

Compositional diversity among primitive lavas of Mauritius, Indian Ocean: Implications for mantle sources

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Abstract

Three distinct phases of basaltic volcanism (Older Series, 7.8–5.4 Ma; Intermediate Series, 3.5–1.9 Ma; Younger Series, 0.7–0.03 Ma), related to the Deccan–Réunion mantle–plume, occurred over a time span of nearly 8 million years on the island of Mauritius, Indian Ocean. Bulk rock compositions of 52 analyzed samples (including samples from 32 recent borehole sections), as well as the compositions of olivine and spinel phenocrysts, reveal significant temporal variations in the composition of the Mauritius magmas. Two distinct compositional groups are identified based on their major and trace element compositions. The Group 1 basalts comprise the Younger Series, Intermediate Series and the earlier products of the Older Series rocks, and have higher MgO (7.6–13.6 wt.%) and lower K₂O (0.2–0.5 wt.%) and La/Sm (2.1–3.5) compared to Group 2 basalts (MgO 6.2–9.2 wt.%; K₂O 1.0–1.5 wt.%; La/Sm 3.6–4.1), which exclusively encompass the later differentiation products erupted during the end of the Older Series volcanism, denoted as Older Differentiated (OD) Series. Petrographic and mineralogic studies further confirm the presence of two distinct groups. Relatively primitive olivine compositions (Fo: 87–80) in Group 1 rocks are characterized by increasing CaO (0.2 to 0.3 wt.%) with decreasing Fo content, whereas in Group 2 rocks olivine (Fo: 86–80) show decreasing CaO (0.4 to 0.3 wt.%) with decreasing Fo content. Olivine-hosted spinel inclusions also show strong compositional differences between groups 1 and 2. Unusually Al-rich spinels (compared to that usually found in plume derived magma) and the positive Sr anomalies in Group 1 rocks suggest assimilation of crustal gabbros by the plume magmas. We propose a laterally heterogeneous plume and the contributions from variable plume components to account for the compositional differences observed in the two Mauritian lava groups. The early-Shield building Older Series lavas (oldest Group 1 lavas), characterized with a relatively less enriched trace element abundances, most likely derive from extensive melting of a depleted peridotite matrix in the core of the plume. Melting of this already depleted source produced the later Intermediate and Younger Series eruptions. Towards the late-shield stage, melts presumably derive from the enriched pyroxenite/eclogite components in the outer part of the plume.

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1. Introduction

Almost a century of scientific investigation of “Hawaiian volcanism” has resulted in a fairly detailed picture of ocean island volcanism in general. Recent work has focused on the chemical evolution of the erupted products through time (e.g. [Chen and Frey, 1983, 1985](#); [Hauri, 1996](#); [Lassiter and Hauri, 1998](#); [Hauri, 2002](#)). It has long been established (e.g. [Sterns, 1940](#); [Macdonald and Katsura, 1964](#); [McDonald, 1968](#); [Chen and Frey, 1983](#); [Moore and Clague, 1992](#)) that Hawaiian volcanoes evolved through four general stages of volcanism: Pre-shield or Loihi stage (alkalic composition); Shield-building stage (tholeiitic); Post-Shield Capping Stage (alkalic); and Post-erosional (rejuvenated) stage (highly alkalic).

The Réunion mantle plume has a long history of volcanism starting with the voluminous basalt eruptions of the Deccan Traps in India 66–65 Ma ago, and is thought to be responsible for the current volcanism on Réunion Island in the Indian Ocean ([Peng and Mahoney, 1995](#); [Mahoney et al., 2002](#)). Nearly 2 Ma of volcanic activity in Réunion constructed two shield volcanoes, the Piton des Neiges and the Piton de la Fournaise, composed mainly of transitional olivine basalt (they plot near the compositional divide between alkali and tholeiitic basalts on the alkali–silica diagram of [Macdonald and Katsura, 1964](#)) and its intrusive equivalents ([Upton and Wadsworth, 1965](#)). The recent lavas erupted from Piton de la Fournaise, currently in its shield-building stage, are transitional olivine basalts (with minor hawaiites, feldspathoid basalts) and are similar in composition to the oldest lavas of Piton des Neiges.

Mauritius is considered to be the second youngest island in the long-lived Réunion mantle plume track stretching northward from Mauritius to the Mascarene Plateau, the Chagos–Laccadive Ridge, and the Deccan Traps of western India, respectively ([Morgan, 1981](#); [Duncan and Richards, 1991](#)). Volcanism on Mauritius occurred in 3 phases between 7.8–5.5 Ma, 3.5–1.9 Ma, and 0.7–0.03 Ma ([McDougall and Chamalaun, 1969](#); [Nohda et al., 2005](#)), which have been termed Older, Intermediate, and Younger Series eruptions, respectively. A thorough petrological and geochemical study ([Baxter, 1972, 1975, 1976](#)) of Mauritius basalts revealed that Older Series eruptions gave rise to transitional basalts. This stage seems analogous to the Hawaiian shield-building stage though the Hawaiian shield stage magmas are distinctly tholeiitic.

Some of the samples analyzed by Baxter were subsequently analyzed for Sr, Nd, and Pb isotopic variations

by [Mahoney et al. \(1989\)](#), [Sheth et al. \(2003\)](#), and [Paul et al. \(2005\)](#). [Nohda et al. \(2005\)](#) reported Sr, Nd, and Pb isotopic composition along with selected K–Ar dates of new samples from Mauritius collected during 1994 and 1995. These studies found much wider range in isotopic heterogeneity in Mauritian lavas compared to the Réunion lavas (e.g. [Albarède et al., 1997](#); [Graham et al., 1990](#); [Fretzdorff and Haase, 2002](#)) and confirm that volcanic evolution in Mauritius is more complex than that in Réunion.

In this present study, we report new whole rock major and trace element data of Mauritian lavas, which provide new insights into the stratigraphic evolution and overall chemical diversity of Mauritian volcanism. We report the first geochemical data for the oldest rocks on this island (obtained in boreholes). Significant compositional variations observed between the Shield-building oldest lavas obtained in boreholes and late-Shield stage differentiated products obtained from surface exposures require a re-evaluation of previously suggested volcanic evolutionary models (e.g. [Paul et al., 2005](#)) for Mauritius. We conclude that the compositional variations are likely to result from lateral heterogeneity in the Réunion plume.

2. Geology of Mauritius

The island of Mauritius in the Indian Ocean (57°39'E longitude and 20°19'S latitude, [Fig. 1](#)) is located towards the western side of the inverted Y-shaped Mid-Indian Ocean Ridge system and is a major aseismic structure with an area covering 65×48 km². The volcanic islands, Mauritius, Réunion (170 km to the WSW of Mauritius), and Rodrigues (650 km to the ENE) are often collectively known as Mascarene plateau.

[Simpson \(1951\)](#) identified 3 phases of volcanism on Mauritius, which he termed Older, Intermediate, and Younger Series volcanic rocks; a classification that has been retained by all subsequent workers ([Baxter, 1972, 1975, 1976](#); [Mahoney et al., 1989](#); [Sheth et al., 2003](#); [Paul et al., 2005](#); [Nohda et al., 2005](#)). K–Ar and paleomagnetic data by [McDougall and Chamalaun \(1969\)](#) confirmed Simpson's earlier observations. [Baxter \(1975\)](#) subdivided the Older Series into two stages; an early- and a late-Shield building stage. Subaerially, the early Shield building stage is only visible in the erosional remains of a single shield volcano that was built above sea level by the extrusion of transitional basalts (olivine basalt), erupted between 7.8 and 6.5 Ma ago. Subsequent eruptions gave rise to the late-Shield stage lavas and persisted until about 5.5 Ma ([McDougall and Chamalaun, 1969](#); [Baxter, 1975](#)), and produced

mainly hawaiites and mugearites with only small volumes of basalts and trachytes. After a 2 million year hiatus, renewed volcanism between 3.5 and 1.9 Ma ago

(Baxter, 1976) erupted the olivine-phyric alkali basalts, basanites, and nephelinites of the Intermediate Series lavas. The Younger Series lavas are mostly olivine

