper and lower continental crust compositions (UCC and LCC; Rudnick and Gao, 2014). These endmembers were chosen based on the proposed interaction of the hotspot with the MOR (which represents the DMM source; e.g., Morgan, 1978; Murton et al., 2005) and the suggested presence of a continental crust fragment in the lithospheric mantle beneath Mauritius (e.g., Torsvik et al., 2013; Ashwal et al., 2016, 2017). The model assumes mixing of plume and depleted components in the liquid state, which simulates potential differences in the rate of melting between these components. However, consistent with the idea that solid CC material may be directly assimilated by melts as they ascend through the lithosphere (after Ashwal et al., 2016), the solid compositions of crustal components are utilized in the mixing model. The mixing calculations between two isotopic endmembers were performed using the approach given by Faure (1977; see Supplementary Material for more detail).

The isotope data for Mauritius Older Series predominantly lie within the Réunion field (Fig. 8). Contributions from components other than the Réunion-plume are therefore not required to explain the compositions of these Older Series samples (e.g., Paul et al., 2005). Two Mauritius lavas (MR0704 from the Intermediate Series and MR0708 from the Younger Series), however, trend towards the DMM endmember in all selected isotope space, consistent with previous studies of Mauritius lavas (e.g., Paul et al., 2005; Moore et al., 2011). This indicates that the lavas of the rejuvenation-associated Younger and Intermediate Series have stronger contributions from a DMM component (up to <60%). Direct assimilation of continental crust from the lithosphere during plume ascent (cf. Torsvik et al., 2013; Ashwal et al., 2016, 2017), represented by direct mixing of crustal compositions in Fig. 8, is not supported by these models. Data for the Gasitao Ridge and the adjacent CIR segment plot along the Réunion-DMM mixing line and follow the proposed depletion trend with geographic distance (Fig. 7). While Rodrigues Ridge data agree with this trend in general, they show more scatter in plots involving Pb isotopes and generally more radiogenic ^{206}Pb/^{204}Pb ratios compared to those other locations (Fig. 8b–c).

Most Rodrigues lavas fall outside the calculated mixing arrays, except in ^{87}Sr/^{86}Sr-^{143}Nd/^{144}Nd space (Fig. 8a), and do not clearly trend towards one of the selected model endmembers. Instead, they exhibit lower ^{87}Sr/^{86}Sr, as well as higher ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb compared to the Réunion hotspot endmember (cf. Fig. 8). Contribution of the DMM alone or together with directly assimilated continental crust in the Rodrigues melt source seems unlikely based on combined Sr-Nd-Pb isotopic compositions. Consequently, the genesis of the Rodrigues lavas rather involved contributions of at least one distinct endmember with lower ^{87}Sr/^{86}Sr and more radiogenic Pb isotope ratios than the Réunion hotspot. The exclusive representation of this component in the isotopic compositions of Rodrigues OIB may reflect its uniquely low degree of partial melting, which would favor greater representation of enriched, fusible mantle components compared to more depleted components. At higher melt fractions, such as those typical of Réunion, increased melting of non-enriched components, such as FOZO, may effectively dilute isotopic signatures from enriched mantle components to the point where they are no longer analytically detectible. The potential origins of this enriched Pb isotopic component are considered in the following sections.

4.3.2. *Metasomatized mantle*

Metasomatized lithospheric mantle generally displays more radiogenic Pb isotope ratios than Réunion OIB. Influence of such a metasomatized oceanic mantle component was discussed for the Azores hotspot (Beier et al., 2007; Waters et al., 2020), and was further proposed as a possible explanation for the E-MORB signatures south of the Marie Celeste Fracture Zone along the CIR (e.g., Nauret et al., 2006). Another conceptually related component is a “fossil” Réunion hotspot component, whose presence in the mantle underneath the nearby CIR has been suggested (Füri et al., 2011). In this scenario, as the CIR passed over the Réunion hotspot about 34 Ma ago, unerupted material from the plume infiltrated into the local mantle and changed its elemental and isotopic composition, leading to greater enrichment in incompatible trace elements. Radiogenic ingrowth would then change the Sr-Nd-Pb isotopic compositions of this component. Such a fossil Réunion component was modelled (see Supplementary Material for details) and leads to more enriched Sr-Nd-Pb isotopic compositions than modern DMM, and a (^{208}Pb/^{206}Pb)* composition that increases with time. Consequently, a contribution of ~10% of this metasomatized mantle component is required to explain the higher (^{208}Pb/^{206}Pb)* signature reflected by the Rodrigues lavas (Fig. 9b). However, since radiogenic ingrowth took place over a limited amount of time (i.e., 34 Ma), the resulting isotopic compositions are only marginally different from those of DMM. As a result, the $^{206, 207, 208}$Pb/^{204}Pb ratios of this component are

