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ABSTRACT

Réunion Island is the present surface expression of a major mantle plume whose homogeneity and isotopic signature, near the convergence point of many hotspot isotopic arrays, have long puzzled geochemists. This signature could, in part, reflect oversampling of the most recent (< 0.53 Ma) Piton de la Fournaise volcano. To resolve this issue, we studied the older Piton des Neiges volcano and made a synthesis of the Sr-Nd-Pb isotope compositions of lavas produced during the early stage of La Réunion and contemporaneously at Mauritius, the second youngest island of the hotspot track.

New samples from Piton des Neiges have $^{87}Sr/^{86}Sr$ from 0.70429 to 0.70441, $^{143}Nd/^{144}Nd$ from 0.51282 to 0.51290, $^{206}Pb/^{204}Pb$ from 18.765 to 19.004, $^{207}Pb/^{204}Pb$ from 15.558 to 15.605 and $^{208}Pb/^{204}Pb$ from 38.850 to 39.082. On a Sr–Nd isotope plot, the extended isotope field defined by the Réunion and Mauritius volcanoes overlaps with the OIB field of the Society islands, where an EM-2 signature has been recognized. Réunion also has higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios for a given $^{206}Pb/^{204}Pb$ than expected from a binary mixing between depleted and enriched mantle components. Thus, the overall Sr-Nd-Pb isotope variations shown by Réunion and Mauritius volcanoes require a third source component. In addition to the already known depleted and enriched mantle components, the third component involved in the mixing is interpreted as reflecting a small contribution (≤ 8%) of Seychelles/Madagascar-like continental crust, which is incorporated into the plume before it rises into the depleted mantle. This new model challenges the proposed existence of a hidden continent below the island of Mauritius, by suggesting that the continental component is located in the asthenosphere.

1. Introduction

Oceanic volcanic islands are of great interest to geologists because they provide indirect access to the structure and composition of mantle plumes, to their temporal variations, and hence to the dynamics of the Earth's mantle (Steinberger, 2000). Seismic tomography and isotope geochemistry have revealed that mantle plumes are highly variable in structure, composition and temporal evolution despite their common characteristics (thermal anomaly, buoyancy of deep mantle material, relatively fixed position through time, mixing of enriched lower mantle and depleted upper mantle) (Zhao, 2007).

Several suites of ocean island basalts (OIBs) from individual hotspots generally display large, correlated Sr-Nd-Pb variations (Hart et al., 1992). These arrays constrain the nature and distribution of components within mantle plumes (Abouchami et al., 2005; Bryce et al., 2005; Shorttle et al., 2013) and how they are sampled during the different stages of ocean island volcanism (Paul et al., 2005; Garcia et al., 2010).

One of these hotspots, the Réunion Island in the Indian Ocean, stands out because its basalts show limited isotopic range (Fisk et al., 1988, Graham et al., 1990, Albarède et al., 1997, Hanyu et al., 2001, Fretzdorff and Haase, 2002) and plot near the convergence point of many OIB isotopic arrays. This, together with the occurrence of incompatible trace element ratios similar to primitive mantle (Valer et al., 2017), unusually high Pd/Ir and Ru/Ir ratios (Peters et al., 2016), and ^{142}Nd isotope anomalies (Peters et al., 2018), supports the idea, initially proposed by Vlastélic et al. (2006), that the Réunion mantle source has been isolated from the convecting mantle through much of Earth's history. Nevertheless, the increasing number and precision of isotope analyses has revealed small isotopic heterogeneities between the different volcanoes of Réunion Island (Bosch et al., 2008) and even among historical eruptions of the Piton de la Fournaise volcano (Vlastélic et al., 2009). However, these heterogeneities remain much smaller than those found in the three lava series of Mauritius, the second youngest island along the Réunion hotspot track (Nohda et al., 2005; Paul et al., 2005; Moore et al., 2011). The compositional variations of Réunion and Mauritius lavas have been interpreted as reflecting a heterogeneous plume structure (Paul et al., 2005; Bosch et al., 2008) with major contributions from the C-FOZO and EM-1 (Bosch et al., 2008) or EM-2

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like plume components (Smietana, 2011), mixed with depleted mantle from the Central Indian Ridge (Nohda et al., 2005; Füri et al., 2011; Moore et al., 2011). Small variations in the historical volcanic activity of the Réunion hotspot have been interpreted as being due to interaction of Réunion magmas with the oceanic crust or the volcanic edifice (Pietruszka et al., 2009).

In contrast with this apparently simple geochemical model, recent seismic tomography and SKS splitting results depict the Réunion hotspot as a complex low-velocity structure interacting with the Central Indian Ridge (Mazzullo et al., 2017; Scholz et al., 2018). In addition, the recent discovery of Archean zircons in Mauritius has raised the possibility that plume magmas may also be contaminated by fragments of continental crust left behind when India separated from Madagascar (Torsvik et al., 2013; Ashwal et al., 2017).

Most of what we know about the isotopic signature of the Réunion plume over the past 10 Ma is derived from the study of Piton de la Fournaise (PF), which has received considerable attention due to its intense activity (> 500 samples analyzed for at least one of Sr, Nd, Hf and/or Pb isotope systems since 2000). Mauritius Island is also relatively well studied (> 140 samples, mostly after 2000). In comparison, Piton des Neiges (PN), the other now dormant volcano of Réunion Island, is less studied (< 80 data, half of them prior to 1990). As PN is by far the largest and longest-lived emerged edifice on La Réunion Island, this relatively limited number of studied samples might bias our knowledge of the plume's isotopic signature.

Here, we present a new set of Sr-Nd-Pb isotope data from samples belonging to PN. Our first objective is to increase the number and precision of the isotope data for PN, and second to compare our data with those from PF and Mauritius Island. Based on this comparison, we propose a new plume model taking into account all the geochemical, geophysical and geodynamic studies available for the Indian Ocean. This model adds fuel to the controversy about the existence of hidden continental fragments left behind during the northward migration of Indian plate.