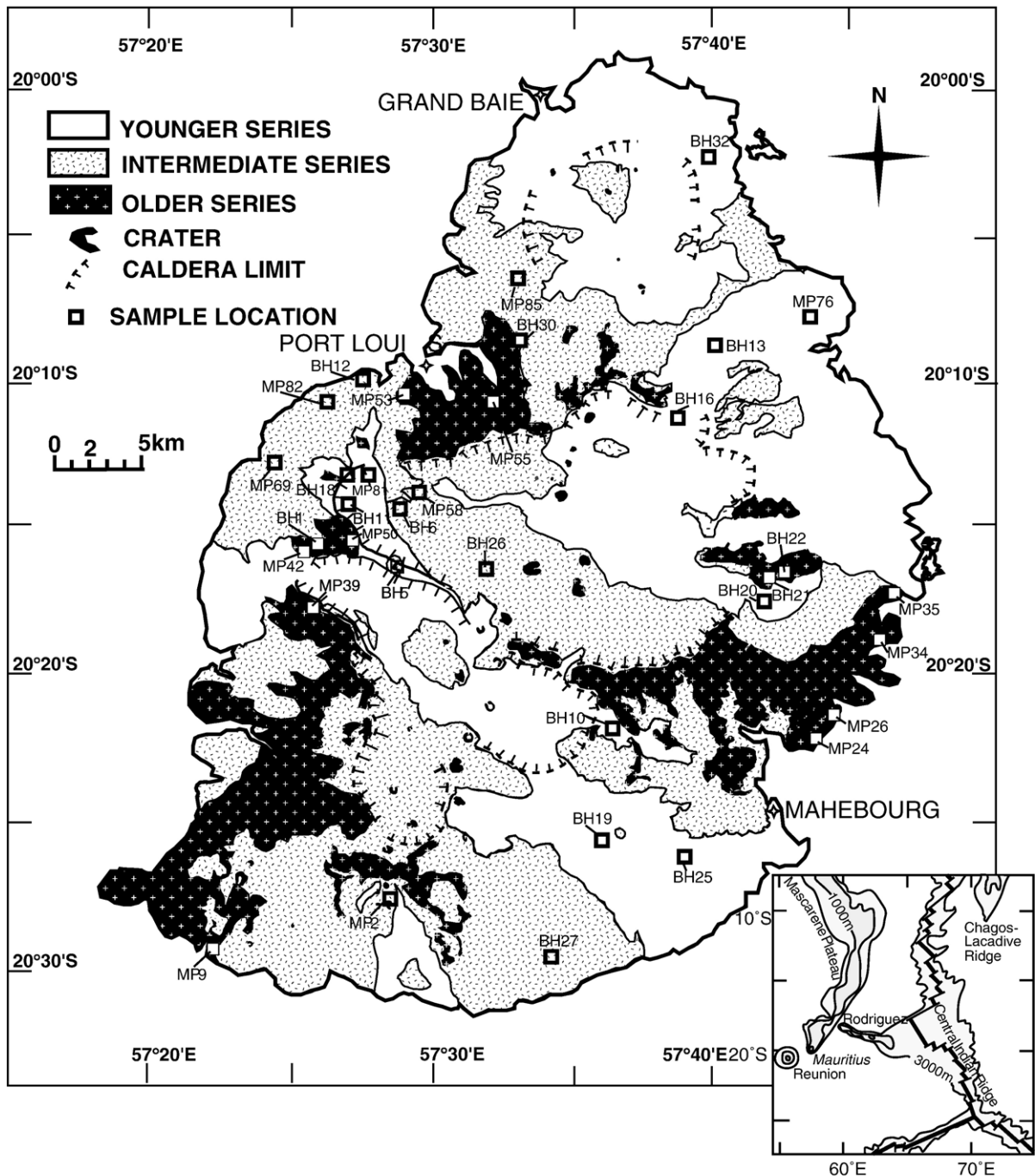


Fig. 1. Simplified geologic map of Mauritius modified from the recent 1:50,000 scale geologic map of the island obtained from the Water Resources Unit of Mauritius. Compared to the earlier mapping scheme (e.g. Baxter, 1975, 1976), which revealed restricted exposures of Intermediate Series lavas to the SW tip of the island, this map reveals extensive out cropping of Intermediate Series eruptions and more restricted yet extensive out cropping of Younger Series lavas. Solid squares represent sampling locations that include boreholes (generously made available by the Water Resource Unit, Mauritius) and samples collected from surface exposures.

basalts with smaller volumes of basanite. The K–Ar radiometric dates by McDougall and Chamalaun (1969) suggest an eruption interval 0.7–0.17 Ma. However, Nohda et al. (2005) reported 6 samples that yielded younger ages (0.12 to 0.03 Ma) that extend the eruption interval for the Younger Series to 0.7 to 0.03 Ma. Comparison of eruption ages suggest that during the Younger series eruptions in Mauritius, both Piton des Neiges and Piton de la Fournaise were active simultaneously on Réunion, whereas during the eruption of the late phase of Intermediate Series, only Piton des Neiges was active (McDougall, 1971; Gillot and Nativel, 1989; Deniel et al., 1992; Nohda et al., 2005).

3. Sampling and field observations

The samples presented in this study are collected by the first author in June 2003. A revised geologic map (1:50,000 scale) of Mauritius, obtained from the Water Resources Unit (WRU), Mauritius, is presented in Fig. 1. Earlier mapping and field observations revealed geographically restricted exposures of the Intermediate Series lavas, and larger Younger Series exposures that cover about three-quarters of the island (e.g. Baxter, 1976) apparently suggesting that the Intermediate Series are less voluminous than the Younger Series eruptions. Fig. 1, however, shows more extensive exposures of the Intermediate Series lavas and a slightly more restricted, but still extensive exposure of the Younger Series compared to earlier maps. The WRU also provided us with samples from boreholes of variable depth (some ranging up to 500 ft deep). We collected samples from 32 borehole sections (some include multiple samples from a single borehole) and numerous subaerial samples for comparison with borehole representative unit (sampling locations are shown in Fig. 1). Multiple samples from a single borehole comprise of one from the deeper sections of the borehole (150–516 ft) and the other from the shallow parts (8–15 ft) of the borehole. Below about 100 ft depth, the Older Series lavas are present in all the boreholes, and can be observed continuously down to about 745 ft deep (the deepest borehole available on Mauritius; personal communication with the Chief Hydrologist, WRU). The borehole Older Series samples are light to dark grey in color consisting of mm long clear to light green colored olivine crystals. In contrast, the subaerial lavas of the Older Series are dark in color, and contain larger (cm scale) yellowish olivine grains along with clinopyroxene, plagioclase and rare hornblende phenocrysts. On the basis of the compositional differences and relative position in the stratigraphic column, we infer that these

two units represent two different stages of the Older Series volcanism. In this paper, we termed the borehole Older Series samples (earlier products) as Older Series and those collected from outcrops as Older Differentiated (OD) Series. This is consistent with the earlier classification of Baxter (1975). Due to the lack of exposure of Older Series lavas in the field, it is possible that these rocks are not included in previous studies. For example, the oldest Older Series rock collected from surface exposure by Nohda et al. (2005) is dated 6.49 Ma, which may represent our OD Series. The Intermediate Series rocks are easily identifiable in the field based on the color (reddish compared to light grey color of Younger Series) and are characteristically devoid of any vesicles in contrast to Younger Series rocks. We classify the samples into four Series with decreasing age: Older, Older Differentiated (OD), Intermediate, and Younger Series.

4. Analytical techniques

Based on the examination of thin sections, only the freshest samples were selected for chemical analyses. Small pieces of these samples were crushed using mortar and pestle, and sieved to collect the fraction between 500 μm and 1 mm, followed by picking of individual olivine, clinopyroxene and plagioclase grains under the microscope. These mineral grains were analyzed for major element composition using the JEOL Superprobe 8200 at the Max Planck Institut für Chemie (MPI), Mainz. During the analyses (30 s on the peak and 15 s on background) of minerals an accelerating voltage of 20 kV, beam current of 15 nA, and a beam size of 1–2 μm was maintained. During the analyses of clinopyroxene and plagioclase, a chromium augite standard (USNM 164905; Jarosewich et al., 1987) was monitored, and during the analyses of olivine, a San Carlos olivine standard was monitored.

About 200 g of fine powder was prepared for each sample using agate mortars and care was taken to minimize contact with metals during all stages of sample handling. The whole rock major element composition was determined on fused glass disks and selected trace element (Sc, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th, and U) concentrations were determined using pressed powder pellets with X-ray fluorescence (XRF) at the University of Mainz. A set of 31 trace element (including the rare earth elements) analyses were performed at the MPI by using Laser Ablation (New wave UP-213 system) technique coupled with a Finnigan Element 2 high-resolution single-collector ICP-MS following the procedure described by Jochum

et al. (2005). The glass samples were analyzed in three separate sequences along with a set of standard glasses, KL2-G, NIST SRM-612, BHVO-1, BCR-1, ML3BG, and T1G. A typical analysis on glass samples comprised of analysis of trace element concentrations on 3 to 5 random points and the average of these points was reported as representative concentration of the sample only if they result in similar values suggesting sample homogeneity. Each sequence also included 3 to 5 of the above rock standards analyzed simultaneously with the unknowns to determine the accuracy of measurements. The expected and measured (average of 10 analyses) values for two standards BHVO-1 and BCR1 were reported in Table 2. The reproducibility [given by (standard deviation/average) $\times$ 100] of measurements as determined from 10 in-run analyses of BHVO-1 results in 2–6% for all the elements except for Cs (10%) and Pb (12%).

5. Results

Major and trace element variations in the Older, Intermediate, and Younger Series samples lie on common fractionation trends (e.g. Figs. 2 and 3). The Older Differentiated Series samples, however, define a trend oblique to that of the other Series. According to the trends based on the major and trace element variations, we group the Mauritius samples into two compositionally distinct groups; the Older, Intermediate and Younger Series samples together form Group 1 lavas; and the Older Differentiated Series samples form Group 2 lavas.

5.1. Phenocryst composition

Average major element oxide compositions for olivine, clinopyroxene, and plagioclase phenocrysts

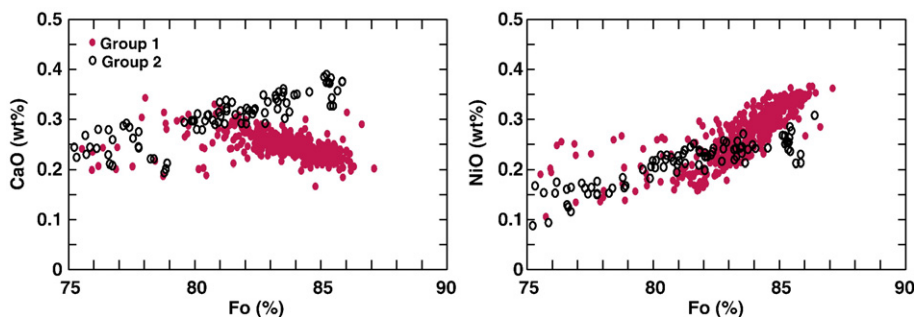


Fig. 2. Compositional variation in CaO and NiO with Fo ($\text{Fo} = \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$) content of olivine phenocrysts in Group 1 (Older, Intermediate, and Younger Series lavas) and Group 2 (Older Differentiated Series) lavas. The figure shows two different trends for both the Groups. In the range of Fo 86–80, the CaO content in the Group 1 increases with decrease in Fo content, whereas the CaO content in Group 2 lavas increase with increasing Fo. In the same Fo range, NiO–Fo correlation in Group 1 shows steeper slope compared with the trend of Group 2 lavas.

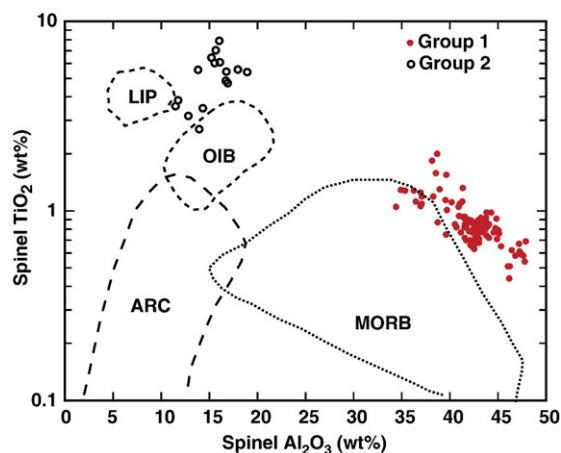


Fig. 3. Compositions of olivine-hosted inclusions of spinel in the Group 1 and 2 lavas. Spinel composition of Group 1 lavas is characterized with decrease in TiO_2 with increase in Al_2O_3 , whereas the correlation is poor in Group 2 lavas, nevertheless show two distinct fields. The fields shown for MORB, OIB, Arc, LIP (Large Igneous Provinces) are from Kamenetsky et al. (2001).

found in Mauritian lavas are given in Table 1. Although rare olivine phenocrysts (BH19b and BH21) from the Older Series contain 87% forsterite (Fo ; $\text{Fo} = \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$), a strong maximum is observed at 83–85. Olivine in Intermediate and Younger Series have $\text{Fo} \leq 85$. The Fo values of less than 80 for the OD Series suggest that these olivines crystallized from more fractionated melts than the Older Series lavas.