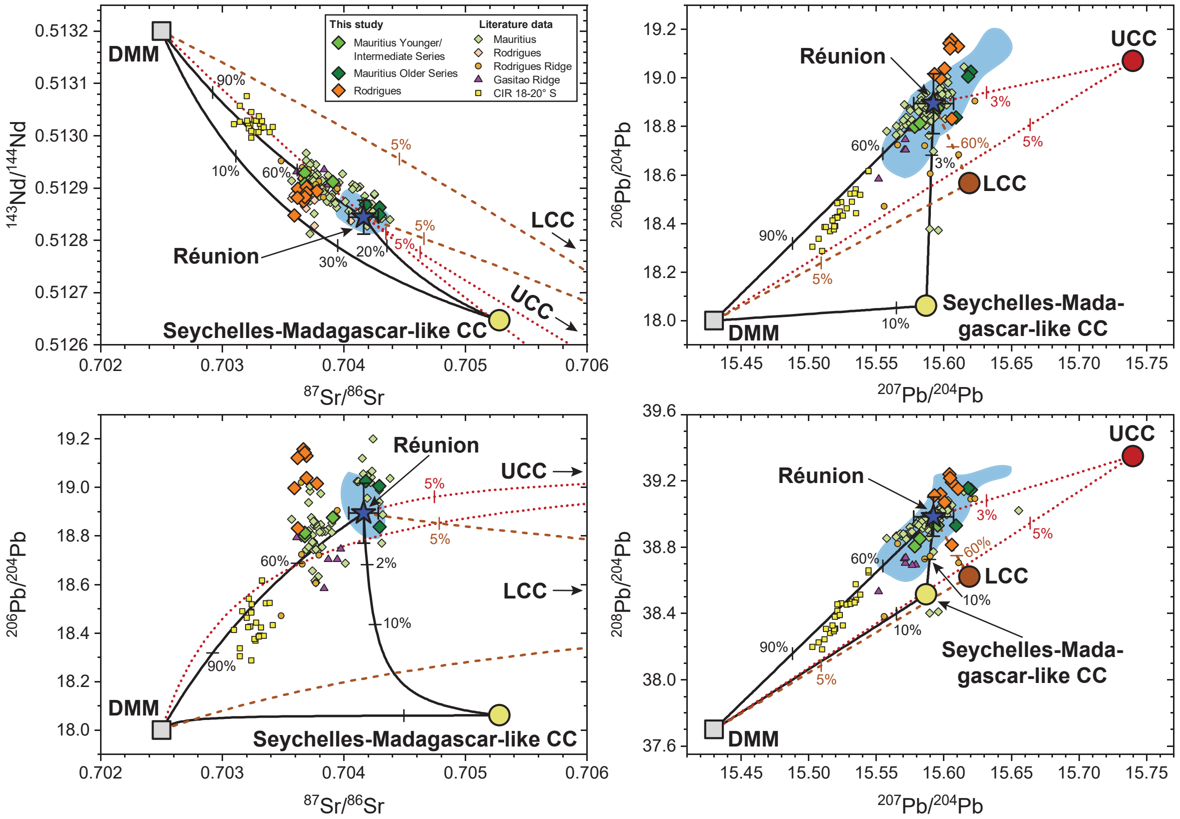

Fig. 8. Isotope mixing models and data for the Mascarene Islands along with selected literature data. The models are based on the (a) ^{87}Sr/^{86}Sr versus ^{143}Nd/^{144}Nd, (b) ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb, (c) ^{87}Sr/^{86}Sr versus ^{206}Pb/^{204}Pb, and (d) ^{207}Pb/^{204}Pb versus ^{208}Pb/^{204}Pb ratios. Literature data for Mauritius are from Peng and Mahoney (1995), Sheth et al. (2003), Nohda et al. (2005), Paul et al. (2005), and Moore et al (2011), for Rodrigues from Baxter et al. (1985), for the Rodrigues Ridge from Mellor (1998), and for the CIR at 18–20°S and Gasitao Ridge from Nauret et al., (2006). The blue shaded fields represent the range of our and literature samples from Réunion (same sources as in Fig. 6). All plots contain modeled mixing lines between selected endmembers: a Réunion-like endmember (blue star; error bars represent 2 SD), depleted MORB mantle melt (DMM; gray square), a Seychelles-Madagascar-like continental crust (yellow circle), upper continental crust (UCC; red circle), and lower continental crust (LCC; brown circle). The data for these endmembers together with their references are tabulated in Table S.5. Mixing arrays involving the Seychelles-Madagascar-like CC component are delimited with black solid lines, those including LCC with brown dashed lines, and UCC with red dotted lines. The marks on the mixing lines represent the proportion (in %) of the involved continental crust component, or DMM on the mixing lines with the Réunion-like endmember.

all distinctly less radiogenic and the ^{143}Nd/^{144}Nd ratio is significantly more radiogenic than most Rodrigues rocks (Fig. 9c, d). It is therefore considered unlikely that a lithospheric fossil Réunion plume strongly contributed to the isotopic compositions of Rodrigues OIB.

4.3.3. *Enriched mantle*

The isotope space of (^{208}Pb/^{206}Pb)* versus ^{87}Sr/^{86}Sr is useful for distinguishing the reservoirs that were involved in the formation of OIB sources (e.g., Stracke, 2012; Nauret et al., 2019). Since Th and U possess different incompatibilities, different OIB source reservoirs may possess distinct Th/U ratios and, therefore, evolve to distinct (^{208}Pb/^{206}Pb)* ratios. In this isotope space, most Rodrigues samples have ^{87}Sr/^{86}Sr ratios comparable to those from the Younger/Intermediate Series of Mauritius (Fig. 9a, b). However, some Rodrigues