Isotopic variations with distance and time in the volcanic islands of the Cameroon line: evidence for a mantle plume origin

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Abstract

The oceanic sector of the Cameroon line consists of three volcanic islands: Principe, São Tomé and Pagalu. New $^{40}Ar-^{39}Ar$ data for Pagalu basalts, combined with published K–Ar ages for Principe and São Tomé, indicate that all three islands have been active in the past 5 Ma. They have similar petrogenetic histories, with basements of basaltic flows capped by more evolved rocks. However, the age of the earliest exposed volcanic rocks decreases oceanward from Principe (31 Ma) to São Tomé (13 Ma) to Pagalu (4.8 Ma). This age progression is consistent with the suggested motion of the African plate over this period of time. The average incompatible trace element compositions of < 10 Ma lavas with ⩾ 4 wt% MgO on each island are very similar. However, $(^{87}Sr/^{86}Sr)_t$ increases from 0.7029 to 0.7037 and $(^{206}Pb/^{204}Pb)_t$ decreases from 20.2 to 18.9 from Principe through São Tomé to Pagalu for all samples younger than 10 Ma. In addition to the overall spatial isotopic variations, Principe and São Tomé display temporal isotopic variations, with Pb isotopic ratios becoming progressively more radiogenic. Pagalu shows no temporal geochemical or isotopic differences and the island has the least radiogenic Pb but most radiogenic Sr. These distinctive Pb, Sr and Nd isotopic compositions are also found in the early tholeiitic hyaloclastite breccia from Principe (31 Ma). Similarly, the Nd and Sr isotopic compositions are identical to those of the earliest São Tomé lavas (13 Ma) and the Pb isotopic compositions of early São Tomé samples are only slightly radiogenic relative to Pagalu. Therefore, it is probable that all these islands were initiated from a common source, similar to that of Pagalu, that migrated relative to the melt zone of each island with time. Since their initiation, the magma conduits at Principe and São Tomé have been gradually modified by the introduction of a HIMU component. The common source from which the islands were initially derived probably represents ambient upper mantle, entrained with the plume head during ascent. This entrained component is like 'PREMA', but the Nd and Sr isotopic data indicate that it represents variably mixed depleted and enriched components, such as DMM and EMI. The HIMU component is probably representative of a lower mantle source from which the plume head was derived. The long-lived episodic magmatism on Principe provides evidence that the initial melt migration paths from the upper mantle form a hot zone that can be re-activated after long periods (10^7 yr) of apparent quiescence. The progression to HIMU characteristics within each island probably reflects the gradual flattening of the contaminated plume head within this hot zone, near the base of the lithosphere, and the melting of a stem composed of relatively uncontaminated HIMU mantle.