Fig. 2 shows variations in Fo content of olivine phenocrysts with CaO and NiO in Group 1 and Group 2 lavas. The CaO content of olivine in the Group 1 increases with decreasing Fo content (Fo: 86–80) with a peak at 0.3 wt.%, similar to that observed in Réunion lavas (Albarède et al., 1997). In the Group 2 olivines, the Fo content (in the range: 86–80) decreases with decreasing CaO (0.4 to 0.3 wt.%). In the same Fo

Table 1

Major element (oxide in wt.%) data of Mauritius basalts determined by XRF

	Rock type	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	NiO	LOI	Sum	Mg#
<i>Younger Series</i>																
BH10	OB	45.66	1.69	14.74	14.14	0.18	11.34	9.53	2.30	0.28	0.13	0.060	0.041	0.56	100.7	64
BH11	OB	45.85	1.50	14.95	13.64	0.18	10.43	9.69	2.61	0.27	0.13	0.053	0.042	0.42	99.8	63
BH13	OB	46.18	1.39	14.81	13.65	0.18	11.23	9.61	2.48	0.21	0.11	0.058	0.048	0.01	100.0	64
BH20a	OB	46.35	1.78	15.36	13.36	0.17	9.70	10.56	2.54	0.27	0.13	0.056	0.028	−0.24	100.1	62
BH32a	B	45.64	1.63	14.21	13.91	0.18	11.41	10.12	2.88	0.38	0.17	0.059	0.042	−0.58	100.1	64
MP76	OB	46.89	1.59	14.93	13.14	0.17	10.05	10.38	2.78	0.32	0.14	0.060	0.032	−0.59	99.9	63
MP81	AOB	45.40	2.22	14.03	14.38	0.18	9.83	10.37	2.78	0.43	0.20	0.052	0.031	−0.56	99.3	60
<i>Intermediate Series</i>																
BH6	OB	45.63	1.90	14.63	13.82	0.18	10.95	10.46	2.39	0.37	0.18	0.069	0.039	0.26	100.9	64
BH12	AOB	45.35	2.16	15.04	13.45	0.17	9.07	11.15	2.78	0.48	0.21	0.045	0.019	0.00	99.9	60
BH27a	AOB	45.34	1.71	14.35	14.05	0.18	11.81	9.84	2.55	0.36	0.15	0.061	0.042	−0.42	100.0	65
MP2	AOB	43.76	1.78	14.42	14.45	0.18	11.84	9.47	2.45	0.30	0.16	0.063	0.044	1.21	100.1	64
MP58	AOB	45.70	2.0	14.98	13.42	0.17	9.44	11.05	2.77	0.41	0.19	0.057	0.023	−0.60	99.6	61
MP69	AOB	45.56	1.77	15.18	13.98	0.18	10.89	9.34	2.77	0.40	0.16	0.022	0.027	−0.70	99.6	63
MP82	AOB	45.57	2.11	15.02	13.52	0.17	9.33	11.11	2.84	0.48	0.21	0.049	0.022	−0.56	99.9	60
MP85	AOB	45.73	1.85	15.00	13.61	0.19	9.14	10.77	2.75	0.36	0.16	0.053	0.024	−0.38	99.3	60
<i>Older Series</i>																
BH1	PB	44.92	1.97	15.08	13.65	0.18	10.65	10.85	2.38	0.45	0.19	0.062	0.037	0.70	101.1	63
BH5	PB	44.79	2.09	14.11	14.09	0.18	11.95	10.39	2.45	0.55	0.24	0.065	0.043	−0.23	100.7	65
BH16b	OB	46.29	1.48	14.69	14.02	0.18	11.27	9.71	2.78	0.27	0.12	0.055	0.043	−0.47	100.4	64
BH18	OB	44.53	2.04	14.58	13.81	0.17	9.82	9.83	1.85	0.41	0.23	0.066	0.037	3.34	100.7	61
BH19b	B	44.28	2.33	13.29	14.25	0.18	12.32	10.15	2.75	0.72	0.28	0.065	0.045	−0.27	100.4	66
BH21	OB	43.72	1.36	14.12	12.70	0.16	13.07	8.60	1.73	0.20	0.10	0.065	0.045	4.64	100.5	69
BH22b	OB	46.41	1.85	15.00	13.76	0.18	10.13	10.27	2.70	0.33	0.16	0.058	0.030	−0.46	100.4	62
BH25b	OB	46.24	1.56	14.60	13.60	0.18	11.16	10.01	2.72	0.29	0.12	0.058	0.038	−0.90	99.7	64
BH26b	AOB	45.50	2.14	14.03	14.28	0.18	10.62	9.91	2.88	0.47	0.22	0.056	0.036	−0.63	99.7	62
BH30b	PB	44.88	1.70	13.39	13.90	0.18	13.17	9.89	2.55	0.40	0.20	0.069	0.048	−0.76	99.6	68
BH32b	PB	44.44	1.80	13.90	13.86	0.19	11.42	10.25	2.38	0.42	0.22	0.067	0.047	0.59	99.6	64
<i>Older Differentiated Series</i>																
MP9	H	46.86	1.99	12.69	12.51	0.16	11.44	9.92	2.72	0.66	0.31	0.076	0.049	0.85	100.2	67
MP26	OB	47.82	2.64	14.24	12.31	0.17	6.84	10.16	2.93	1.06	0.37	0.033	0.014	1.71	100.3	55
MP39	H	46.08	3.26	13.87	13.77	0.18	7.19	9.62	2.85	1.25	0.44	0.024	0.016	1.41	100.0	53
MP50	OB	47.01	3.14	14.55	12.67	0.17	6.83	9.62	2.99	1.45	0.52	0.028	0.015	0.61	99.6	54
MP53	OB	46.47	2.97	13.97	12.75	0.17	8.12	10.46	2.71	1.21	0.44	0.060	0.023	0.95	100.3	58
MP55	H	46.91	2.90	13.95	12.64	0.18	7.69	10.06	2.87	1.34	0.48	0.041	0.019	0.86	99.9	57
MP24	OB	46.19	2.84	13.63	13.35	0.18	9.15	10.11	2.64	0.98	0.37	0.082	0.025	0.37	99.9	60
MP34	OB	46.18	3.13	14.40	13.36	0.19	6.09	10.39	2.71	1.19	0.42	0.013	0.009	1.48	99.6	50
MP35	OB	46.28	3.15	14.20	12.63	0.17	6.18	10.28	2.72	1.30	0.44	0.014	0.007	1.66	99.0	52
MP42	T	46.82	3.05	13.74	13.44	0.18	6.77	10.05	2.92	1.18	0.43	0.028	0.013	0.56	99.2	53
Rel. RMS (%)		0.4	1.4	1.1	1.0	3.5	0.5	1.0	1.3	0.9	1.30	4.2	1.7			
Avg. Cpx		49.40	1.78	4.08	6.96		14.29	21.78	0.40	0.01		0.31	0.02		98.5	
Avg. Plag		51.69	0.11	28.57	0.78		0.15	12.47	4.14	0.66		0.01	0.01		98.7	
Avg. Olivine		39.48		0.06	15.63	0.21	44.16	0.28				0.06	0.25		101.1	83

Group 1 lavas: Younger, Intermediate, and Older Series rocks; Group 2 lavas: Older Differentiated Series rocks. Rock type abbreviations: OB — Olivine basalt; AOB — Alakaline Olivine Basalt; B — Basanite; PB — Picro Basalt; H — Hawaiiite; T — Trachybasalt. Fe₂O₃ is the raw data reported by XRF. Mg # [$\text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$] is calculated by converting the raw Fe-oxide data to FeO and assuming that 10% of the total Fe-oxide is Fe³⁺. LOI represents the Loss on Ignition. The error on the major oxide analyses is reported as relative root mean square deviation determined using a range of USGS and in-house basaltic rock standard analyses. Average values reported for 143 individual analyses of clinopyroxene (Cpx), 60 analyses of plagioclase (Plag), and 945 analyses of Olivine are obtained by Electron Microprobe. All the major element oxides are recalculated to a sum of 100% on an anhydrous basis and this corrected data are used in all the figures herein. Note that sample BH21 from the Older Series resulted in highest Loss on Ignition, however, recalculating the oxides to a sum of 100 results in similar composition as other Older Series lavas.

range (Fo: 86–80), Group 1 shows steeper slope than the Group 2 rocks with respect to the Fo–NiO trend. These trends suggest varying degrees of olivine fractionation for the two groups.

Fig. 3 reveals strong compositional differences amongst olivine-hosted spinel inclusions (140 analyses) in both the Groups. The Group 1 spinels are characterized by decreasing TiO_2 (1.6–0.4 wt.%) with increasing Al_2O_3 (34–48 wt.%). There is only a poor correlation between Al_2O_3 and TiO_2 in the spinel phenocrysts of the Group 2 lavas (Al_2O_3 : 11–19 wt.% and TiO_2 : 2.7–7.9 wt.%). Furthermore, Group 1 spinels display lower TiO_2 and higher Al_2O_3 than Group 2 spinels. The Cr # (Cr/Cr+Al) in Group 1 spinel range from 16 to 30 mol%. Group 2 spinels have Cr#s between 41 and 70 mol% and are similar to spinel compositions reported in Réunion lavas by Fretzdorff and Haase (2002).

5.2. Major element composition

Major element compositions of a set of selected samples belonging to all four Series are reported in Table 1. The rock names (and normative compositions) were determined using the software “Magma” (Source: www-geo.lanl.gov/Wohletz/Magma.htm). The majority of the samples contain normative nepheline, whereas

only 8 samples contain normative hypersthene. In the total alkali–silica diagram (Fig. 4), the majority of the data plot in the alkalic field; only two Older Series samples (BH18 and 31b) plot on the tholeiitic field. All of the Group 2 lavas plot on the high alkali side and are similar in composition to previously reported Older Series Mauritius lavas (Baxter, 1975, 1976; Nohda et al., 2005).