lavas show higher (^{208}Pb/^{206}Pb)* for a given ^{87}Sr/^{86}Sr ratio, deviating from the Réunion-DMM trend towards an EM1-like endmember. To assess these relationships in more detail, mixing calculations between a Réunion endmember with DMM and an EM1-like component were conducted on the same, and selected other isotope spaces (Fig. 9). The considered EM1-like endmember is designated as "Pitcairn-like" because it is based on the composition of an extreme sample associated with Pitcairn. This, however, is not meant to propose a direct relationship between Rodrigues and Pitcairn, but that the processes that changed the parent-daughter ratios in the Rodrigues source may be comparable to those that changed the parent-daughter ratios of the Pitcairn source.

Importantly, our isotope mixing models reflect liquid state melt mixing. This likely reflects a more physically realistic scenario compared to mixing of solid sources, which would unlikely result in a homogeneous product that then melts congruently. While our models cannot determine the proportion of each involved component in the solid source of Rodrigues OIB, liquid mixing allows constraints on proportions in the final, mixed product and thus simulates incongruent mixing of enriched and depleted mantle components. This requires some assumptions. For example, the melting conditions beneath each island are not specifically defined. However, the larger proportion of isotopically enriched material inferred to be present in the Rodrigues mantle source implies that the degree of melting was lower there than for the other Mascarene Islands. In this way, our approach can approximate the contribution of mantle components with variable compositions to the final, mixed melt that generated the Rodrigues lavas.

The variation displayed by Mauritius samples can be reproduced by a binary mixture of a Réunion-like endmember and up to ~60% DMM. This supports the inference from Fig. 8 that Mauritius rocks do not require contributions from an enriched component (Fig. 9a, b). No binary mixing relationship between Réunion (within a 95% c.i. of available Pb isotopic compositions as presented by the yellow shaded envelope in Fig. 9b, d) and one of the typical OIB endmembers reproduces the observed variation of Rodrigues. Thus, a two-stage mixing is proposed (second stage represented by the red lines in Fig. 9) in which a Réunion-like component is mixed with DMM melt and an EM1-like