2. Geological setting

Plate displacement over the Réunion hotspot has resulted in an alignment of intraplate volcanism starting in the Indian plate at the Deccan Traps (66–61 Ma), continuing on to the Maldives (~58 Ma), the Chagos archipelagos (~50 Ma), and then on to the Somalian plate with the Saya de Malha bank (50–40 Ma), the Chargados-Carajos islands (~30 Ma), Mauritius (10–0 Ma) and finally Réunion Island (5–0 Ma) (Fig. 1a). Mauritius is built at the tip of the Mascarene plateau on a ~4000 m-deep ocean floor, in a zone where the crustal structure does not present an organized magnetic fabric (Dyment, 1991, Bernard and Munschy, 2000, Bissessur, 2011). The growth of Mauritius is classically subdivided into three major stages separated by erosion periods: an Older Series (8.9–4.7 Ma) with a complete transitional evolution from shield building to postshield stages; and two periods of more alkalic rejuvenation- an Intermediate Series (3.5–1.8 Ma), and a Younger Series (1–0.031 Ma) (McDougall, 1971; Baxter, 1972; Nohda et al., 2005; Moore et al., 2011). These two rejuvenation stages are chemically and isotopically indistinguishable from each other, but differ from the Older Series in being not only more alkalic but also less enriched in radiogenic isotopes, due to the higher contribution of a MORB like component (Moore et al., 2011). The Older Series ends up with trachytes containing Archean zircons, possibly originating from the Madagascar continental crust (Torsvik et al., 2013; Ashwal et al., 2017). Given the lack of oceanic magnetic fabric in the area, this raises the possibility that the Mascarene plateau might contain continental fragments left behind during the separation of the Indian plate from Madagascar. Alternatively, the trachytes may be interpreted as derived from partial melting of a mantle contaminated by recycled continental crust (Ashwal et al., 2016).

Unlike Mauritius, the lithosphere beneath Réunion Island displays well-defined magnetic anomalies (Dyment, 1991; Bernard and Munschy, 2000; Bissessur, 2011), a bathymetry and a seismic velocity structure typical of oceanic lithosphere (Fontaine et al., 2015). Recent marine geophysical surveys have established that PN is the main edifice on Réunion Island, with PF constituting an adventive edifice which developed on the eastern flank of PN (Lebas et al., 2018). Based on major element geochemistry and K/Ar dating of the emerged portion of PN (Fig. 1b), the shield building stage has been dated at between > 2.2 Ma and 430 ka, whereas the post-shield stage lies between 340 and 29 ka and is characterized by differentiated, often plagioclase-rich magmas including hawaïte and mugearite, and a more explosive phase which produced syenite, benmoreite and trachyte magmas (McDougall, 1971, Gillot and Nativel, 1982, Salvany et al., 2012). The emerged portion of Piton de la Fournaise began at 540–430 ka with differentiated plagioclase-rich basalts, followed by a shield building phase (400–0 ka) dominated by basalts and picrites (Gillot et al., 1994; Albarède et al., 1997; Smietana, 2011).

3. Materials and analytical methods

Great care was taken to constitute a suite of 43 samples spanning the entire lifetime of Piton des Neiges from its emergence, encompassing its shield building and differentiated stages, and including the whole range of intrusive and extrusive rock compositions (location Fig. 1b, Table 1). Two samples from Piton de la Fournaise were also collected to check the consistency of our analyses with previous isotopic studies. Samples were selected by cross-correlated dating and major element studies (published and unpublished), geological maps, and discordances or changes in slopes observed in the field. The samples are divided into two sets: the first set was analyzed for trace elements and Pb isotopes in 2006 (19 samples named RUN XXX) at IPGP (Nauret et al., 2007), and the second one comprises samples analyzed from 2011 to 2017 (26 samples named by locality). The latter were analyzed for major- and trace-elements, and Sr–Nd isotopes by the Service d'Analyse des Roches et des Minéraux (SARM) of the Centre de Recherches Pétrographiques et Géochimiques (CRPG), Nancy, France. For Sr and Nd isotopes, between 100 and 200 mg of sample were weighed in a 15 mL Savillex and digested using a solution of 14 M HNO_3 and 28 M HF (4 mL and 1 mL, respectively). The whole mixture was heated on a hot plate at 115 °C for 24–48 h, evaporated to dryness and dissolved in 6 M HCl and heated again for 24 h. After complete dissolution and subsequent evaporation, the residue was diluted in 2 ml of 2 M HNO_3. Sr, Pb and REE were separated using the Sr spec and Tru Spec resins (Pin et al., 1994). An additional step was carried out to isolate Nd from Sm using the Ln spec resin (Pin et al., 1994, Pin and Zalduegui, 1997). The Sr cuts were loaded onto Re filaments and analyzed by TIMS Triton Plus (Thermo electron) in static multicollection. The $^{87}Sr/^{86}Sr$ ratios were normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194. Repeated analysis of the NBS 987 standard yielded an average of 0.710255 ± 0.000017. Blanks were always negligible with mean values of < 300 pg. Nd and Pb were measured on an MC-ICP-MS Neptune plus (Thermo electron). The $^{143}Nd/^{144}Nd$ ratios were normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Repeated analysis of the JnDi-1 yielded 0.512104 ± 10. The procedural blanks (< 100 pg) were negligible compared to the amount of lead purified (> 200 ng). In both laboratories, instrumental mass fractionation was corrected using Tl-doping (White et al., 2000). The measured ratios were subsequently normalized by linear interpolation using the values of (Todt et al., 1984) for NBS981:16.9456 for $^{206}Pb/^{204}Pb$, 15.4891 for $^{207}Pb/^{204}Pb$, 36.7006 for $^{208}Pb/^{204}Pb$ in order to be consistent with the large database published for Piton de la Fournaise by Vlastélic et al. (2005, 2006, 2009).

The samples are younger than 3 Ma and have relatively low parent/daughter ratios (e.g., average ratios of Rb/Sr ≈ 0.15, Sm/Nd ≈ 0.23 and U/Pb ≈ 0.27). For this reason, no age correction was applied to the isotopic data reported here.