Bulk rock compositional variations in Mauritius lavas are shown in Fig. 5. This plot reveals two distinct fields; one defined by the Group 1 that have higher MgO (7.6–13.6 wt.%) and lower K_2O , P_2O_5 ; and the other defined by the Group 2 with lower MgO (6.2–9.2 wt.%) and higher K_2O , P_2O_5 . Except for the two most magnesian Older Series lavas, SiO_2 and Al_2O_3 contents in both the groups increase with decreasing MgO (increasing fractionation). This is also the case for the CaO–MgO variation in Group 1 rocks, where the trend reverses at ~9 wt.% MgO for both Intermediate and Younger Series lavas. These trends (and positive MgO–Ni trend) indicate that olivine fractionation dominates the whole rock composition until about 9 wt.% MgO. At lower MgO contents other phases (mostly clinopyroxene) become important. Compared with the Group 1, Group 2 lavas have higher TiO_2 and lower Al_2O_3 concentrations for a given MgO content

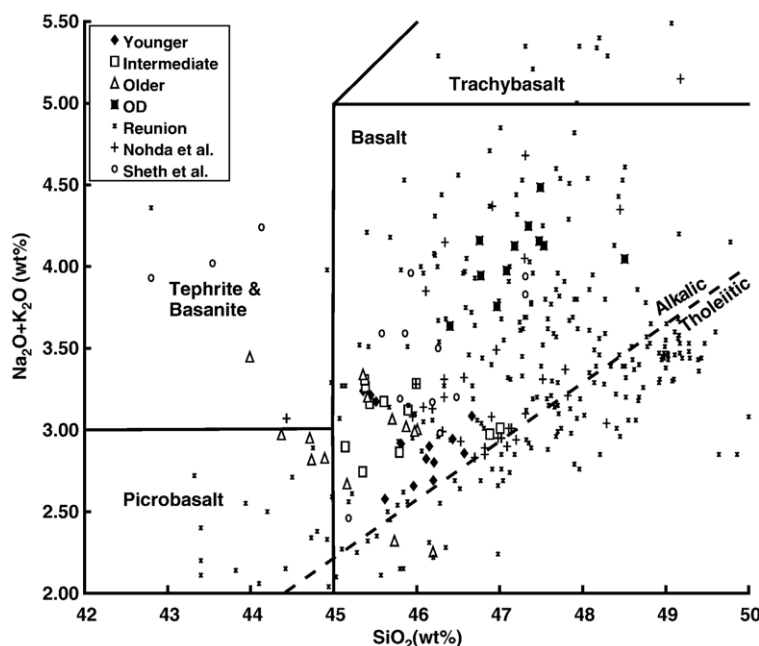


Fig. 4. Total-alkali ($\text{Na}_2\text{O}+\text{K}_2\text{O}$)–silica diagram for Mauritius lavas as described by Le bas et al. (1986). The dashed line is the dividing line separating the alkalic and tholeiitic lavas according to MacDonald and Katsura (1964). Also shown for comparison are data from Réunion (GEOROC data base) and Mauritius (Sheth et al., 2003; Nohda et al., 2005). Note that two samples from the Older Series plot in the tholeiitic field, and incidentally these two samples have highest Loss on Ignition values during analyses.

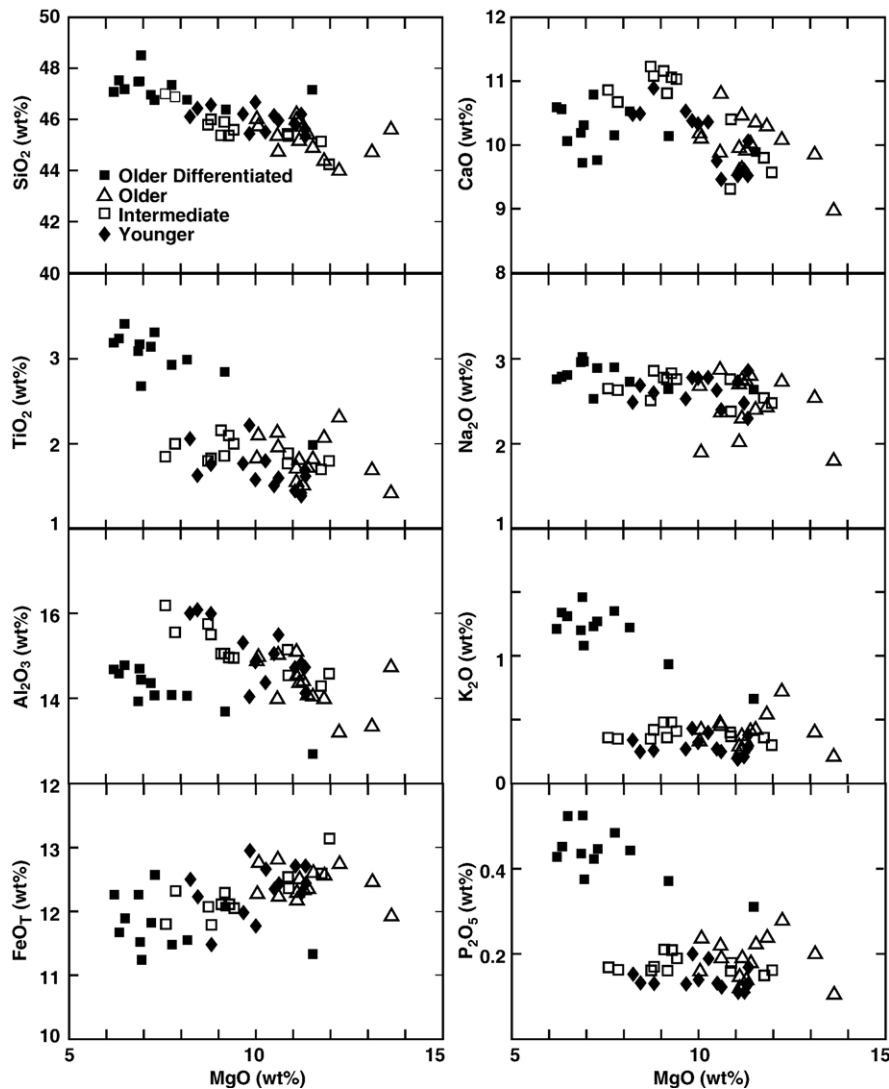


Fig. 5. Whole rock oxide–magnesia variation diagrams for Mauritius lavas. See text for discussion on variations in oxides with MgO content in these lavas.

indicating that plagioclase fractionation had a significant effect on the whole rock composition. Na_2O , K_2O , and P_2O_5 display no good correlation with MgO for both Groups.

The variations in P_2O_5 with K_2O content (Fig. 6) demonstrate the difference between the two groups. A first order observation is that the compositions lie on a linear trend. However, careful observation reveals that the slope of the Group 2 lavas is shallower than that of the Group 1 lavas (Fig. 6).

5.3. Trace element composition

Trace element compositions (31 elements in total) for the Mauritius lavas are presented in Table 2. Primitive

mantle (McDonough and Sun, 1995) normalized element patterns in the Mauritius lavas are shown in Fig. 7. It is evident that the Group 1 lavas exhibit similar patterns distinct from those of the Group 2 lavas. The Group 1 lavas display a wider range in composition (and less steeper pattern) compared to the Group 2 lavas with a relatively narrow compositional range (and steeper pattern). The degree of both light rare earth element (LREE) enrichment compared to the heavy rare earth element (HREE) and LREE/HREE fractionation decreases from Group 2 to Group 1 lavas. The Group 2 lavas have negative Ba, K, Sr anomalies (except for Sr these patterns are similar to that observed in Réunion reported by Fretzdorff and Haase, 2002), a pattern exactly opposite to that defined by the Group 1 lavas.

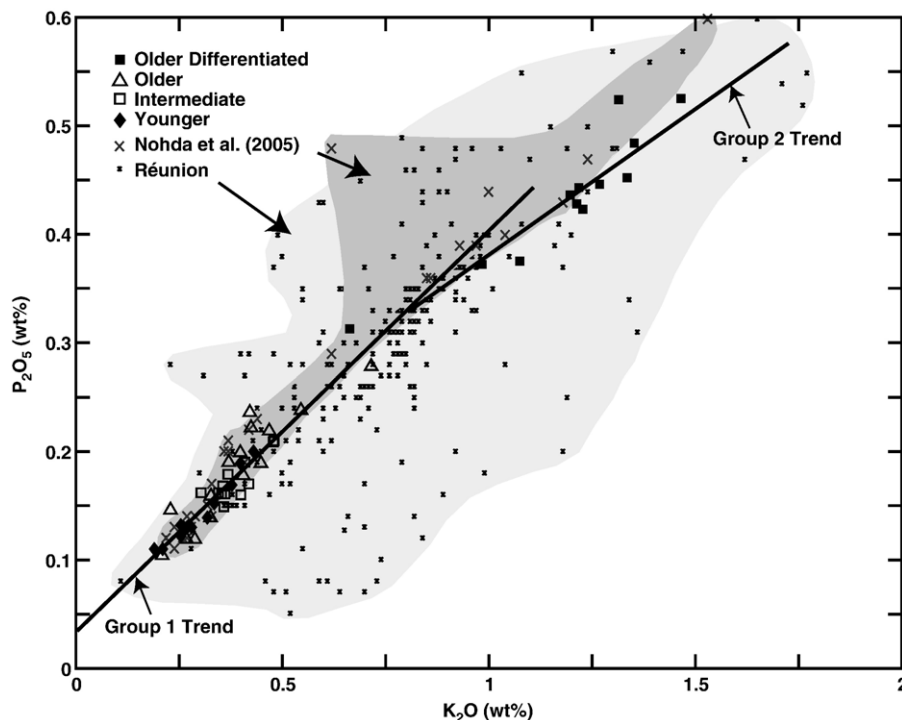


Fig. 6. Variations in P_2O_5 vs. K_2O content in Mauritius lavas. The Group 2 trend is shallower compared with that of the Group 1 lavas. Fields for Réunion (GEOROC data base) and Nohda et al. (2005) data are shown for comparison.

The pattern (and the absolute abundances to some extent) displayed by the average of Réunion basalts is more similar to the pattern defined by the Group 2 lavas, except for the distinct negative Pb anomaly in the Réunion pattern. On the other hand, the negative Pb anomaly is present in the Group 1 lavas. Sample MP9 (Group 2) has a very similar pattern compared to the average Réunion basalt, although the HREE concentrations are slightly higher in the latter. When the compositions with different MgO content are plotted together, a cross-cutting relationship of the HREE is observed in Mauritian lavas.

The Group 1 lavas are characterized by $(La/Sm)_N$ ratio (where N stands for normalizing value, which is an element concentration in the McDonough and Sun, 1995 primitive mantle) in the range 1.32–2.37 and corresponding $(Gd/Yb)_N$ ratio in the range 1.47–2.33 (Ce/Yb ratios of 1.9–5.9), whereas the $(La/Sm)_N$ ratios in Group 2 lavas range from 2.26 to 2.56 with a range of $(Gd/Yb)_N$ ratio of 2.19 to 2.74 (Ce/Yb ratio of 6–8.67) (Fig. 8). Fig. 9 shows the variation in K_2O with the Sr/Sr^* ratio in the Mauritius lavas. Sr^* is calculated assuming a smooth pattern between Pr and Nd in a Primitive mantle normalized spidergram (Fig. 7). A positive Sr anomaly ($Sr/Sr^* \sim 1.1$ –1.8) is observed for the Group 1 lavas with low K_2O , whereas a negative Sr

anomaly (more restricted range of Sr/Sr^* with an average of ~ 0.76) is observed for the Group 2 lavas with high K_2O . The absence of Sr anomaly in sample MP9 (Group 2) that has a Sr/Sr^* value of 1, may represent the composition of the parent magma that gave rise to the Group 2 lavas.