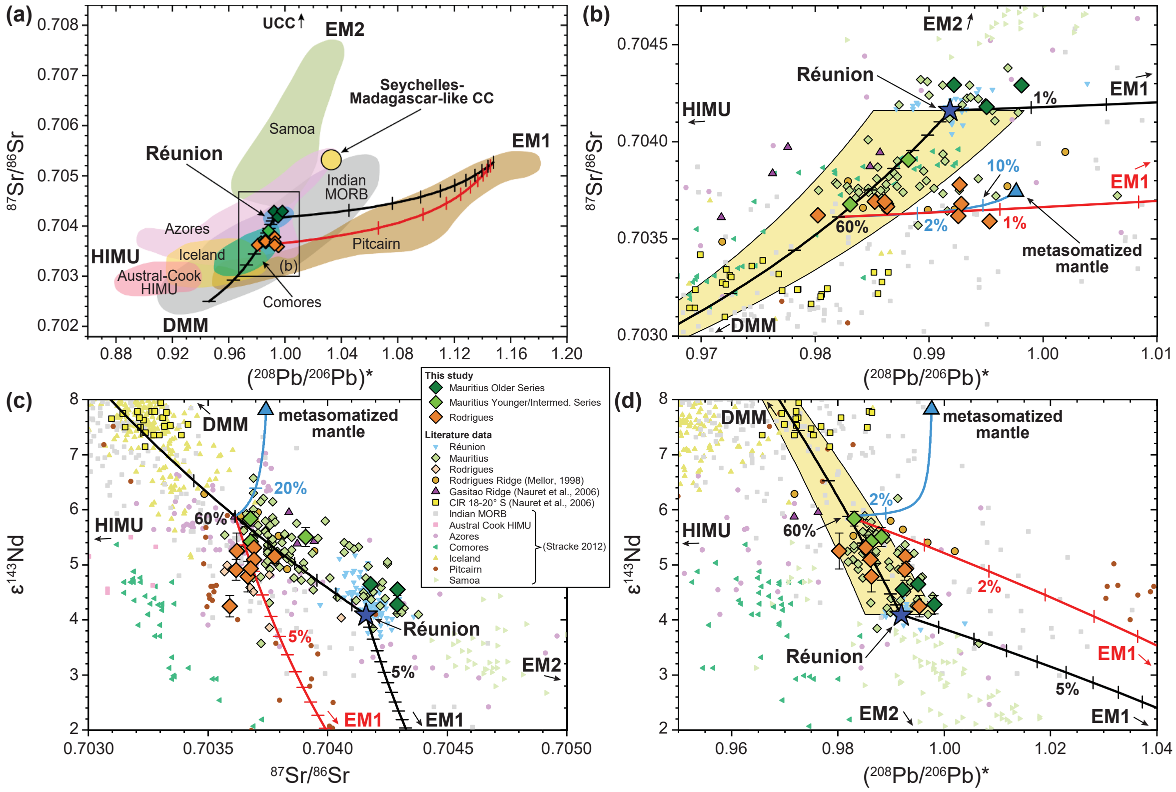

Fig. 9. (a, b) $(^{208}Pb/^{206}Pb)^*$ versus $^{87}Sr/^{86}Sr$, (c) $^{87}Sr/^{86}Sr$ versus $\varepsilon^{143}Nd$, and (d) $(^{208}Pb/^{206}Pb)^*$ versus $\varepsilon^{143}Nd$ for the Mascarene Island samples from this study along with data of selected hotspots and Indian MORB from the compilation of Stracke (2012), Réunion, Mauritius, Rodrigues, the Rodrigues Ridge, the Gasitao Ridge, and the adjacent CIR segment at 18–20° S (same sources as in Figs. 6 and 8). Panel b is an inset as indicated by the black box in panel a. The two black curves represent mixing curves between a Réunion-like endmember (blue star) and (1) a DMM endmember (both similar to Fig. 8; Table S.5) and (2) an EM1 component (volcano 5 Pitcairn seamount sample 57DS1 of Woodhead and Devey, 1993). A secondary mixing line (red lines), mixing a 60% DMM-40% Réunion-like component (first mixing stage) with a Pitcairn-like EM1 endmember (second mixing stage), is also displayed. This secondary mixing line indicates that small contributions (<5%) of an EM1-like component reproduces the isotopic signature of the Rodrigues samples. Note that all sub-divisional ticks in panel a mark 10% mixing increments, whereas they represent either 1% or 10% increments in panels b–d, unless otherwise indicated. The yellow envelope represents the 95% confidence interval of the Réunion-DMM mixing line, considering the available Pb isotopic compositions of Réunion. The previously discussed Seychelles-Madagascar-like CC (yellow circle) and UCC components are shown in panel a and similar to those in Fig. 8. A mantle component that was metasomatized by the Réunion hotspot (light blue triangle; Section 4.3.2) with corresponding secondary mixing lines (blue lines) are also displayed in panels b-d for comparison.