1. Introduction

The Cameroon line has been active for at least 65 myr and is currently defined by a 1600 km long, Y-shaped chain of intraplate volcanic centers, extending from the Atlantic island of Pagalu inland to west Africa. Young basaltic lavas are compositionally identical in oceanic and continental sectors, providing evidence that the lavas have been derived from sublithospheric depths [1]. However, rocks from the continent/ocean boundary region, as represented by the island of Bioko and the continental volcanic centers of Etinde and Mt. Cameroon, have relatively radio-
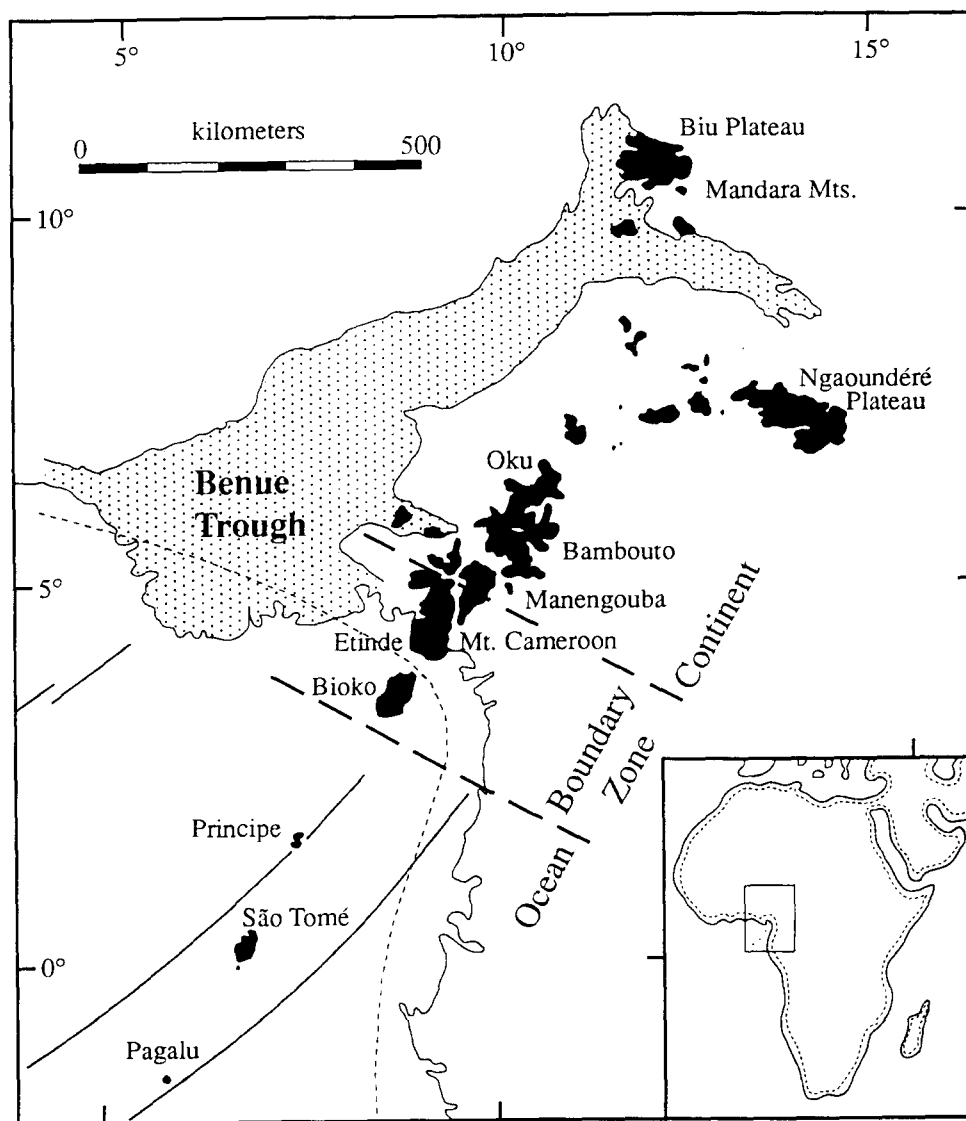

Fig. 1. Geological map showing the major Cenozoic volcanic centers of the Cameroon line and the Gulf of Guinea [adapted from 2]. The boundary between the continental and oceanic crust (thin broken line) and the oceanic transform faults are taken from Emery and Uchupi [51] and Sibuet and Mascle [52], respectively.

genic Pb: there is a systematic decrease in ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb from the continent/ocean boundary (c.o.b.) toward either end of the volcanic chain [2]. This has been explained in terms of the remelting of an enriched fossil plume head located beneath the site of continental break up in the present Gulf of Guinea. This model, however, provides no mechanism for remelting and does not explain the long-lived nature of magmatism along this lineament. The ocean islands of Principe, São Tomé and Pagalu exhibit episodic and protracted volcanic histories (e.g., over 30 myr for Principe [3]). These most oceanward islands, located away from both the continent/ocean boundary and the effects of crustal contamination that may complicate interpretations of data from the continental sector, provide an ideal location for studying changes in source composition with time in the Cameroon line.