Variation of primitive mantle normalized La/Sm with other trace element (elements having similar incompatibility during partial melting) ratios in Mauritius lavas are shown in Fig. 10, which reveals two distinct fields for both the groups. Group 2 is characterized by low Sr/Nd (also low Ba/Rb and high Hf/Eu, which are not shown in the figure) compared to Group 1, suggesting the effect of plagioclase fractionation in the formation of the former. They also have low Sc/Yb and Ca/Yb ratios indicating clinopyroxene fractionation (Sc is compatible in clinopyroxene). The Zr/Nb ratios in Group 1 lavas show a negative correlation with the La/Sm ratios indicating partial melting trend, whereas the Group 2 lavas have a constant Zr/Nb ratio (except for MP9) for a range of La/Sm ratio.

6. Discussion

Century-long scientific investigations have been directed towards establishing a general model to explain

Table 2

Trace element (including the rare earth elements) composition (in parts per million, ppm) of Mauritius basalts

	Younger Series							Intermediate Series							
	BH10	BH11	BH13	BH20a	BH32a	MP76	MP81	BH6	BH12	BH27a	MP2	MP58	MP69	MP82	MP85
Sc	26.3	27.1	26.0	28.2	27.6	28.2	24.8	29.3	29.7	27.0	28.9	30.2	23.6	27.4	29.8
Co	61.1	63.3	64.9	57.5	65.2	56.2	55.1	63.7	58.4	64.6	68.7	56.5	65.7	53.0	58.1
Ni	309	287	337	214	316	244	231	305	168	322	346	180	210	158	193
Cu	78.0	96.9	86.3	77.8	77.7	81.2	81.0	73.3	78.2	78.3	81.5	73.6	63.7	72.3	81.6
Zn	113	127	122	117	124	123	117	119	127	114	128	114	122	108	129
Rb	3.7	4.3	2.2	4.1	7.4	5.7	8.2	6.3	11.2	6.2	3.7	8.2	7.2	9.6	6.8
Sr	271	239	205	297	291	256	325	323	400	302	277	322	318	411	290
Y	20.9	20.3	20.3	19.0	19.8	20.4	23.9	23.1	20.1	19.8	19.9	19.1	20.2	20.0	26.1
Zr	88.7	76.7	68.1	81.0	90.0	81.1	107	97.5	113	87.3	91.1	103	94.7	110	84.6
Nb	10.2	10.4	7.3	9.6	12.8	10.6	16.7	14.1	17.8	11.7	12.6	14.4	14.6	17.8	12.8
Cs	0.04	0.01	0.01	0.07	0.04	0.07	0.07	0.05	0.14	0.06	0.02	0.09	0.06	0.13	0.06
Ba	70	71	53	66	99	77	124	106	133	91	98	100	102	113	121
Hf	2.33	1.95	1.71	1.99	2.25	2.04	2.88	2.33	2.81	2.25	2.29	2.53	2.35	2.74	2.20
Ta	0.61	0.59	0.41	0.54	0.73	0.59	0.99	0.81	1.06	0.71	0.74	0.86	0.85	1.04	0.74
Pb	0.64	0.64	0.40	0.54	0.88	0.64	1.26	0.85	1.32	1.29	0.91	0.96	0.92	1.20	0.86
Th	0.80	0.83	0.59	0.72	0.97	0.79	1.48	1.17	1.54	0.91	0.98	1.24	1.17	1.46	1.16
U	0.15	0.17	0.10	0.10	0.13	0.16	0.29	0.23	0.36	0.18	0.25	0.27	0.25	0.27	0.22
La	7.44	7.18	5.57	6.61	9.12	7.42	12.1	11.5	12.9	9.19	9.79	10.5	11.0	12.0	11.3
Ce	17.8	16.4	13.3	15.8	21.3	17.5	26.3	22.1	28.2	20.8	21.9	23.2	21.7	26.6	21.4
Pr	2.49	2.27	1.91	2.21	2.88	2.38	3.56	3.18	3.70	2.83	2.97	3.09	2.99	3.49	3.03
Nd	11.6	10.2	8.85	10.1	12.9	10.9	16.0	14.0	16.3	12.8	13.3	13.9	13.2	15.5	13.5
Sm	3.15	2.73	2.50	2.73	3.27	2.90	4.05	3.46	4.04	3.31	3.46	3.58	3.36	3.94	3.56
Eu	1.16	1.05	0.98	1.06	1.20	1.10	1.48	1.26	1.39	1.20	1.20	1.26	1.20	1.36	1.24
Gd	3.87	3.51	3.33	3.48	3.88	3.66	4.78	4.21	4.34	3.84	3.88	3.96	3.82	4.28	4.25
Tb	0.64	0.59	0.56	0.56	0.61	0.60	0.76	0.65	0.66	0.59	0.60	0.61	0.59	0.64	0.68
Dy	3.95	3.65	3.53	3.45	3.67	3.64	4.59	3.89	3.95	3.69	3.71	3.73	3.59	3.85	4.23
Ho	0.78	0.73	0.71	0.67	0.70	0.71	0.88	0.76	0.73	0.73	0.71	0.71	0.70	0.73	0.85
Er	2.18	2.07	2.00	1.83	1.96	2.02	2.45	2.09	2.05	2.04	2.02	1.98	1.94	1.98	2.42
Tm	0.29	0.27	0.27	0.25	0.26	0.27	0.31	0.27	0.27	0.28	0.27	0.26	0.26	0.26	0.32
Yb	1.90	1.83	1.81	1.60	1.70	1.76	2.04	1.75	1.70	1.77	1.74	1.61	1.62	1.66	2.02
Lu	0.27	0.26	0.26	0.22	0.25	0.25	0.29	0.25	0.24	0.25	0.24	0.22	0.22	0.23	0.28

	Older Series										Older Differentiated Series			
	BH1	BH5	BH16b	BH18	BH19b	BH21	BH22b	BH25b	BH26b	BH30b	BH32b	MP9	MP26	MP39
Sc	30.5	25.5	26.9	30.0	25.8	26.7	24.0	29.6	26.2	27.7	27.5	24.5	30.3	25.7
Co	64.7	65.4	65.4	62.7	64.0	64.2	58.1	60.8	59.0	65.2	65.0	54.7	42.1	48.7
Ni	296	336	332	291	345	348	228	302	284	369	342	336	112	124
Cu	73.7	74.0	89.9	86.6	76.3	78.3	86.8	69.1	81.1	69.1	71.4	73.4	69.6	61.7
Zn	106	118	122	114	120	105	123	112	125	112	112	116	124	154
Rb	8.2	11.9	5.1	7.1	18.4	3.25	7.3	5.6	8.6	8.3	8.4	12.9	25.2	31.5
Sr	366	403	220	357	382	183	271	235	328	300	443	390	376	468
Y	19.8	18.9	19.1	22.2	20.3	16.9	20.4	18.5	21.7	19.5	20.2	22.6	29.3	29.2
Zr	89.0	117	72.0	108	120	64.6	87.9	74.3	109	92.2	98.4	131	214	256
Nb	19.1	19.3	7.3	19.2	26.4	8.4	12.2	8.3	14.5	15.0	17.6	29.9	31.3	38.2
Cs	0.10	0.12	0.05	0.09	0.18	0.04	0.11	0.07	0.17	0.10	0.12	0.09	0.07	0.22
Ba	162	163	58	151	203	64	89	66	110	121	145	255	226	278
Hf	2.25	2.77	1.87	2.67	3.04	1.69	2.56	2.04	2.93	2.41	2.43	3.31	5.43	6.45
Ta	1.00	1.16	0.44	1.09	1.56	0.50	0.78	0.52	0.98	0.88	0.98	1.61	1.96	2.43
Pb	1.12	0.96	1.16	1.34	1.36	0.93	0.96	0.61	1.32	1.13	1.19	1.93	3.30	3.89
Th	1.68	1.54	0.68	1.67	2.28	0.78	0.94	0.69	1.13	1.32	1.47	2.56	3.09	3.68
U	0.40	0.39	0.16	0.34	0.55	0.17	0.26	0.19	0.32	0.35	0.30	0.65	0.80	1.01
La	13.7	14.2	6.39	14.3	17.5	6.35	8.72	6.39	11.8	11.9	13.4	22.1	25.6	31.6
Ce	27.6	30.9	15.4	30.0	36.5	14.2	20.6	15.2	27.4	25.7	28.6	44.3	56.9	69.5
Pr	3.45	3.98	2.18	3.91	4.55	1.94	2.88	2.15	3.67	3.33	3.63	5.41	7.25	8.83
Nd	15.1	17.2	10.1	17.1	19.4	8.85	13.2	10.2	16.5	14.6	15.7	22.5	30.6	36.9

(continued on next page)

Table 2 (continued)