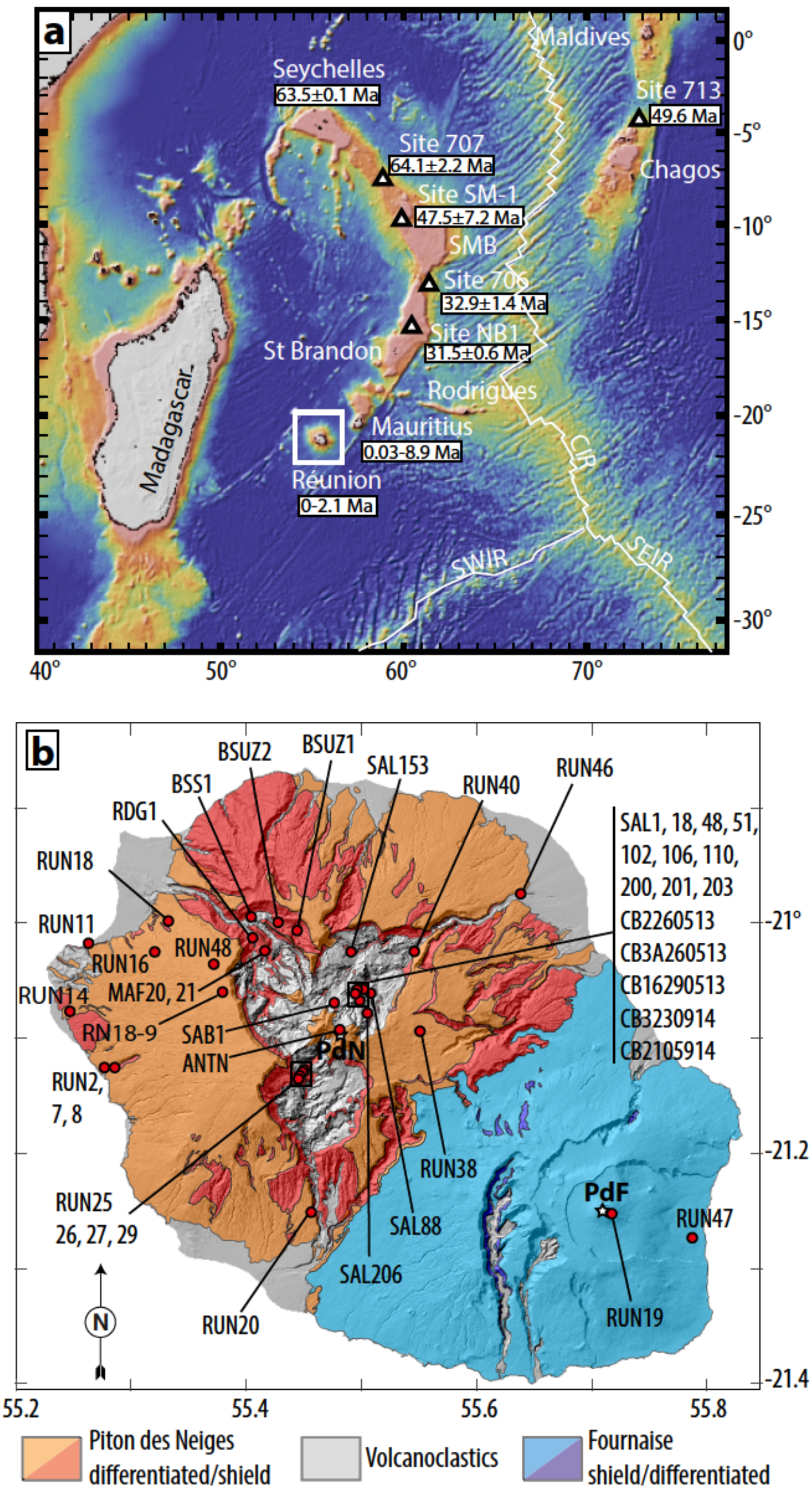

Fig. 1. a) Hotspot track of the Réunion plume from the Deccan trapps to the island of La Réunion. b) Location of samples onto a simplified geological map of Piton des Neiges (PN) and Piton de la Fournaise (PF) subdivided into shield building and differentiated stages.

4. Results

Sr-Nd-Pb isotope and major-trace element data are reported in Table 1. Sr and Nd isotope ratios for PN range from 0.70404 to 0.70429 and from 0.51282 to 0.51290, respectively. These data are within the range reported by previous authors ($^{87}Sr/^{86}Sr$: 0.70397–0.70437 and $^{143}Nd/^{144}Nd$: 0.51280–0.51288, (Fisk et al., 1989, Smietana, 2011), Fig. 2). The variations are even more restricted compared to those from PF ($^{87}Sr/^{86}Sr$ from 0.70398 to 0.70432 and $^{143}Nd/^{144}Nd$ from 0.512786 to 0.512786, (Vlastélic and Pietruszka, 2016)). For comparison, samples from PN plot on the radiogenic side of the Mauritius field ($^{87}Sr/^{86}Sr$: 0.70357–0.70438 and $^{143}Nd/^{144}Nd$: 0.51281–0.51297 (Nohda et al., 2005, Paul et al., 2005, Moore et al., 2011), excluding Mauritian trachytes: $^{87}Sr/^{86}Sr$: 0.70408–0.71034 and $^{143}Nd/^{144}Nd$:

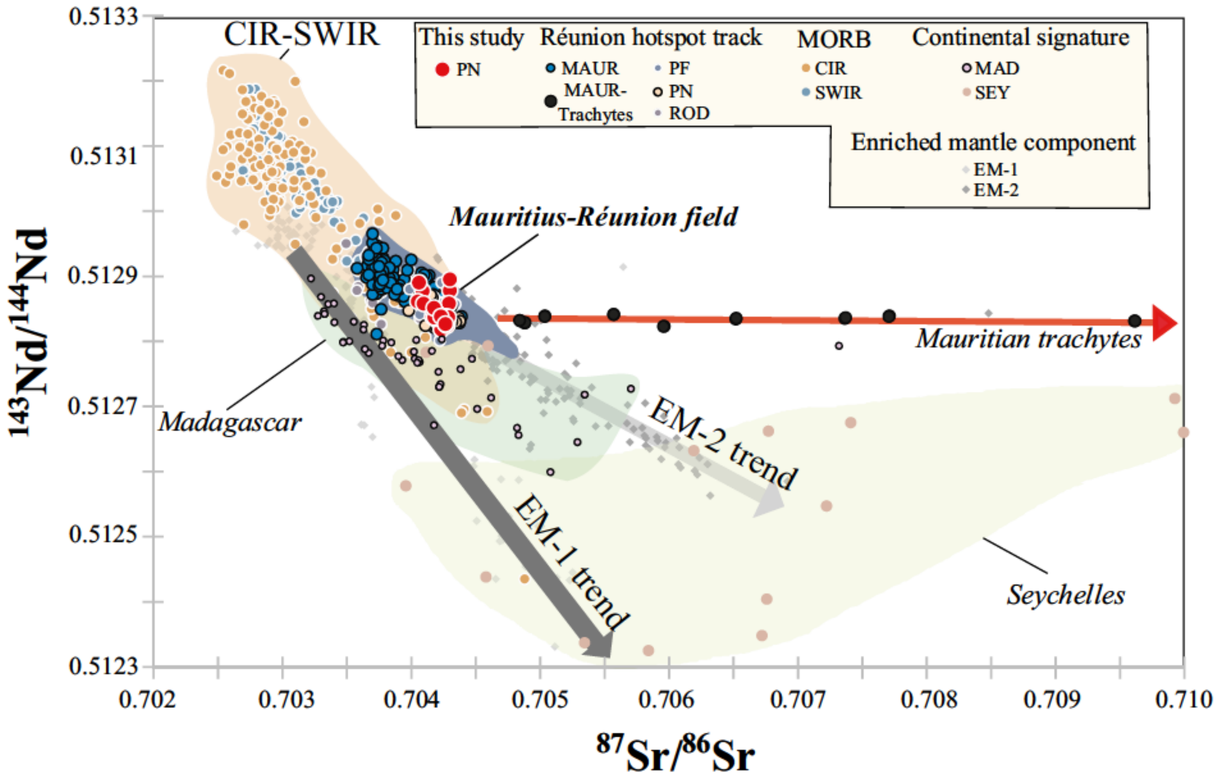

Fig. 2. $^{87}S/^{86}Sr$ vs $^{143}Nd/^{144}Nd$ comparing our data with those for PN, PF, Mauritius, Rodrigues, Madagascar and Seychelles, Central Indian Ridge (CIR) and South West Indian Ridge (SWIR) (http://www.earthchem.org/petdb). Mauritius-Réunion field is defined using data from (Fisk et al., 1988; Fretzdorff and Haase, 2002; Nohda et al., 2005; Vlastélic et al., 2005; Vlastélic et al., 2007; Bosch et al., 2008; Pietruszka et al., 2009; Moore et al., 2011; Di Muro et al., 2014; Valer, 2016). The blue field highlights data from (Smietana, 2011), Mauritian trachytes are from (Ashwal et al., 2016). Trends EM-1 and EM-2 are defined by data for Pitcairn and Society islands respectively, from Petdb database (https://www.earthchem.org/petdb). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.512825–0.512858, (Ashwal et al., 2016)). PN, PF and Mauritius Sr–Nd data plot along the EM-2 trend (Fig. 2).

Pb isotopes range from 18.765 to 19.004, from 15.558 to 15.605 and from 38.850 to 39.082 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$, respectively, in agreement with selected published data (18.069–18.976, 15.552–15.601 and 38.069–39.072, respectively) (Smietana, 2011; Vlastélic and Pietruszka, 2016) (Fig. 3). However, they are clearly distinct from the previously published dataset from Bosch et al. (2008) (Fig. 4).

Our Pb isotope compositions define elongated fields in $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ spaces, with poor correlation coefficients for the regression lines ($R^2 < 0.8$). These fields overlap those of PF and Mauritius. In $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ space, PN data cover the fields defined by PF and Mauritius. We note that the PN field, together with Mauritius and PF, forms a triangular shape (Fig. 5A). Compared to Mauritius in a $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ diagram, PN samples have higher $^{208}Pb/^{206}Pb$ for a given $^{207}Pb/^{206}Pb$. This is also the case for PF. In a $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ plot, individual regression lines through Mauritius, PF, and PN sets converge at low $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$, but diverge towards high $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ values (Fig. 5). According to a Principal Component Analysis (PCA), 90% of the PN isotopic composition is explained by mixing between two major components. The same mixing (89%) is observed when PN and PF are combined in the PCA. However, adding the Mauritius data to PN and PF increases the variability due to the third minor component in the PCA (see Supplementary material).

To summarize, Mauritius, PF and PN samples define a triangular field in Pb–Pb space (Fig. 5A). At least three components are required to explain this Pb isotope variability in the younger part of the Réunion hotspot track.

5. Discussion

5.1. Building a high-precision isotope database for the Réunion hotspot

The first step to be taken while interpreting the isotopic variations is to compile a reliable database of Réunion hotpot rocks younger than 10 Ma, i.e. including samples from Piton des Neiges, Piton de la Fournaise, Mauritius, and possibly Rodrigues. Regarding Piton des Neiges, seventy-eight Sr, Nd or Pb data are available in the literature (McDougall and Compston, 1965, Cooper and Richards, 1966, Oversby, 1972, Ludden, 1978, Dupré and Allègre, 1983, Fisk et al., 1988, Bosch et al., 2008, Smietana, 2011; Vlastélic and Pietruszka, 2016), but many of them are unsuitable for investigating the small heterogeneities of the Réunion hotspot due to their large uncertainties. For this study we filtered the data, excluding 26 Sr analyses with large uncertainties ≥5 digits (McDougall and Compston, 1965; Cooper and Richards, 1966; Oversby, 1972; Ludden, 1978). We then compared our Pb isotope analyses with data from the literature, bearing in mind that they were obtained in different institutes, and using different analytical protocols. In a $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ diagram (Fig. 4), a significant scatter can be seen and there is an important shift between one group composed of our data and those from (Smietana, 2011; Vlastélic and Pietruszka, 2016) on the one hand, and the dataset of (Bosch et al., 2008) on the other hand, even though all the data are normalized to the same NBS981 reference values. PN compositions from Bosch et al. (2008) have systematically lower $^{208}Pb/^{206}Pb$ for a given $^{207}Pb/^{206}Pb$ (Fig. 4) than other data. We precise here again that our data were obtained at IPGP in 2006 and at LMV over the period 2011–2017. Data from Smietana (2011) were obtained at IFREMER and data from Vlastélic and Pietruszka (2016) were also obtained at LMV, all by MC-

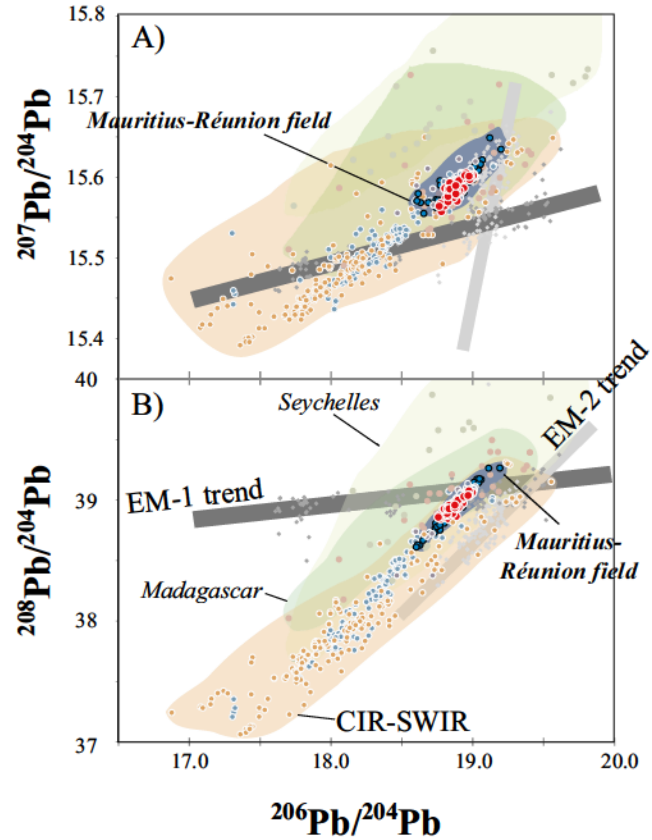

Fig. 3. ^{208}Pb/^{206}Pb and ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb. Data and symbols are the same as in Fig. 2.