Isotopic variations in MORB and OIB are generally attributed to mixing of several distinct components in the mantle. It has been suggested that a minimum of four mantle end-members are required to generate the observed isotopic variations in OIB [4–7]. Long-lived ocean island chains offer the opportunity to study how these components are incorporated into the source regions of OIB with time. The Hawaiian island chain is the classic example of a chain of OIB volcanoes originating from a hotspot. Many studies have shown that temporal isotopic variations exist within individual Hawaiian volcanic centers [8–13]. Similarly, the Samoan islands display an increase in Sr with decreases in Nd and Pb isotopic ratios westwards along the island chain [14,15], although White and Hofmann [16] have argued that these variations are not systematic. The Canary Islands display a systematic correlation between major elements and isotopic compositions, which are attributed to the assimilation of shallow enriched mantle components during differentiation [17,18]. However, no temporal isotopic variation is found in the Canary Islands. The Cameroon line has not been explicable by hotspot models because there has been no systematic migration in the inception of volcanism with time, as deduced from published isotopic ages. Furthermore, the individual centers have continued to be active for very long

periods at the same time as the African plate has undergone considerable rotation. This study provides new geochronological data and trace element and Sr–Nd–Pb isotopic compositions for predominantly basaltic rocks from Pagalu, São Tomé and Principe. It is found that the source regions have migrated laterally relative to the volcanic centers through time, providing the first evidence for an active mantle plume origin for the magmatism of the Cameroon line.

2. General geology

The geology, petrology and geochronology of the Cameroon line have been reviewed elsewhere [1,19–21], so only a brief summary is given here. There are at least 17 plutonic complexes, all in the continental sector, ranging in age from 65 to 30 Ma. Only a few of them have been studied with modern isotope geochemistry and the available data indicate that these plutonic complexes were primarily of mantle origin but contaminated by crustal components [22–24]. In addition, there are 12 major volcanic centers extending into the oceanic sector (Fig. 1), ranging in age from 35 Ma to the present. The only currently active volcano is Mt. Cameroon [25,26], which erupted last in 1982, situated on the boundary between the oceanic and the continental sectors of the volcanic chain. Basic lavas, ranging in composition from basanite to *hy*-norm basalt, are present in all the volcanic centers except for Etinde, which is composed entirely of nephelinite. The evolved rocks in the continental volcanic centers comprise trachyte, trachyphonolite, rhyolite and rare phonolite. In Manengouba, evolved magmas form a complete compositional continuum with the basic lavas. However, other centers, such as Bambouto and Oku, are strongly bimodal. Two basaltic plateaus (Ngaoundéré and Biu) mark the continental ends of the Y-shaped volcanic chain. The Mandara mountains include some of the oldest continental volcanic rocks on the Cameroon line. Basaltic lavas from the oceanic sector are compositionally similar to those of the continental sector [1], but trachytes are rare and rhyolite is

absent. Phonolites are found on Principe and São Tomé.

Several models have been proposed to explain the origin of the Cameroon line. These include membrane tectonics [27], a hotspot [28,29] and rejuvenation of a fracture zone [30]. The membrane stress model is in conflict with the fact that the region would have been under compression, instead of extension, during the emplacement of the plutonic complexes. The lack of systematic progression in the published ages of volcanism for the Cameroon line [1] appears to rule out the conventional hotspot model. The fracture zone model does not offer any explanation for the cause of partial melting in the mantle. Fitton and Dunlop [1] suggested that the Cameroon line lavas originated from an upwelling asthenospheric hot zone which was emplaced underneath the Benue Trough, but became displaced relative to the lithosphere by the rotation of the African plate, and has been located beneath the Cameroon line and the Gulf of Guinea since the Cretaceous.