	Older Series										Older Differentiated Series			
	BH1	BH5	BH16b	BH18	BH19b	BH21	BH22b	BH25b	BH26b	BH30b	BH32b	MP9	MP26	MP39
Sm	3.72	4.05	2.78	4.19	4.62	2.49	3.63	2.95	4.23	3.69	3.91	5.40	7.04	8.29
Eu	1.27	1.40	1.02	1.43	1.54	0.93	1.33	1.10	1.50	1.29	1.38	1.85	2.29	2.70
Gd	3.94	4.24	3.31	4.52	4.67	2.99	4.16	3.45	4.57	3.94	4.15	5.44	6.77	7.64
Tb	0.61	0.63	0.54	0.69	0.70	0.48	0.66	0.56	0.71	0.62	0.63	0.80	1.00	1.10
Dy	3.72	3.69	3.47	4.17	4.02	3.07	4.13	3.56	4.25	3.79	3.79	4.66	5.84	6.13
Ho	0.72	0.70	0.69	0.81	0.74	0.61	0.80	0.70	0.82	0.73	0.73	0.85	1.09	1.10
Er	2.04	1.87	2.02	2.25	2.00	1.79	2.31	2.01	2.28	2.06	2.06	2.27	2.98	2.95
Tm	0.28	0.25	0.28	0.30	0.26	0.24	0.30	0.27	0.30	0.27	0.28	0.29	0.39	0.37
Yb	1.75	1.55	1.75	1.92	1.63	1.58	2.04	1.77	1.98	1.79	1.74	1.80	2.51	2.34
Lu	0.25	0.21	0.25	0.27	0.22	0.22	0.28	0.25	0.27	0.25	0.25	0.25	0.35	0.31
	Older Differentiated Series								BHVO-1		BCR-1			
	MP50	MP53	MP55	MP24	MP34	MP35	MP42	Recom.	Meas.	Recom.	Meas.			
Sc	24.1	27.4	27.4	27.5	26.5	28.9	27.9	32	33	—	—			
Co	42.2	45.3	47.0	49.4	44.6	41.7	46.2	45	44	—	—			
Ni	127	174	162	189	69	66	109	121	122	—	—			
Cu	69.6	57.3	88.0	62.0	64.1	43.4	84.2	136	120	—	—			
Zn	142	131	144	122	131	146	149	105	106	—	—			
Rb	38.3	29.4	34.1	22.1	29.7	31.9	28.6	11	10	47.2	46.2			
Sr	528	515	517	418	460	481	448	403	406	330	336			
Y	30.6	28.3	28.5	28.8	28.7	29.3	30.0	27.6	26.6	38	37.8			
Zr	284	246	271	219	237	257	240	179	176	190	186			
Nb	43.1	37.4	40.5	32.1	34.5	37.4	33.1	19	19.5	14	13.2			
Cs	0.43	0.28	0.25	0.13	0.21	0.17	0.17	0.13	0.09	0.96	0.93			
Ba	326	306	308	235	270	279	250	139	135	681	675			
Hf	6.90	6.11	6.60	5.49	6.15	6.49	6.18	4.38	4.54	4.95	4.82			
Ta	2.70	2.36	2.59	2.07	2.25	2.42	2.16	1.23	1.19	0.81	0.78			
Pb	4.71	3.91	4.15	2.64	3.50	3.54	3.66	2.6	2.4	13.6	15.3			
Th	4.19	3.74	4.21	3.09	3.41	3.73	3.34	1.1	1.2	5.98	5.85			
U	1.17	0.97	1.15	0.85	0.89	0.96	0.85	0.42	0.40	1.75	1.55			
La	35.4	30.5	33.8	29.5	28.8	30.8	29.3	15.8	15.3	24.9	25.6			
Ce	76.7	66.9	74.0	63.6	64.0	68.1	65.5	39	37.9	53.7	54.5			
Pr	9.58	8.46	9.25	8.08	8.20	8.69	8.36	5.7	5.4	6.8	7.1			
Nd	39.7	35.6	38.1	33.5	34.7	36.6	35.5	25.2	24.3	28.8	29.5			
Sm	8.72	8.06	8.23	7.48	7.96	8.41	8.13	6.2	6	6.6	6.7			
Eu	2.78	2.57	2.64	2.50	2.61	2.67	2.57	2.06	2.08	1.95	1.99			
Gd	7.94	7.47	7.51	7.13	7.53	7.76	7.66	6.4	6.36	6.7	7.1			
Tb	1.12	1.06	1.06	1.04	1.09	1.10	1.11	0.96	0.95	1.05	1.1			
Dy	6.32	5.90	5.86	5.93	6.12	6.16	6.26	5.2	5.4	6.3	6.6			
Ho	1.14	1.06	1.06	1.07	1.09	1.10	1.14	0.99	0.98	1.26	1.33			
Er	3.01	2.81	2.84	2.89	2.94	2.92	3.07	2.4	2.6	3.63	3.86			
Tm	0.38	0.35	0.36	0.38	0.37	0.37	0.39	0.33	0.33	0.56	0.54			
Yb	2.44	2.21	2.25	2.40	2.32	2.30	2.43	2.02	2.09	3.38	3.63			
Lu	0.33	0.30	0.31	0.32	0.32	0.31	0.34	0.29	0.29	0.51	0.54			

plume-related volcanism consistent with the geochemical signatures observed in global ocean island basalts (OIB). In the light of the new borehole data, the obvious question is how does the volcanic evolution of Mauritius compare to volcanism on both Réunion and Hawaii?

In general, the volcanic evolution of both Mauritius and Réunion (e.g. Baxter, 1976; Albarède et al., 1997) is similar to that of Hawaii (Macdonald and Katsura,

1964; McDonald, 1968; Chen and Frey, 1983, 1985; Sobolev et al., 2005), albeit minor differences. A pre-shield stage has yet not been discovered on both Réunion and Mauritius. The shield building magmas in both Mauritius and Réunion are transitional basalts whereas those in Hawaii are tholeiitic. Post-shield alkalic capping stage lavas in Hawaii are distinctly more alkaline and typically more differentiated than those from earlier

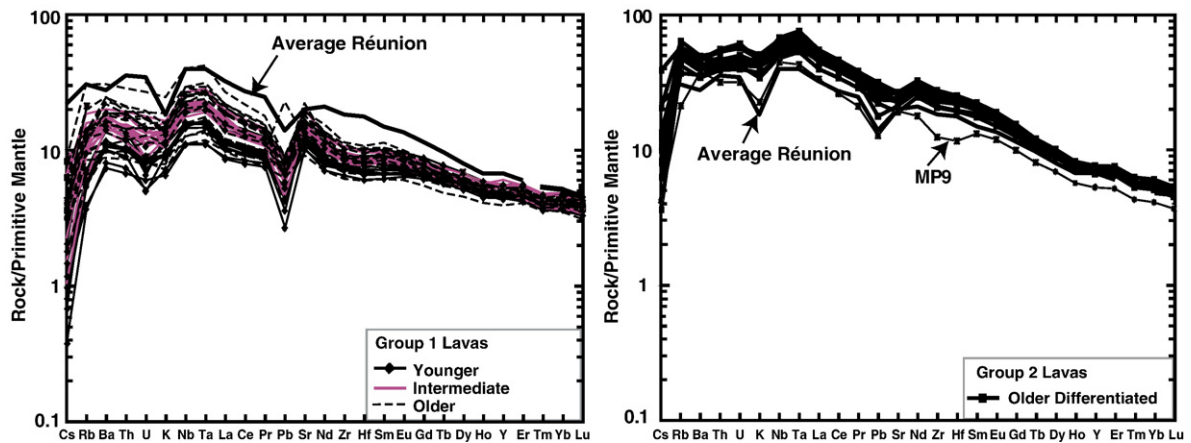


Fig. 7. Primitive mantle (McDonough and Sun, 1995) normalized spider diagram for Mauritius lavas. The patterns for Group 1 lavas are quite different from Group 2. Pattern for average composition of Réunion lavas (GEOROC data base) is shown for comparison, which is similar to the Group 2 pattern.

volcanic stages. Although the late stage magmas erupted on Piton des Neiges of Réunion are more differentiated, no such increase in alkalinity can be observed. Our new data on the OD Series (Group 2) lavas on Mauritius are more alkaline than the earlier Older Series lavas, suggesting that Mauritius lavas became more alkaline in composition towards the later part of the shield building stage. Therefore, the OD Series lavas may be analogous to the post-shield capping alkalic lavas from Hawaii. Post-erosional volcanism is yet to be documented in Réunion, but the Intermediate and Younger Series of Mauritius might be analogous to the post-erosional series of Hawaii (Paul et al., 2005).

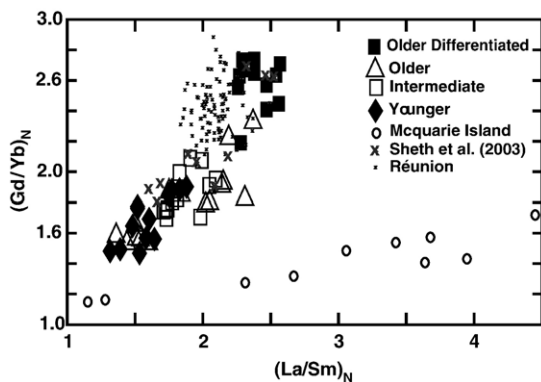


Fig. 8. Variations in primitive mantle (McDonough and Sun, 1995) normalized $(La/Sm)_N$ – $(Gd/Yb)_N$ ratios in Mauritius lavas. High Gd/Yb ratios in Older differentiated Series compared to the other three Series suggest higher LREE/HREE fractionation. Data on Macquarie Island basalts (garnet-free source) is shown for comparison (Kamenetsky et al., 2000; Kamenetsky and Maas, 2002).

6.1. Mauritius Older Series eruptions

Though there is a broad similarity between volcanism in Mauritius and Hawaii, the current data suggest different volcanic evolution of the Mauritius and Réunion plume. Major (Fig. 6) and trace element abundances (and ratios) (Figs. 7, 9 and 10) in Mauritian lavas suggest two distinct trends typically formed by varying degrees of melting and/or distinct sources, one defined by the earlier Older Series lavas (and Group 1 lavas) and

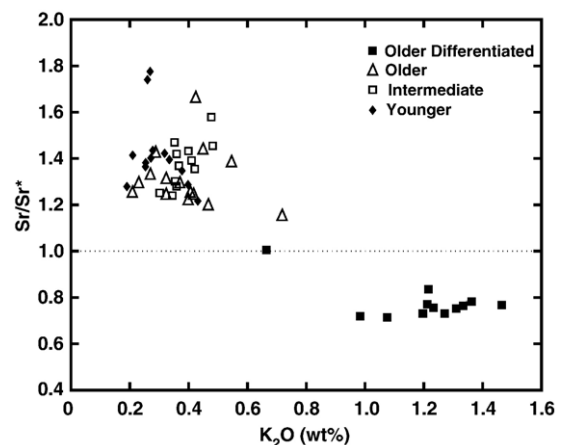


Fig. 9. Variation in Sr/Sr^* ratio vs. K_2O in Mauritius lavas. Sr^* is the calculated concentration of Sr from the Primitive mantle (McDonough and Sun, 1995) normalized spidergram (Fig. 7) assuming a smooth pattern between Pr and Nd concentrations in these lavas. Older Differentiated Series characterized with high K_2O shows a negative Sr anomaly, whereas the Group 1 lavas characterized with low K_2O show a positive Sr anomaly. Only one sample MP9 belonging to the Group 2 shows no anomaly, perhaps representative of primitive melt.