component. Since the trend of the Rodrigues data is parallel to the mixing line between the Réunion-DMM array and the EM1 endmember, first stage mixing is suggested between the Réunion hotspot and DMM. Mixing of about 60% DMM with 40% Réunion hotspot material, followed by second-stage addition of few percent (~1–4%) of a Pitcairn-like EM1 component best fit the data. Importantly, since the selected endmember composition for the mixing calculation represents a relatively extreme EM1 isotopic composition, these percentages represent minimum contributions from an EM1-like source. Strikingly, a few literature samples from the Mauritius Younger/Intermediate Series likewise show elevated $(^{208}Pb/^{206}Pb)^*$ but no systematic relationship comparable to our Rodrigues data has been identified in these studies (Sheth et al., 2003; Nohda et al., 2005; Paul et al., 2005; Moore et al. 2011).

In $(^{208}Pb/^{206}Pb)^*$- $\varepsilon^{143}Nd$ space (Fig. 9d), the Rodrigues rocks fall closer to the Réunion-DMM mixing line. Nevertheless, some Rodrigues samples deviate from this mixing line towards higher $(^{208}Pb/^{204}Pb)^*$, which also argues in favor of an EM1 contribution. These slight differences in the inferred contribution from the enriched component most likely reflect relative differences in the relative abundance of Sr, Nd, and Pb in this component. In the case of Rodrigues, the enriched component may have relatively high Nd and Pb abundances, leading to stronger changes in the isotopic compositions of these elements, whereas a lower Sr abundance of this component means that the Sr isotopic compositions are set primarily by mixing between DMM and a Réunion hotspot component.

4.3.4. *Trace element tests of the enriched component*

An EM1-like component, here represented by a parental magma composition calculated from Pitcairn OIB in the manner previously described, was subjected to models simulating trace element enrichment from this source (Fig. 10; see Supplementary Material for details and endmember compositions) using inputs that are self-consistent with Fig. 5. The basis of this model is a calculated liquid endmember composition, which was mixed according to the two-stage mixing scenario envisaged by Fig. 9. In a first mixing step, a calculated Réunion parental magma was mixed with a DMM melt in the proportions 0.4/0.6. Subsequently, 3% of the EM1-like melt was added, as implied by the mixing proportions in Fig. 9. It was then tested whether the trace element compositions of this mixture can reproduce those of the Rodrigues parental magma.

The calculated EM1-like melt is, similar to the Réunion parental magma, less enriched in the highly incompatible trace elements than the Rodrigues parental melt (Fig. 10). Consequently, the EM1 model mixture (red solid line in Fig. 10) displays incompatible trace element compositions that are generally less enriched than the Rodrigues parental magma. However, the EM1 model is in good accordance with the pattern of the Rodrigues parental magma, sharing relative depletions in U and Pb of a similar magnitude to the calculated Rodrigues parental magma and the flattening towards the heavy REE. For the latter, the