3. Methods

Major and trace elements were measured by XRF at the University of Edinburgh. For isotopic analyses, roughly 30 mg of each sample was dissolved and, when necessary, about 15% of the solution was spiked for isotope dilution work. The separation of Pb and U was achieved with HBr and HNO_3 chemistry, respectively, using roughly 0.3 ml of AG-1 × 8 anion resin. The remaining solution was used for further separations. Rb, Sr and the bulk REE were separated using 3 ml of AG50W × 8 cation resin, while Sm and Nd were separated using a 3 ml column of PTFE coated with H-DEHP. Three mixed spikes were used for isotope dilution analyses: ^{235}U–^{208}Pb, ^{87}Rb–^{84}Sr and ^{149}Sm–^{150}Nd. The total procedural blanks for Pb, Sr and Nd were typically 150, 70 and 25 pg at the time when these samples were analyzed; insignificant for Sr and Nd and generally smaller than 0.3% for Pb. All the isotopic measurements were made on two VG

Sector thermal ionization mass spectrometers equipped with 6 and 7 Faraday collectors, respectively. Nd and Sr isotopic compositions were measured in multi-dynamic mode. We obtained 0.710245 ± 10 (2σ, $n = 20$) for the ^{87}Sr/^{86}Sr of NIST standard SRM 987, and 0.511850 ± 10 (2σ, $n = 20$) for the ^{143}Nd/^{144}Nd of La Jolla Nd at the time of these analyses. Pb isotope ratios and all isotope dilution measurements were made using static multi-collection. All Pb analyses were corrected for fractionation and mass discrimination (0.1% per a.m.u. in this case) based on replicate analyses of NIST standard SRM 981. Our long-term reproducibility for ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb is better than 0.1%. A recent problem with Pb reproducibility is thought to have been associated with a fault on one Faraday collector [see 31]. This has been rectified. Duplication (total process) for 6 samples are presented in Table 2. The average difference for the 18 ratios duplicated is 0.05%. The initial ^{208}Pb/^{204}Pb of samples in this study were calculated assuming Th/U = 4.0, since isotope dilution of Th is not available and XRF Th data are generally poor. This simplification introduces negligible uncertainty to the initial Pb isotopic compositions.

All ^{40}Ar–^{39}Ar incremental heating analyses were performed at the University of Michigan. Basalt chips, roughly 4 mm in size, were washed with de-ionized H_2O and acetone then dried. About 100 mg of each sample was used, along with Fish Canyon Tuff biotite (with an age of 27.9 Ma, which was cross-calibrated with a second standard Mmhb-1 with an age of 520.4 Ma), as the standard for determining the J factor. The samples were irradiated at the Phoenix Memorial Reactor at the University of Michigan for 2 h with 2 MW operating power. Samples were placed individually into a Ta furnace and heated incrementally for 10–12 steps, with each step lasting 20 min. The released Ar was cleaned with hot Ti and SAES GP50-W getters before being released into a MAP 215 mass spectrometer equipped with a Faraday collector and an electron multiplier. The apparent age for individual steps was calculated from the measured ^{40}Ar/^{39}Ar after correction for background and interfering isotopes generated by neutron irradiation.

4. Petrology and geochronology of the oceanic sector of the Cameroon line

There are four volcanic islands in the Cameroon line: Bioko, Principe, São Tomé and Pagalu (Fig. 1). Bioko is a young volcanic island consisting entirely of basaltic lavas, ranging from basanite to *hy* basalts. The island was included in the continent/ocean boundary (c.o.b.) zone by Halliday et al. [2,32], along with Etinde and Mt. Cameroon. These three volcanic centers are located at the seismically determined continent–ocean boundary and have similar isotopic compositions [32]. Therefore, this study is focused just on Principe, São Tomé and Pagalu.