ICP-MS Thermo Scientific Neptune. Thus, data from this group were acquired on 3 different MC-ICP-MS from the same manufacture, always with the same method (White et al., 2000) and with different methods of Pb purification: White et al. (2000) for those obtained at IPGP and at IFREMER and Vlastélic et al. (2013) and Pin et al. (2014) for those obtained at LMV. We ascribe the difference between Bosch et al. (2008) and the other data to an undefined analytical artefact, and therefore do not include their dataset in the following discussion. However, we use their Sr—Nd isotopes compositions, which are consistent with the range of other published values. We also rejected two Pb data from Smietana (2011) on Piton des Neiges, one for which the two duplicates were inconsistent (sample DR7-1), and one whose re-analysis by Vlastélic and Pietruszka (2016) gave a clearly different result (PN 17). Data filtering narrows the whole selection down to 50 sample analyses for Sr and Nd isotopes and only 13 for Sr, Nd and Pb isotopes.

The same filtering procedure was applied to Piton de la Fournaise, resulting in the exclusion of old and/or suspicious data. Following the suggestion of Bosch et al. (2008), we also chose to exclude the Nd data of (Luais, 2004) because of possible analytical artefacts, a choice supported by their inconsistency with those of Smietana (2011) and Bosch et al. (2008). The remaining dataset still includes > 500 Sr ± Nd ± Pb data. We filtered the Mauritius database in the same way. Following the strategy of (Moore et al., 2011), we decided to use only the Pb data from (Nohda et al., 2005), rejecting those from (Paul et al., 2005) because of their larger scatter. For Rodrigues, the data are so sparse that we only excluded the oldest Sr data (McDougall and Compston, 1965) and kept all the others (Baxter et al., 1985; Mellor, 1998).

5.2. Comparison between Réunion Island and Mauritius

As already mentioned in previous studies, the isotopic evolution of Mauritius from 8.9 Ma to 31 ka is interpreted as reflecting a diminishing contribution of the Réunion plume and an increase in the depleted mantle contribution (Duncan et al., 1989; Moore et al., 2011). In terms of Pb isotopes, the temporal evolution observed can be described as binary mixing between a Réunion plume component and the depleted upper mantle represented by the CIR.

However, this binary mixing scenario is questioned when data are plotted into ^{87}Sr/^{86}Sr or ^{143}Nd/^{144}Nd vs. ^{208}Pb/^{206}Pb diagrams (Fig. 5). In these isotope diagrams, samples from Mauritius do not plot along a well-defined RP-CIR hyperbolic binary mixing line (Fig. 5), but instead have variable ^{208}Pb/^{206}Pb ratios at rather constant ^{87}Sr/^{86}Sr or ^{143}Nd/^{144}Nd. Mauritius samples from the Older Series are distinguished from those belonging to the Intermediate and Younger Series within ^{143}Nd/^{144}Nd vs. ^{208}Pb/^{206}Pb space. Mauritius Older Series samples, as well as PN and PF, define an elongated field with a negative slope, while Mauritius Younger Series samples plot on a distinct sub-parallel array with higher ^{143}Nd/^{144}Nd for a given ^{208}Pb/^{206}Pb (Fig. 5). From these observations, a simple binary mixing between a depleted MORB mantle and an enriched Réunion plume is no longer consistent. At least one more component is required, having high ^{208}Pb/^{206}Pb, ^{207}Pb/^{206}Pb, ^{87}Sr/^{86}Sr and low ^{143}Nd/^{144}Nd.

The presence of a third component in the Mauritius source has been already suggested (Paul et al., 2005), and revisited later (Paul et al.,

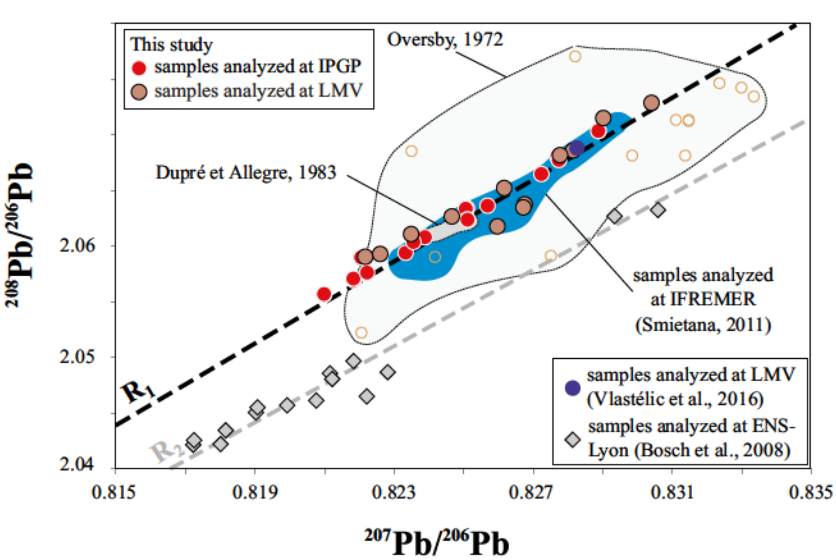

Fig. 4. ^{208}Pb/^{206}Pb vs. ^{207}Pb/^{206}Pb for PN. Pb isotope compositions are from (Oversby, 1972; Dupré and Allègre, 1983; Bosch et al., 2008; Smietana, 2011; Vlastélic and Pietruszka, 2016) and this study. Data from Cooper and Richards, (1966) are not shown as their very high ^{207}Pb/^{206}Pb and ^{208}Pb/^{206}Pb plot away from the field of the more recent data. Data from Dupré and Allègre (1983) and Oversby (1972) were obtained by TIMS. Data from Vlastélic and Pietruszka (2016) where obtained by MC-ICP-MS at Laboratoire Magmas et Volcans (LMV), Clermont-Ferrand, these from Smietana (2011) by MC-ICP-MS at IFREMER, these from Bosch et al. (2008) by MC-ICP-MS at ENS, Lyon. Our data were obtained by MC-ICP-MS at IPGP-Paris and at LMV. All these MC-ICP-MS were obtained following analytical procedure given by White et al. (2000).
Regression line equations are ^{208}Pb/^{206}Pb = 1.77*(^{207}Pb/^{206}Pb) + 0.60 (r^2 = 0.95) when calculated with our data (R_1), and ^{208}Pb/^{206}Pb = 1.61*(^{207}Pb/^{206}Pb) + 0.72 (r^2 = 0.96) when calculated with data from Bosch et al. (2008) (R_2).