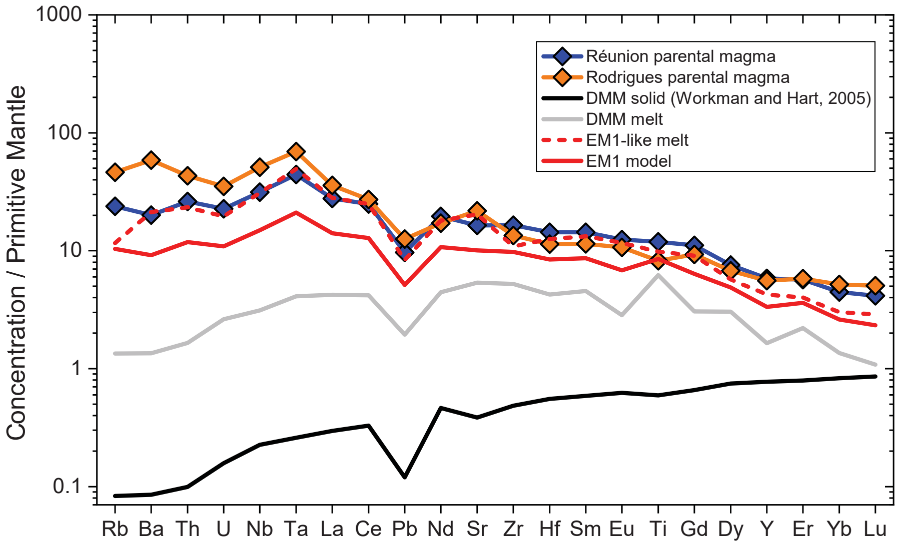

Fig. 10. Trace element enrichment model for an EM1 model. The red dashed line represents the calculated EM1-like melt. The red solid line is a mixture of 60% DMM melt (grey line) and 40% Réunion parental magma (blue line), with a second stage addition of 3% of the EM1-like melt. The EM1 model reflects the calculated melt composition of basalts from the Pitcairn-Gambier chain. Model endmember compositions and used partitioning coefficients are listed in Table S.6. All concentrations are primitive mantle (McDonough and Sun, 1995) normalized.

EM1 model evolves to compositions approaching those of Rodrigues but continues to be less enriched. The disparity between the Rodrigues parental magma and the EM1 model compositions, in particular for the highly incompatible elements, could be reconciled by decreasing the contribution from DMM. This, however, is inconsistent with isotopic data. Alternatively, using a higher assumed MgO abundance (>9 wt%) for the Rodrigues parental magma results in a stronger depletion of its trace element abundances and thus achieves the desired overlap. A model involving mixing of 40% Réunion plume and 60% DMM, followed by a second-stage addition of 3% EM1-type magma, can satisfactorily reproduce the measured trace element and isotopic signature of Rodrigues samples. Consequently, contribution of an EM1-like component (∼1–4%) to the source of Rodrigues basalts is favored based on isotopic and trace elemental compositions. A minor contribution of an EM1 component to OIB from Réunion was similarly proposed by Bosch et al. (2008). Importantly, while the implied enriched component was modeled based on Pitcairn, the fundamental conclusion drawn from the model is only that this component possesses elevated (^{208}Pb/^{206}Pb)*.

4.3.5. *Comparing the mechanisms of potential continental contributions*

Contributions of continental material was previously discussed to explain the geochemical and chronological data available for Mauritius, Réunion, and EM1 hotspots. However, the mechanism by which such materials are assimilated into the erupted OIB magma differ strongly between these settings. In the following discussion, we evaluate the proposed mechanisms for inheritance of this continental signature by their parental magmas to further constrain its potential involvement to the Rodrigues source.

Rare trachytic lavas on Mauritius possess Sr and Nd isotopic compositions interpreted to result from partial assimilation of a fragment of Precambrian continental crust (Torsvik et al., 2013; Ashwal et al., 2017) situated in the lithosphere beneath Mauritius (Ashwal et al., 2016). Ashwal et al. (2016) further suggested that the trachyte parental magma formed as a low degree partial melt of enriched mantle that probably experienced prior metasomatism. Although our measured Mauritius samples do not have isotopic signatures that support direct assimilation of CC (Fig. 8), this process may still be required to explain the presence of Archean-aged zircons in Mauritius OIB (e.g., Ashwal et al., 2017). However, Archean-aged zircons have also been found in Atlantic MORB, far from the influence of continental crust (e.g., Skolotnev et al., 2010), meaning that their presence in Mauritian lavas may be coincidental. Additionally, Singh et al. (2016) concluded that seismic characteristics of the sub-Mauritius lithosphere were inconsistent with shallow crustal fragments. For Rodrigues, the measured ^{87}Sr/^{86}Sr, ^{206}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb ratios clearly invalidate direct CC assimilation (Figs. 8 and 9). Another mechanism, such as deep recycling, may have introduced a continental signature into the Rodrigues source.