4.1 Principe

Principe is a small, deeply eroded island measuring roughly 20×15 km. The petrology and K–Ar geochronology of the island have been described by Fitton and Hughes [33] and Dunlop and Fitton [3]. The oldest rocks on the island are basal hyaloclastite breccias, which contain fragments of fresh tholeiite, dated at 31 Ma. On top of this basal unit are subhorizontal basaltic flows, intruded by tristanite and trachyphonolite plugs, and overlain by phonolite lavas. The basaltic flows can be divided into a lower series of alkali basalt and hawaiite overlain by a suite of nephelinite and basanite flows, which Fitton and Hughes [33] termed the older and the younger lava series, respectively.

The older lavas range in age from 24 (alkali basalt) to 19 Ma (hawaiite), while the younger lavas range from 5.6 (nephelinite) to 3.5 Ma (basanite). The plugs give ages ranging from 6.9 to 3.9 Ma. Dunlop and Fitton [3] reported a Rb–Sr isochron of ca. 5.9 Ma, defined by the younger lava series and all the intrusive rocks, which suggests a cogenetic relationship between the intrusive rocks and the younger lava series. The isotopic compositions of Sr, Nd and Pb for Principe are chiefly taken from Halliday et al. [2,32]. In addition, data for four hawaiites from the older lava series were analyzed as part of this study. We have also selected five samples from Halliday et al. [2], for which only isotopic ratios were measured, and analyzed their Rb/Sr, Sm/Nd and U/Pb ratios through isotope dilution in order to better determine their initial isotopic compositions.

4.2 São Tomé

The oldest rocks on São Tomé are conglomerates, sandstones and shales of the Ubabudo Formation, which have a similar lithology to the Cretaceous sandstones in Gabon [34]. The volcanic successions are dominated by basic lavas, although evolved rocks are common and form part of a continuum from basalt to trachyte and phonolite with no compositional gap [20]. The chemical variations between these rocks can be explained by fractional crystallization of the observed phenocryst phases. Trachytes seem to be the oldest dated volcanic rocks on the island, with two K–Ar ages of 15.7 Ma [35] and 13 Ma [1], while all the other rocks are younger than 7.6 Ma [1,34]. Lavas erupted in the last million years are entirely basaltic. The isotopic data for São Tomé were reported by Halliday et al. [2,32]. Only one sample, a ca. 13 Ma trachyte from São Tomé has been analyzed in this study to complement the existing data base.

4.3 Pagalu

Pagalu lies on the southwestern end of the volcanic chain. The petrology and geochemistry of the island have been reported by Cornen and Maury [36] and by Liotard et al. [37]. The oldest rocks on the island are hyaloclastite breccias that contain large clinopyroxene megacrysts and are intruded by numerous basaltic dikes. This basal unit is overlain by basaltic flows ranging in composition from basanite to *hy*-normative basalt. Numerous basanitic dikes intersect and feed the pile. The lava pile has also been intruded by tristanite and trachyte plugs. The evolved rocks in the island were probably produced by fractional crystallization of basanitic magmas, involving kaersutite, clinopyroxene and plagioclase [37].

Only one sample from Pagalu exists for which Sr, Nd and Pb isotopic compositions have been reported [32]. This sample exhibits distinctly un-

radiogenic Pb compared with other young oceanic sector Cameroon line basalts. In order to understand the origin of the Cameroon line magmas it is essential to obtain more comprehensive data for this island. The island is uninhabited and largely inaccessible at the present time. However, a suite of samples for a paleomagnetic study were collected by Piper and Richardson [38]. We have therefore used these samples in an attempt to complete our coverage of the Cameroon line.