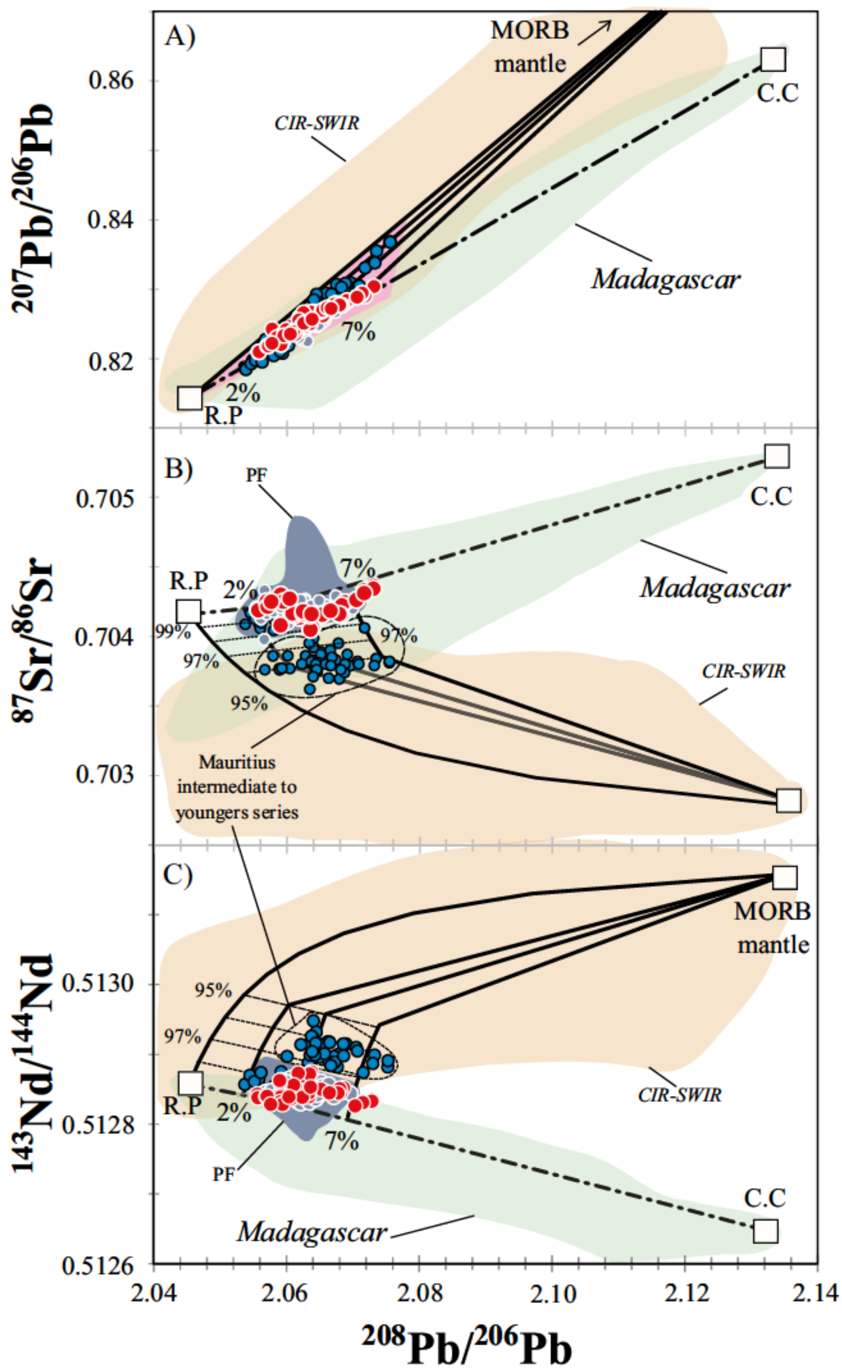

Fig. 5. A) $^{208}Pb/^{206}Pb$, B) $^{87}Sr/^{86}Sr$ and C) $^{143}Nd/^{144}Nd$ vs. $^{207}Pb/^{206}Pb$. Parameters for our three-component mixing scenario are: 1) Réunion plume component (R.P): $^{87}Sr/^{86}Sr = 0.70416$, $^{143}Nd/^{144}Nd = 0.512857$, $^{206}Pb/^{204}Pb = 19.1997$, $^{207}Pb/^{204}Pb = 15.6350$, $^{208}Pb/^{204}Pb = 39.2697$, [Sr] = 150 ppm, [Nd] = 10 ppm, [Pb] = 3 ppm; 2) Seychelles/Madagascar continental crust (C.C): $^{87}Sr/^{86}Sr = 0.70528$, $^{143}Nd/^{144}Nd = 0.512647$, $^{206}Pb/^{204}Pb = 18.0610$, $^{207}Pb/^{204}Pb = 15.5870$, $^{208}Pb/^{204}Pb = 38.5150$, [Sr] = 270 ppm, [Nd] = 38 ppm, [Pb] = 16 ppm, which represent the average of magmatic rocks from Seychelles Islands (Georoc database); 3) Indian MORB mantle $^{87}Sr/^{86}Sr = 0.702824$, $^{143}Nd/^{144}Nd = 0.513157$, $^{206}Pb/^{204}Pb = 17.3631$, $^{207}Pb/^{204}Pb = 15.3923$, $^{208}Pb/^{204}Pb = 37.0698$, [Sr] = 100 ppm, [Nd] = 11 ppm, [Pb] = 0.5 ppm. The first step consists of mixing the Réunion plume component with the Seychelles/Madagascar like component. The second step mixes the result of the first step with a MORB mantle component. Binary mixing equation is from Langmuir et al. (1978). PF is for Piton de la Fournaise.

2005; Moore et al., 2011). The most recent arguments in favor of a third component at Mauritius are the discovery of continental zircons within trachytes of the Older Series (Torsvik et al., 2013; Ashwal et al., 2017) and the radiogenic Sr isotope composition ($0.70477 < {^{87}Sr/^{86}Sr} < 0.710336$) of these trachytes (Ashwal et al., 2016), although the origin of such compositions is, from our point of view, largely uncertain. This third component could either be a piece of continental crust hidden below Mauritius or some metasomatized lithospheric mantle containing continental material. In both cases, the continental component has a Seychelles-Madagascar-like composition. The occurrence of this third component, though minor, has also been suggested for Réunion Island, although there is no consensus as to its nature. It has been proposed that the Réunion plume contains a minor EM-2 like component in addition to the two major C-FOZO-like and EM-1 like components (Bosch et al., 2008; Smietana, 2011). However, the unradiogenic Os isotope compositions measured at PF basalts ruled out the involvement of an old enriched component, suggesting that recycled oceanic crust and/or continental sediment do not play a significant role in the Réunion plume source (Schiano et al., 2012; Peters et al., 2016).