Based on binary Sr-Nd-Pb isotope mixing models, Nauret et al. (2019) proposed that a minor, CC-influenced signature was present in the geochemical compositions of lavas from the Piton des Neiges volcano on Réunion. They argued that this signature may derive from a crustal component residing in the underlying asthenospheric mantle that has been mixed into the Réunion plume during the plume's ascent. The Sr and Pb isotope data can be used to evaluate if the enriched component inferred to be present in the Rodrigues source is similar to this proposed Réunion component (Fig. 11). The samples from Rodrigues display elevated (^{208}Pb/^{206}Pb)* ratios for a given ^{87}Sr/^{86}Sr ratio relative to most rocks from Mauritius, and therefore a greater proportion of the enriched component at an equivalent contribution from a DMM-like source. By comparison, the compositions of Piton des Neiges lavas

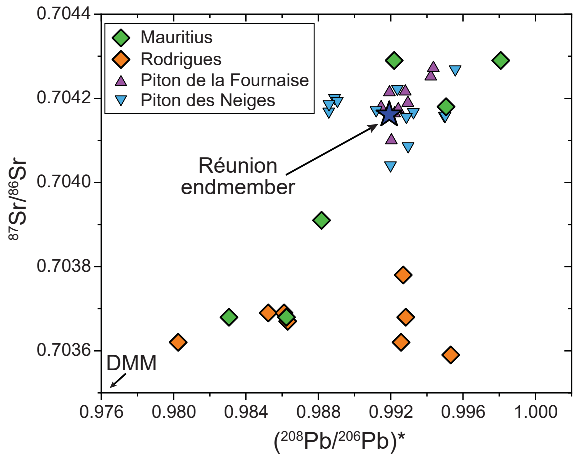

Fig. 11. (^{208}Pb/^{206}Pb)* versus ^{87}Sr/^{86}Sr ratios for the Mauritius and Rodrigues samples (this study), Piton de la Fournaise, and Piton des Neiges (Dupré and Allègre, 1983; Nauret et al., 2006, 2019; Vlastélic et al., 2009). Also included is the Réunion-like endmember (blue star) from the isotope mixing models (Figs. 8 and 9). The direction towards the DMM endmember is indicated by an arrow. While the samples from Piton de la Fournaise and Piton des Neiges are part of the same cluster, some Rodrigues samples show compositions clearly distinct from the Réunion-DMM mixing trend. The Piton des Neiges samples with the highest (^{208}Pb/^{206}Pb)* ratio on this plot are the ones with the largest proposed CC contribution by Nauret et al. (2019).

(with proposed continental component) and those from Piton de la Fournaise lavas (without continental component) cluster around the Réunion endmember composition without elevated ($^{208}Pb/^{206}Pb$)* ratios (Fig. 11). Consequently, the enriched component considered by Nauret et al. (2019) is interpreted to be distinct from the elevated ($^{208}Pb/^{206}Pb$)* component discussed here for Rodrigues. The Rodrigues enriched component may either uniquely reside in the asthenospheric source of Rodrigues, may have only been melted at Rodrigues due to plume processing during sub-lithospheric transport, or may have been effectively diluted in Réunion and Mauritius melts due to higher degree of melting and is therefore undetectable in those lavas.

Alternatively, the enriched isotopic signature of Rodrigues may be explained by recycled sediments (e.g., Chauvel et al., 1992; Eisele et al., 2002; Garapić et al., 2015; Delavault et al., 2016; Wang et al., 2018) or continental lithospheric materials (e.g., Milner and le Roex, 1996; Escrig et al., 2005; Willbold and Stracke, 2006; 2010; Boyet et al., 2019), as suggested for OIB from EM1 hotspots. Such continental material may have been introduced to the asthenosphere through subduction or delamination (e.g., Willbold and Stracke, 2010), which was also considered for the enriched component in Réunion OIB by Nauret et al. (2019). In contrast to this enriched component proposed for basalts from Piton des Neiges, the one inferred for Rodrigues may represent a deeply recycled component of the Réunion plume, which was preferentially channeled towards the CIR without erupting on Réunion and Mauritius. Fine-scale, "unmixed" components of mantle plumes like this are known in other settings, such as the Society Islands (Cordier et al., 2016) and Hawai'i (Weis et al., 2020). Such spatially small, enriched mantle domains are often predicted by geodynamical models determining the distribution of recycled domains in Earth's mantle (e.g., Brandenburg et al., 2008). A relatively large "blob" of enriched material in the plume conduit may also explain the fact that Rodrigues represents a melt volume large enough to form an island, despite the low melting fraction of the source inferred from the trace element compositions (Section 4.1; e.g., Gibson and Richards, 2018). While we interpret this component to be intrinsic to the plume stem, it could also reside in the ambient "plum-pudding" mantle (e.g., Phipps Morgan and Morgan, 1999) and was entrained by the plume during its ascent. Although the discovery of an enriched component in the source of Rodrigues basalts was not anticipated based on the composition of Réunion OIB, such small-scale mantle heterogeneities may be widespread in the source regions of hotspots.