All the Pagalu samples have a similar mineralogy but variable modal compositions; phenocrysts (mostly olivine and lesser amounts of pyroxene) make up roughly 20–45% of the total volume, and the matrix contains 10–20% of olivine plus pyroxene, 25–40% of plagioclase, and 5–15% of Fe–Ti oxides. Some samples contain up to 10% of glass in their matrix. Phenocrysts are mostly

euhedral to subhedral, varying from 0.5 to 4 mm in size, while the matrix grain size is generally less than 0.5 mm. According to Piper and Richardson [38], these samples were collected from two series of lava flows. The early lava flows range in composition from basanite to *hy*-norm basalt (Table 1), while the more recent lava flows are entirely basanite. All samples have experienced variable degrees of secondary alteration. In particular, the phenocrysts and groundmass olivine have been partially serpentinized or replaced by red–brownish iddingsite. However, most of the pyroxenes in the matrix and the remaining minerals (e.g., plagioclase and Fe–Ti oxides) are fresh. In general, the matrix contains most of the incompatible trace elements (e.g., U, Pb, Rb, Sr) and REEs that are of interest in this study, while olivines contain negligible amounts

Table 1
Rb--Sr and Sm--Nd isotopic data

Sample	Rock Type	Age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ atomic	$^{87}Sr/^{86}Sr$ ± 2σ errors	$(^{87}Sr/^{86}Sr)_i$ ± 2σ errors	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ atomic	$^{143}Nd/^{144}Nd$ ± 2σ errors	$(^{143}Nd/^{144}Nd)_i$ ± 2σ errors	$\varepsilon(Nd)_i$
Pagalu													
AN3	nb	4.8	33.8	713	0.136	0.70334 ± 1	0.70333 ± 1	12.23	57.76	0.1280	0.512926 ± 5	0.512922 ± 5	5.7
AN4	bn	4.8	41.2	924	0.128	0.70364 ± 1	0.70363 ± 1	17.03	85.11	0.1210	0.512858 ± 7	0.512854 ± 7	4.3
AN7	hb	4.8	32.2	752	0.123	0.70374 ± 1	0.70373 ± 1	14.66	74.19	0.1195	0.512878 ± 6	0.512874 ± 6	4.7
AN8	hb	4.8	35.4	757	0.134	0.70353 ± 1	0.70352 ± 1	7.67	36.40	0.1274	0.512935 ± 9	0.512931 ± 9	5.8
AN10	bn	4.8	42.5	839	0.146	0.70325 ± 2	0.70324 ± 2	10.29	48.21	0.1290	0.512948 ± 6	0.512944 ± 6	6.1
AN11	hb	4.8	33.2	937	0.102	0.70338 ± 1	0.70337 ± 1	14.43	69.15	0.1262	0.512909 ±13	0.512905 ±13	5.3
AN7BM	bn	≤1	41.2	815	0.145	0.70335 ± 1	0.70335 ± 1	17.11	81.68	0.1266	0.512929 ± 9	0.512929 ± 9	5.7
AN12	bn	≤1	21.4	833	0.074	0.70334 ± 1	0.70334 ± 1	10.93	51.42	0.1285	0.512936 ± 5	0.512936 ± 5	5.8
AN13	bn	≤1	41.7	834	0.144	0.70328 ± 1	0.70328 ± 1	13.87	65.09	0.1289	0.512972 ± 6	0.512972 ± 6	6.5
AN14	bn	≤1	41.2	1035	0.115	0.70343 ± 1	0.70343 ± 1	13.73	67.14	0.1236	0.512930 ± 7	0.512930 ± 7	5.7
AN17	bn	≤1	36.7	963	0.110	0.70340 ± 1	0.70340 ± 1	14.66	70.42	0.1259	0.512922 ± 9	0.512922 ± 9	5.5
AN18	bn	≤1	48.7	931	0.150	0.70336 ± 1	0.70336 ± 1	7.21	33.76	0.1292	0.512931 ± 7	0.512931 ± 7	5.7
AN19	bn	≤1	47.6	944	0.145	0.70337 ± 2	0.70337 ± 2	14.14	68.69	0.1244	0.512913 ± 6	0.512913 ± 6	5.4
AN20	bn	≤1	29.5	855	0.099	0.70340 ± 1	0.70340 ± 1	15.58	74.30	0.1268	0.512922 ± 8	0.512922 ± 8	5.5
Principe													
P6	hw	19	16.5	940	0.0535	0.70317 ± 1	0.70317 ± 1	11.20	55.68	0.1217	0.512902 ± 9	0.512853 ± 7	4.7
P21	hw	19	19.8	609	0.0935	0.70315 ± 1	0.70311 ± 1	7.89	36.08	0.1322	0.512900 ± 9	0.512853 ± 7	4.7
P25	hw	19	27.7	898	0.121	0.70311 ± 1	0.70297 ± 1	11.36	53.42	0.1286	0.512893 ± 8	0.512849 ± 8	4.6
P26	hw	19	26.5	917	0.0831	0.70311 ± 2	0.70312 ± 1	10.70	50.19	0.1290	0.512895 ±11	0.512868 ± 7	5.0
P12*	tr	6	165	1097	0.434	0.70322 ± 1	0.70318 ± 1	5.70	35.29	0.09764	0.512922 ±10	0.512918 ±10	5.6
P13*	tr	6	174	1183	0.424	0.70301 ± 2	0.70297 ± 2	6.227	39.36	0.09564	0.512865 ±20	0.512861 ±20	4.5
P39*	ph	6	262	77.5	9.74	0.70378 ± 2	0.70294 ± 2	1.603	12.99	0.07463	0.512940 ± 8	0.512937 ± 8	5.9
P40*	ph	6	209	235	2.56	0.70328 ± 1	0.70306 ± 1	2.598	20.34	0.07722	0.512906 ± 8	0.512903 ± 8	5.3
P41*	tp	6	169	485	1.01	0.70300 ± 1	0.70291 ± 1	3.675	25.77	0.08623	0.512930 ± 7	0.512927 ± 7	5.8
São Tomé													
ST57	ty	13	120	223	1.54	0.70388 ± 1	0.70360±3	10.55	71.73	0.08894	0.512875 ± 5	0.512867 ± 8	5.0