Our new Sr-Nd-Pb analyses for PN implies that this third component extends the isotopic data towards the Seychelles/Madagascar continental field in $^{143}Nd/^{144}Nd$ or $^{87}Sr/^{86}Sr$ vs. $^{208}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ spaces. If our hypothesis is correct, lower Nb/U and Ce/Pb ratios than those reported for MORB would be expected (i.e. Nb/U = 47 ± 10, Ce/Pb = 25 ± 5 (Hofmann et al., 1986)). When we plot Mauritius-PN-PF onto a Nb/U vs. $^{87}Sr/^{86}Sr$ diagram (Fig. 6), we observe very large variations in the Nb/U ratio (17 to 100) at nearly constant $^{87}Sr/^{86}Sr$ (~0.7042), whereas Mauritius samples from the Younger Series with a stronger MORB signature have Nb/

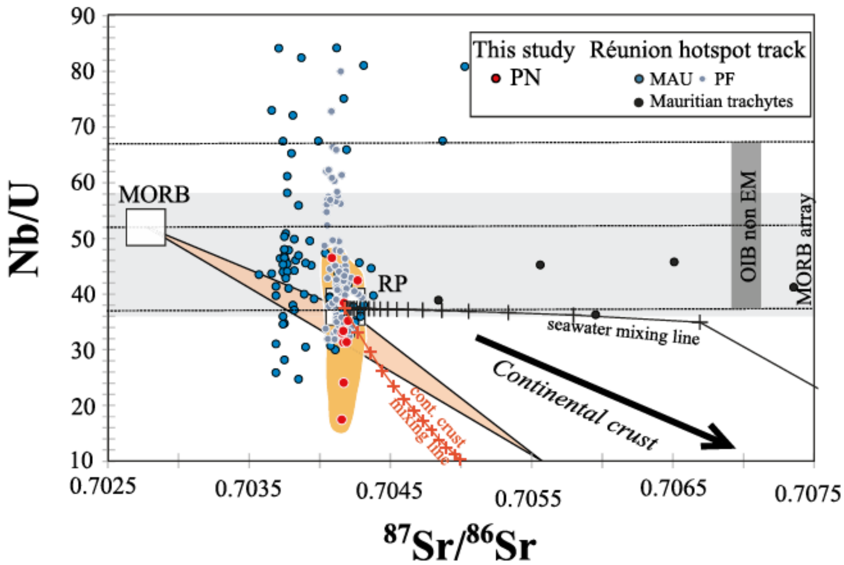

Fig. 6. Nb/U vs $^{87}Sr/^{86}Sr$. MORB and OIB reference values are from (Hofmann, 2007). RP box corresponds to the Réunion plume component. Binary mixing lines between the RP component and seawater, and between the RP and CC components are also reported. Parameters for calculating these mixing lines are for RP: [Nb] = 32.1 ppm, [U] = 0.85 ppm, [Sr] = 150 ppm, $^{87}Sr/^{86}Sr$ = 0.70424 (corresponding to sample MP 24 from Moore et al., 2011); for seawater: [Nb] = 0.01 ppb, [U] = 3.2 ppb, [Sr] = 8000 ppb (data selected from EarthRef.org database), $^{87}Sr/^{86}Sr$ = 0.70916; for CC: [Nb] = 9.8 ppm, [U] = 2.4 ppm, [Sr] = 270 ppm, $^{87}Sr/^{86}Sr$ = 0.70528 (corresponding to the average given by GEOROC database for plutonic rock from Seychelles islands).

U ranging from 25 to 50 and lower $^{87}Sr/^{86}Sr$ ratios (~0.7036). Taking into account that Nb/U higher than 60 is most likely due to loss of U, and assuming that the pure Réunion component has the same Nb/U as the oceanic mantle sampled by OIB and MORB (47 ± 10) (Hofmann et al., 1986), Mauritius-PN-PF samples define a triangular distribution, where MORB and the pure Réunion component define one side of the triangle with Nb/U = 47, and the opposite angle corresponds to the third component with a low Nb/U ratio (down to 18 for trachytic sample named SAL 1).

5.3. Mixing model

On the basis of the above arguments, we propose a two-step binary mixing model involving three components. We suggest that one component is the Indian MORB mantle represented by the least radiogenic sample of the South West Indian Ridge (Meyzen et al., 2005), because the regression line through Mauritius points towards this sample. Another component, which we term the “pure” Réunion plume (RP) component, is best represented by sample MP 24 in Moore et al. (2011), which has high MgO and high Ni contents (MgO = 9.15 wt%; Ni = 189 ppm), with Nb/U = 37.8 and Ce/Pb = 24 and the most enriched isotope composition ($^{87}Sr/^{86}Sr$ = 0.70424, $^{143}Nd/^{144}Nd$ = 0.512857, $^{206}Pb/^{204}b$ = 19.1997, $^{207}Pb/^{204}b$ = 15.6350, $^{208}Pb/^{204}b$ = 39.2697). The third component is chosen to represent a crustal component with a Seychelles/Madagascar-like signature, as suggested for Mauritius (Ashwal et al., 2016). Compositions are averages calculated with literature data for Seychelles Islands downloaded from the Georoc database (Sarbas and Nohl, 2008). All the key parameters used in the model are given in the caption of Fig. 5.

Two important constraints must be taken into account in our model. First, the amount of crustal component must be low to be consistent with previous work and with the PCA. A second constraint is derived from the relatively constant $^{143}Nd/^{144}Nd$ at variable $^{208}Pb/^{206}Pb$ (Fig. 5C). In this diagram, the main variations shown by PF-PN and the Mauritius Older Series occur along a curve between the RP component and the crustal component, while Mauritius samples of the Intermediate and Younger Series with the highest mantle contribution are shifted towards the MORB mantle component. This suggests that the crustal component is added to the RP component before the MORB mantle component. Accordingly, the model that best fits the isotope variations in Fig. 5A–C is a two-step binary mixing, with a first step of RP and continental crust mixing. This first step is required to fit variations in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ vs. $^{208}Pb/^{206}Pb$. The second step consists of mixing this hybrid component with the Indian MORB component, and produces the composition of the young Mauritius lavas. Our model here takes up the idea of mixing of mixtures already proposed on a large scale throughout the Indian Ocean (Hanan et al., 2013; Graham et al., 2014).

Model calculations are shown on Fig. 5A–C. Numerical results are strongly dependent on the choice of the model parameters. Addition of 1–8% of Seychelles/Madagascar-like continental crust during the first step, and 0–30% of Indian MORB mantle during a second step, reproduces Mauritius, PN and PF isotope variations. Our scenario implies that the Seychelles/Madagascar-like crustal component is always present in the Mauritius-Réunion hotspot volcanism.