Regardless of its specific origin, the isotopically distinct composition of OIB from Rodrigues compared to those from Réunion reveals that small-scale heterogeneities in the mantle can play an important role in the compositions of some hotspot volcanoes while remaining absent in compositions of other volcanoes of the same hotspot chain. This observation underscores that geochemical investigation of multiple hotspot volcanoes in a single hotspot chain is of great importance when characterizing a volcanic hotspot system with the goal to identify all potential mantle plume components. Further, this provides geochemical context to the geodynamical prediction that geochemically diverse mantle domains may be present at all scales in Earth's mantle.

5. Conclusions

This study characterizes the mantle sources of the Mascarene Island lavas and re-evaluates their contributions to the Réunion hotspot. Based on REE modelling, lavas from Réunion and Mauritius were generated by higher degrees of partial melting than those from Rodrigues, which likely resulted in a significant relative enrichment of incompatible elements for the latter. The melting beneath Rodrigues may have occurred at shallower depths compared to Réunion and Mauritius, and involved a mixture of DMM-like and more primitive mantle material. This agrees with the formerly proposed migration of Réunion plume material towards the CIR (Morgan, 1978; Murton et al., 2005).

Isotope mixing models do not provide evidence for contributions from a directly assimilated fragment of lithosphere-hosted continental crust to rocks from Mauritius, as presumed by previous studies (Torsvik et al., 2013; Ashwal et al., 2016, 2017). Instead, the isotope data implies that Mauritius rocks are the result of mixing between a Réunion plume and up to 60% of a depleted MORB component. An enriched component, such as a CC fragment directly assimilated in this lithosphere, is not necessary to explain the Sr-Nd-Pb isotopic characteristics of Mauritius OIB. Moreover, direct assimilation of a CC component was disqualified to explain the compositional variation of the measured Rodrigues samples. Particularly, direct CC assimilation should result in more radiogenic $^{87}Sr/^{86}Sr$ ratios and distinct Pb isotopic signatures than those displayed by Rodrigues. Consequently, the Rodrigues data requires contribution of a distinct enriched component with elevated ($^{208}Pb/^{206}Pb$)* ratios in addition to a Réunion plume-DMM mixture.

The Sr-Nd-Pb isotope and trace element compositions point towards EM1 as this enriched endmember. A first stage mixing of 40% Réunion plume with 60% DMM material, followed by a second stage addition of ~1–4% of a Pitcairn-like EM1 component reproduces the isotope variations shown by Rodrigues OIB, as well as the trace element signature of the parental melt. Consequently, this EM1 model is favored as source composition for OIB from Rodrigues. The enriched component may derive from continental material, which has been recycled into the mantle and ultimately incorporated into the source of Rodrigues lavas. It might represent a fine-scale component inside or outside the Réunion plume, which potentially only erupted on Rodrigues due to differences in its melt regime. Further investigation is required to better resolve the character of the enriched signature identified in the lavas from Rodrigues. The observation that some literature samples from the Younger/Intermediate Series on Mauritius show similarly elevated ($^{208}Pb/^{206}Pb$)* also suggests further study of these rocks for this enriched component.

Research data

Research data has been supplied via a repository: https://doi.org/10.26022/IEDA/112931.

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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Appendix A. Supplementary material

Geological maps with sampling locations, chemical dissolution and separation procedure (Table S.2), leaching experiments, Sr-Nd-Pb isotope analysis, data selection and filtering, model descriptions and parameters (Table S.5). Supplementary Tables: Mascarene Islands sample information (Table S.1), major and trace element data (Table S.3), Sr-Nd-Pb isotope data and leaching results (Table S.4), trace element enrichment model endmembers and partitioning coefficients (Table S.6). Supplementary material to this article can be found online at https://doi.org/10.1016/j.gca.2023.06.030.

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