All Sr isotopic analyses were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and Nd analyses were normalized to $^{146}Nd/^{144}Nd = 0.7219$. $\lambda^{87}Rb = 1.42 \pm 10^{-11}y^{-1}$; $\lambda^{147}Sm = 6.54 \pm 10^{-12}y^{-1}$; $^{143}Nd/^{144}Nd_{CHUR} = 0.512638$ and $^{147}Sm/^{144}Nd_{CHUR} = 0.1966$. nb = *ne*-norm basalt, hb = *hy*-norm basalt, bn = basanite, hw = hawaiite, tr = tristanite, tp = trachyphonolite, ph = phonolite, ty = trachyte.
* Isotopic compositions were taken from [2].

of these trace elements. This implies that even with the secondary alteration, the samples still retain information about the isotopic and trace element characteristics of their mantle sources. The Ba/Rb ratio is particularly sensitive to alteration [39]. The Rb/U, Ba/Rb and Rb/Sr ratios are plotted against the percentage of grains (Fig. 2) and display some degree of alteration. In general, Rb may easily be leached out during alteration, while Ba and Sr are relatively immobile. The lack of any correlation in Fig. 2 and consistency with data for OIB elsewhere [39] suggests that the trace element compositions in these samples are probably valid, although they should be treated with caution and are not interpreted in detail in this study.