5.4. Where is the crustal component located?

The recent discovery of Neoproterozoic to Archean (0.7 to 3 Ga) zircons in Mauritius has raised the possibility that the lithosphere of the Mascarene plateau may contain a remnant of continental crust left behind during the northward migration of Indian plate. Because those zircons have an isotopic affinity and an age range compatible with the Madagascar continental crust (Torsvik et al., 2013; Ashwal et al., 2017), it is very likely that they originate from the same source as the Seychelles/Madagascar crustal component identified here. If so, our three-component mixing model adds constraints on the provenance of the crustal signature revealed by zircons. Firstly, the crustal contamination of PN and PF magmas cannot be attributed to a continental fragment, because the lithosphere beneath Réunion Island is clearly oceanic, as shown by its bathymetry, magnetic fabric and seismic velocity structure. Secondly, our two-step mixing model implies that the continental crust component mixes with the Réunion plume before the MORB component. These two arguments suggest that mixing of the Réunion plume with continental crust, as seen from Sr-Nd-Pb isotopes and zircons, occurs within the asthenospheric mantle before the plume interacts with the oceanic lithosphere.

Should the crustal component reside within the Réunion plume source since billions of years, the derived material should show high $^{187}Os/^{188}Os$ ratios. This is not the case at Réunion Island (Schiano et al., 2012; Peters et al., 2016), whose lavas do not have Os isotope ratios as extreme as those observed in Society islands where a strong EM-2 signature is observed. Therefore, mixing between the RP and crustal components unlikely occurs at the source of the plume. Instead, the continental component must be introduced shortly before lava emission because otherwise, magmatic products would show very high Os isotopic ratios. We therefore tentatively place the first step of mixing between the RP and crustal components in the asthenosphere. It has been

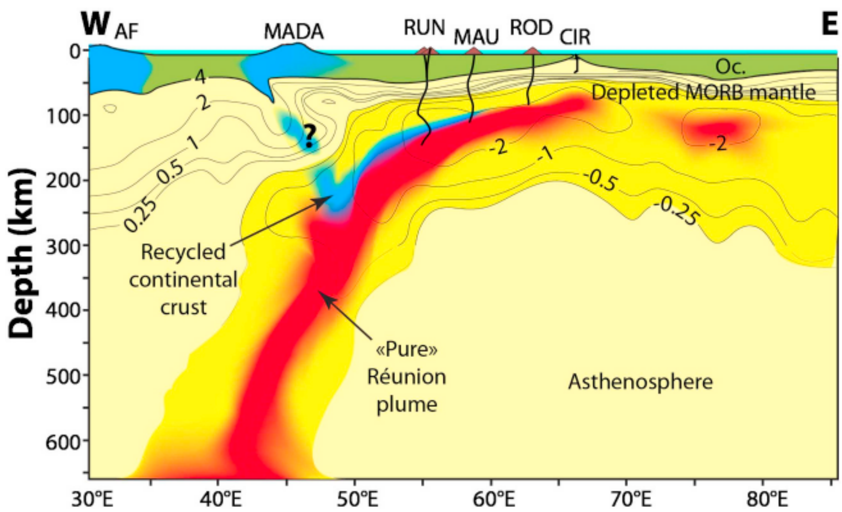

Fig. 7. Schematic conceptual model of Réunion plume interaction with recycled Seychelles/Madagascar continental crust, introduced into the asthenosphere by the East Africa orogeny. The mixture then rises into the upper depleted MORB mantle of the Indian Ocean, while the crustal fraction decreases from Réunion Island to Mauritius, Rodrigues and the CIR. Model geometry is chosen based on the seismic tomography of Mazzullo et al. (2017) (D1-D2 cross section from their Fig. 10, contour lines are iso-ratios of shear velocity over average shear velocity), and the eastward inflection of the Réunion plume shown by SKS splitting (Scholz et al., 2018).

proposed that Mauritius magmas, including the trachytes containing crustal zircons, might stem from a mantle metasomatized by recycled continental crust (Sheth et al., 2003; Ashwal et al., 2016). The new corpus of isotopic data concurs with this interpretation, and suggests the presence of recycled continental crust in the Indian mantle, as already found along the South West Indian Ridge (SWIR) (Hamelin et al., 1986; Mahoney et al., 1992; Meyzen et al., 2005). We thus propose that the crustal contamination detected in the OIBs of Réunion Island, in the Mauritian trachytes and perhaps elsewhere in the Indian Ocean, reflects a degree of recycling of Seychelles/Madagascar continental crust into the asthenosphere (Fig. 7).

Continental recycling in the mantle requires a subduction or collision process. Given the age of the youngest pre-Miocene zircons from Mauritius (700 Ma), the East Africa orogeny occurring between 800 and 650 Ma in west Madagascar (see review by Fritz et al., 2013) could have supplied the Indian Ocean mantle with recycled continental crust. Recent seismic tomography and SKS splitting studies in the Indian Ocean suggest, on the one hand, the existence of a low-shear-velocity root beneath Madagascar, and an inflection of the Réunion plume towards the CIR (Mazzullo et al., 2017; Scholz et al., 2018). Based on these recent studies, we favor a scenario in which the crustal component of the Réunion hotspot results from interaction of the plume with continental material from the West Madagascar orogeny, recycled into the mantle by subduction or delamination (Fig. 7). The plume contaminated by continental crust then interacts with the upper depleted lithospheric mantle, explaining the second step mixing with MORB-type component. In this scenario, the amount of continental crust in the asthenospheric mantle decreases from Réunion Island to Mauritius, Rodrigues and the CIR, as suggested by Figs. 3 to 6. This continental crust component would also be preferentially tapped by low-degree melts, explaining why it is more apparent in the most differentiated products of Piton des Neiges and Mauritius. Our scenario predicts that continental zircons could occur in Piton des Neiges trachytes as well.

6. Conclusion

We report a new set of Sr-Nd-Pb isotope compositions from samples collected at Piton des Neiges volcano. These data, together with filtered literature data from both Réunion and Mauritius Islands, are used to create a high-precision isotope database for the Réunion hotspot products younger than 10 Ma. This database is used to discuss the origin of the isotopic variations along the Mauritius-Réunion hotspot track. These variations best explained by a three-component, two-step mixing involving first the Réunion plume and a Seychelles/Madagascar-like continental crust, and then addition of depleted Indian MORB mantle. The geodynamic implication of this model is that the Seychelles/Madagascar-like continental crust has been recycled into the Indian asthenosphere, perhaps during the East Africa orogeny. This model reconciles the geochemical, geophysical and geodynamic studies of the Indian Ocean, but challenges the hypothetical existence of a hidden Mauritian micro-continent.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemgeo.2019.06.009.

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