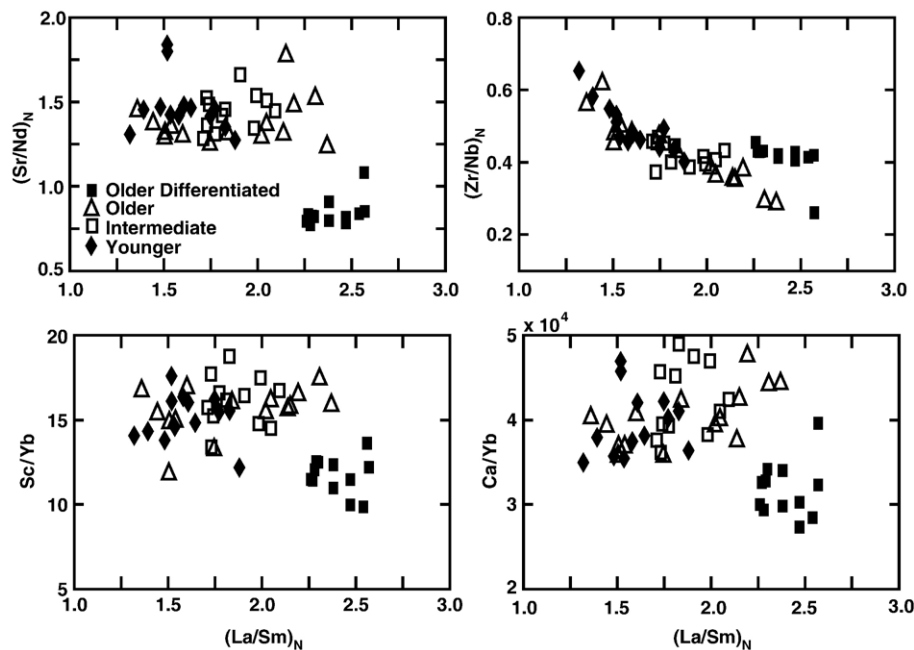


Fig. 10. Variation of $(\text{La}/\text{Sm})_N$ ratio with $(\text{Sr}/\text{Nd})_N$, $(\text{Zr}/\text{Nb})_N$, Sc/Yb , and Ca/Yb ratio in Mauritius lavas. The subscript N represents primitive mantle (McDonough and Sun, 1995) normalized values. See text for description.

the other by the OD Series (Group 2) lavas. The lavas become more alkaline (and enriched in incompatible trace elements) with time as the eruptions progress from Older Series to Group 2 eruptions, and then become less alkalic (much similar to the Older Series) during the Intermediate and Younger Series eruptions.

Variation in magma composition, the near parallel REE patterns, and the uniform helium isotopic composition in Réunion lavas were all taken as evidence for melting of a homogeneous mantle source (e.g. Graham et al., 1990; Albarède et al., 1997; Fisk et al., 1988; Fretzdorff and Haase, 2002; Sobolev and Nikogosian, 1994). This raises the question whether partial melting (along with fractional crystallization) of the already depleted source that gave rise to the Older Series lavas and the later Intermediate and Younger Series products also produced the Group 2 lavas? If not, what is the source of the Older Series and why is it different from the source of the current Réunion plume (and Group 2)?

6.2. Inferences on source composition by modeling the REE

In this section, we attempt to model the source composition of these lavas by taking into account the incompatible behavior of REE during partial melting. Our calculations are based on the equations given by Albarède (1995), and for simplicity assume equilibrium/

batch melting and/or equilibrium crystal fractionation. This approach is essentially the same as in Paul et al. (2005).

First, we followed a fractionation correction procedure (least squares fit) that included the major element oxide compositions. This correction procedure (e.g. Wright and Doherty, 1970) essentially subtracts minerals from the primary lava to obtain the daughter lava composition. We assumed BH21 (containing highest MgO and lowest Lu, and most primitive olivine) to represent the most likely parent lava and utilized the average phenocryst compositions given in Table 1 to compute the percentage of olivine, clinopyroxene, and plagioclase required to be subtracted from this parent melt to form the daughter (other lavas) composition. Computations suggest that about 6–15% olivine fractionation is required for the Older Series lavas, and a higher amount of both clinopyroxene and plagioclase (with minor amounts of olivine) is required for OD Series lavas. These calculations are tentative as the procedure does not take into account relevant P – T conditions for coexisting mineral phases, however, adequate for the purpose below.

Assuming that the mantle source is a lithologically homogeneous garnet peridotite with a primary modal composition of 58% olivine, 27% orthopyroxene, 9% clinopyroxene, and 6% garnet and suitable mineral–liquid partition coefficients (obtained from the GERM

partition coefficient data base (www.earthref.org/GERM), same values were used by Paul et al., 2005), potential source compositions are calculated for a range of melt fractions. The melt composition of BH21 was corrected assuming 20% olivine fractionation (consistent with the results from fractionation correction procedure). To be consistent with Hawaiian estimates that require 7% melting for the production of Hawaiian Shield stage lavas (Watson and Mckenzie, 1992), we also assumed 7% melting (assuming 5% melting would not change our major conclusions) of the primary source. The calculated “primary source” composition for the Group1 lavas along with the model results is shown in Fig. 11. Our next step was to compute the composition of the “secondary source” (assuming a two-stage melting) removing between 0.5% and 5% melt fractions of the primary source. This two-stage melting model is analogous to the model proposed by Ribe and Christensen (1999) to explain post-erosional volcanism in Hawaii where a weak secondary melt zone produces a secondary pulse of volcanism about 3.5–5.5 Ma after the initial episode. We found that about 2% to 5%

melting of the primary source and variable amounts (0.2–1.5%) of melting of the secondary source can generate melt compositions having similar compositions and patterns as observed by Group 1 lavas (Fig. 11). In order to get elevated HREE concentrations, our calculations for secondary melt compositions assume a slightly different modal composition with 4% garnet in the source. However, melting of even the least depleted secondary source could neither produce the patterns nor the abundances similar to the Group 2 lavas (e.g. pattern of 0.2% melting of 0.5% secondary source shown in Fig. 11). Furthermore, correcting for fractional crystallization (for a range of fraction of crystals 0.1 to 0.5, and a range of different modal compositions of olivine, clinopyroxene and plagioclase) of the secondary melt also does not produce the pattern of Group 2 lavas. These results suggest that the sources for Group 1 and Group 2 lavas are different.

We assumed MP9 as the parental magma for the Group 2 lavas based on the fact that MP9 has the highest MgO, lowest Lu content and Sr/Sr* ratio of 1 (Fig. 9) amongst all Group 2 samples, and that the pattern of

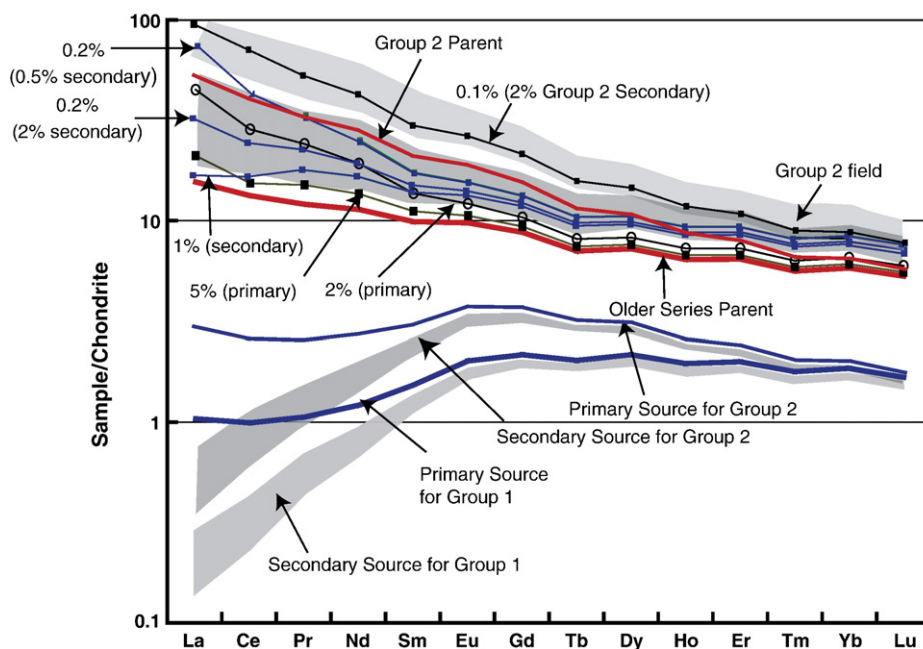


Fig. 11. Modeling of REE patterns produced by a two stage equilibrium batch melting and equilibrium fractional crystallization; first the primary source melts and subsequent melts are derived from the already melted primary source. Primary source for Group 1 lavas is calculated assuming that this source produced sample BH 21 by 7% melting followed by 20% olivine crystallization. The source is also assumed to have a modal composition: 58% Olivine, 27% orthopyroxene, 9% clinopyroxene, and 6% garnet. Composition of secondary source for Group 1 was calculated by removing between 0.5% and 5% melt fractions of the primary source. Variable extent of melting (assuming a slightly different source composition having 4% garnet in the source) in the range 0.2% to 2% of this secondary source can account for the observed variations in the Group 1 lavas. The Primary source for Group 2 lavas is calculated assuming that this source produces sample MP9 by 5% melting followed by 20% olivine crystallization. Secondary source for Group 2 is calculated by removing 2–2.5% melt fractions of the primary source. Extremely lower amounts (<0.1%) of melting of Group 2 secondary source produce similar patterns and abundances observed for Group 2 lavas.

MP9 closely follows the pattern of average Réunion (Fig. 7). Following similar procedure as before and assuming 5% melting consistent with low degree melting for alkalic lavas for Group 2, the primary source for Group 2 was computed and shown in Fig. 11. The source for Group 2 has a steeper middle rare earth pattern compared to the Group 1 primary source. Lower extent of melting (e.g. 0.1%) of Group 2 secondary source (e.g. residue left by 2% melting of primary source) fit the pattern and abundances defined by the Group 2 lavas. These results are not unique and do not exclusively suggest heterogeneous sources, but merely demonstrate that the assumed parameters will produce similar observed REE patterns and fractionation in the Mauritius lavas. It is important to remember that whole rock compositions only provide an average composition of various melts that originate from different mantle-derived magmas and evolve due to crystal fractionation during ascent, along with mixing of evolved melts with the primitive melts, and mixing of melts in shallow magma chambers (e.g. Sobolev, 1996). Therefore, it is pertinent to discuss the results with respect to the ideas of plume lithosphere/asthenosphere interaction and heterogeneities in the plume itself.

6.3. Plume lithosphere/asthenosphere interaction

It is possible that plume-generated melts can also be contaminated by interaction with continental lithosphere and crust (e.g. Mahoney et al., 1983), be diluted by asthenospheric mantle with depleted signature and oceanic lithosphere-derived melts (e.g. Chen and Frey, 1983, 1985; Schilling, 1985; Storey et al., 1988; Keller et al., 2000). It is also a matter of debate whether plumes are diluted by the melts derived from the entrained asthenospheric mantle. The classic model of the Hawaiian evolution (Chen and Frey, 1985) suggests that all Hawaiian magmas represent mixtures of plume material and ambient upper mantle lithosphere or asthenosphere having similar composition as that of the depleted MORB source. However, geodynamic modeling studies concluded that neither the overlying lithosphere nor surrounding asthenosphere is sufficiently heated by the plume to melt (Ribe and Christensen, 1994; Farnetani and Richards, 1995).

In Mauritius, however, the extent of plume lithosphere and/or asthenosphere interaction is less clear. Spinel compositions in Group 1 lavas in Mauritius are characterized with very high Al_2O_3 compared with that observed in typical OIB (Fig. 3). This, taken together with the observed positive Sr anomaly (Fig. 9) in Group 1, suggests that assimilation of oceanic gabbros by the

plume magmas might have played a role in the evolution of these lavas. Kamenetsky et al. (2001) proposed that the spinel Al_2O_3 and TiO_2 systematics can also be used to identify spinel crystallized from different parental magmas in different tectonic settings. Both Sheth et al. (2003) and Nohda et al. (2005) inferred variable amounts of partial melting and mixing between MORB source mantle and mantle with enriched plume source to account for isotopic variations observed in the shield (Group 2 in our case) and post-shield lavas, and that with time the lava compositions tend towards more MORB like signatures. However, based on Sr, Nd, Hf, and Pb variations in these lavas, Paul et al. (2005) argued for a heterogeneous plume model. Their isotopic data precludes post-erosional lavas being mixtures of the MORB and the respective plume source. Although interaction between plume and lithosphere/asthenosphere cannot be ruled out at present, further constraints may come from radiogenic isotopic composition of the Mauritian samples presented in this study.

6.4. Compositional variations and heterogeneity in plume source?

The observed compositional variations with different eruption intervals in Hawaii and Mauritius suggest that heterogeneities present in the plume itself along with different extent of melting account for the observed trace element (and isotopic composition) variations in plume-derived magmas.

One primary candidate for the compositional variation of the plume itself with time may be mixing of plume source with the subducted oceanic crust (with enriched trace element concentrations) that reaches the deeper mantle (Hofmann and White, 1982; White, 1985; Hofmann, 1997; Lassiter and Hauri, 1998; Hofmann, 2003). It is suggested that small-scale heterogeneities (centimeter to a kilometer scale) in the plume itself in the form of pockets, lenses or veins having distinct isotopic characteristics may produce isotopic (and trace element) variation (e.g. Sleep, 1984; Hanson, 1977; Zindler et al., 1984; Hofmann and Hart, 1978; Hauri, 1996; Lassiter and Hauri, 1998; Lassiter et al., 2000; Widom, 2002; Stracke et al., 2003, 2005). Ito and Mahoney (2005) argue that lithologic heterogeneity within plumes can explain much of the isotopic variation seen in oceanic island volcanoes. These observations are strengthened by recent studies on melt inclusions in olivine phenocrysts, which reveal considerable chemical and isotopic heterogeneities even in single olivine crystals (Saal et al., 1998, 2005; Sobolev et al., 2000; Hauri, 2002). Therefore, it is possible that the overall local

homogeneity in the whole rock compositions may be a result of homogenization of heterogeneous melts.

Phipps Morgan and Morgan (1998) and Phipps Morgan (1999) envision that plume-type mantle is randomly distributed throughout the mantle, and that the enriched components (such as pyroxenite or eclogite) undergo preferential melting and leave a residue that replenishes the upper depleted mantle (also Ito and Mahoney, 2005; Stracke et al., 2003, 2005). Based on the observed high Ni and high Si content in the Hawaiian tholeiites from the main shield-building phase, Sobolev et al. (2005) also proposed a lithologically heterogeneous plume having eclogite (recycled oceanic crust) lenses concentrated in the center of the plume surrounded by peridotite matrix (see Fig. 3 in Sobolev et al., 2005). In their model, melting is vertically zoned; eclogite/pyroxenite melts at deeper depth followed by melting of peridotite at a shallow depth of about 100 km. Paul et al. (2005) proposed a similar model to account for the generation of rejuvenated post-erosional magmas in Mauritius, which is consistent with the earlier models proposed by Phipps Morgan (1999) and to an extent by Sobolev et al. (2005). Paul et al. (2005) envisioned a heterogeneous Réunion plume that consists of plums of eclogite/pyroxenite lenses embedded in a peridotite matrix. In their model, the melting is also zoned vertically; shield stage magmas (Group 2 in our case) were derived from hybrid melts (eclogite/pyroxenite+peridotite melts), whereas the rejuvenescent magmas were produced by melting of the peridotitic matrix only.

However, the borehole Older Series lavas do not fit the melting model proposed by Paul et al. (2005). It is evident that the Older Series lavas are derived from a similar source as the Intermediate and Younger Series lavas, but distinct from the Group 2 lavas. The average Rb/Cs ratio in Older Series is 83 ± 17 and in the OD Series is 141 ± 30 (excluding two samples with abnormal Rb/Cs value), which suggests heterogeneities in the source (Hofmann and White, 1983). This is also supported by the distinct Ba/Th ratio (average Ba/Th in Group 1 is 91 ± 7 and in Group 2 is 78 ± 7) in these lavas. Paul et al. (2005) have shown that the Older Series lavas are characterized by high $^{87}\text{Sr}/^{86}\text{Sr}$, low $\varepsilon_{\text{Nd}}-\varepsilon_{\text{Hf}}$, and high radiogenic Pb isotope ratios compared with the Intermediate and Younger Series lavas. Similarly, Sr, Nd, and Pb isotopic data presented by both Sheth et al. (2003) and Nohda et al. (2005) indicate that the Older Series lavas have more enriched isotopic signatures than the Intermediate and Younger Series lavas, and overlap the field for Réunion basalts (see Paul et al., 2005 for comparison of isotopic data). The isotope

data reported in the previous studies clearly suggest that the Younger and Intermediate Series are products of melting of sources different from that of the Older Series. As described earlier, the Older Series lavas reported in the previous studies may represent our OD Series lavas. Furthermore, in the $\varepsilon_{\text{Hf}}-\varepsilon_{\text{Nd}}$ space, Group 2 lavas (range of ε_{Hf} 10.2–10.51 corresponding to a range of ε_{Nd} 4.23–4.61) are quite distinct from Group 1 (range of ε_{Hf} 10.86–11.2 corresponding to a range of ε_{Nd} 5.05–5.77), though at present we have relatively few data on these samples to support this conclusion (unpublished data on eight of the samples presented here). If Group 1 lavas are characterized with low Sr (and Pb) and high Nd (and Hf) isotopic ratios than the Group 2 lavas, then this may suggest that the oldest lavas in Mauritius are derived from melting of isotopically more depleted source. If melting is vertically zoned in the plume, then it is surprising that none of the oldest lavas carry a signature of mixing with enriched melts derived by melting of enriched components presumably present in the plume. This is rather puzzling as there is no analogue in the lavas of Réunion of such oldest material with depleted signatures that later changes to an enriched signature as observed in Group 2 lavas. In this regard, the lavas from Réunion spanning a 2 Ma eruption interval are quite homogenous (Albarède et al., 1997). It is also possible that lavas similar in composition to the Older Series (boreholes) in Mauritius are buried in the deeper sections in Réunion, which is yet to be explored.

However, the above dilemma can be explained if the plume is laterally heterogeneous. Experimental results by Hirose and Kushiro (1993) have shown that for a given increment of partial melting, melts derived from a depleted peridotite contain lower SiO_2 , and higher FeO and MgO compared to the melts derived from a fertile peridotite. Therefore, it is possible that Older Series lavas (with low SiO_2 , and higher FeO and MgO) are produced by melting of a depleted peridotite source in the plume. Since peridotite melts at higher temperature compared with the eclogite and pyroxenite (Yasuda et al., 1994), melting is more likely to take place in the hotter central region of the plume. Therefore, bulk of the Mauritian Older Series magmas are likely to be derived from melting of peridotite matrix distributed in the core of the Réunion plume. Towards the late-Shield building (around 6 Ma ago) phase, the Réunion plume migrated away from the Older Series volcanoes, and therefore, the volcanoes giving rise to Group 2 eruptions would be located off axis. Thus it is possible that the Group 2 lavas are derived from low degree partial melts of eclogite (or pyroxenite) material distributed at the

margin of the plume, which melts at a lower temperature. Intermediate and Younger Series magma are derived from varying degrees of partial melting of the residue (that gave rise to Older Series magmas) already depleted during a previous phase of melting. Such a scenario favors lateral heterogeneity in the Réunion plume, giving rise to magma compositions controlled by the thermal structure of the plume. Our model does not discard the lithologically heterogeneous plume model (plums of eclogite/pyroxenite embedded in peridotite matrix; the plums carry a less depleted isotopic signature than the peridotite) proposed by Paul et al. (2005). A meaningful comparison with the Paul et al. (2005) model can only be done after isotopic data on the borehole and OD Series samples are obtained in future.

7. Conclusions

Composition of lavas from Mauritius share similarity in many respects to the lavas produced in Réunion, suggesting derivation from the same mantle plume. The eruption patterns, in particular transition towards more alkaline nature from Older Series to the later Group 2 lavas is in many respects similar to the Hawaiian pattern. The significant range in composition observed at Mauritius represents a rather complex scenario for the evolution of these lavas compared to previously exiting hypotheses regarding the volcanic evolution in the island. None of the previous studies of Mauritius lavas showed marked compositional difference between the early and late stage (differentiated) Older Series rocks.

Taking into consideration the relative age of the Older Series lavas in the stratigraphic column as observed in borehole sections, we infer that these lavas represent the oldest Shield building eruptions. Towards the end of the Shield building activity (6.5–5.5 Ma) late stage highly alkalic lavas (OD Series, Group 2) erupted in the island, which are represented by surface exposures of the eroded shield. The highly alkaline nature and steeper REE patterns in OD Series lavas suggests a relatively small extent of melting and/or a more enriched source compared to the Older Series. Both REE modeling and trace element patterns suggest that the sources for Older and OD Series are likely to be different. Partial melting (and crystal fractionation) alone does not account for the compositional diversity observed between the Older and OD Series lavas. Mauritius OD Series lavas are probably derived by melting of enriched components (eclogite and/or pyroxenite) present in the outer part of the plume. The Older Series compositions, characterized with a rela-

tively less-enriched trace element as well as primitive mantle normalized abundance patterns, are most likely derived from melting of a depleted peridotite matrix located at the core of the plume. Both the Intermediate and Younger Series lavas are derived from melting of the already depleted source that gave rise to the Older Series lavas. This model is broadly consistent with the heterogeneous plume models of Phipps Morgan (1999) and Sobolev et al. (2005), however, our model suggests lateral heterogeneity and melting controlled largely by the thermal structure of the Réunion plume. The compositional variation between the Older and OD Series is also consistent with the result of Chen and Frey (1985) who concluded that the earlier Shield building lavas in Hawaii show less enriched incompatible trace elements patterns along with lower LREE/HREE fractionation compared with post-Shield stage lavas. However, in case of Mauritius Intermediate and Younger Series lavas become less alkalic compared with the previous high alkalic OD Series lavas. Further constraints on the origin of recorded compositional variations should come from radiogenic isotopes before the effects of mantle source heterogeneities and melting, and effects of interactions between primitive magmas and crustal rocks can be evaluated.

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