Several basalts from Pagalu were dated by $^{40}Ar/^{39}Ar$ step heating and the results are shown in Fig. 3. The data define two series of integrated ages, 4.8 ± 0.2 Ma and ≤ 1 Ma, corresponding to the two series recognized by Piper and Richardson [38]. The calculated plateau ages for three older samples vary from 4.7 to 4.8 Ma (Fig. 3a), consistent with the integrated ages. In addition, the ages calculated from the least-square fits of these samples on correlation diagrams of $^{36}Ar/^{40}Ar$ and $^{39}Ar/^{40}Ar$ also fall in a similar range between 4.7 and 4.8 Ma. The agreement of the age, 4.8 ± 0.2 Ma, from different calculations, plateau ages, regression plots and total gas ages, suggests that the integrated age is the eruption age of the older lavas. The integrated ages for three younger samples vary from 0.2 to 1 Ma (Fig. 3b), with only one sample showing a plateau age of 0.4 ± 0.1 Ma. Nonetheless, they clearly represent a separate and relatively recent (< 1 Ma) volcanic event on the island. Piper and Richardson [38] reported two K–Ar ages, 18.4 and 2.6 Ma, for older and younger lava flows. Although the results from this study confirm the existence of two series of lava flows, the ages are much younger than those obtained by Piper and Richardson [38], despite the use of the same sample suite. Cornen and Maury [36] dated one of the many basanitic dikes, which intersected (and fed) the presumably older lava flows, and obtained a K–Ar age of 5.35 ± 0.25 Ma. This age is similar to that obtained for the older lavas in
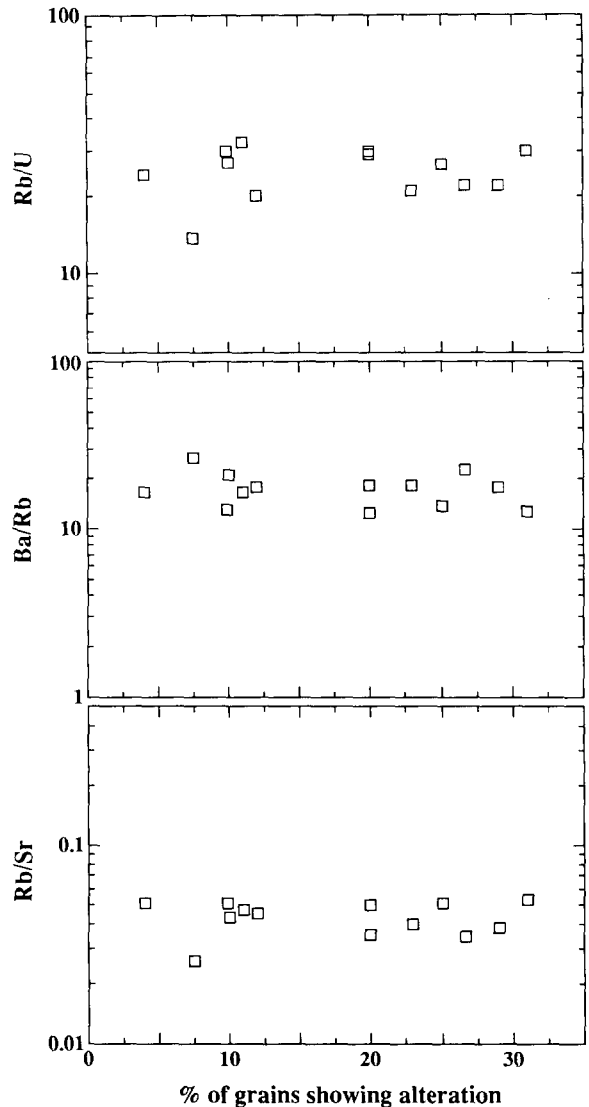

Fig. 2. Plot of Rb/U, Ba/Rb and Rb/Sr ratios of the Pagalu samples versus the percentage of the grains showing alteration within each sample. The percentage of grains showing alteration was obtained through integration over an area of 0.5 cm² in thin section.

this study, suggesting the older lavas and the dikes were coeval.

The most important feature of the new ages is that the earliest volcanism from each island decreases oceanward. Pollitz [40] has suggested that the African plate rotated counter-clockwise about a pole position near the Azores over the past 30

myr, implying that the absolute motion of the African plate did not coincide with the transform faults of the local Atlantic oceanic crust. Similar conclusions have been drawn from the study of space and time distributions of the volcanism in the South Atlantic [41]. Reconstructing African plate motion using the proposed rotation speeds and direction [40] leads to the conclusion that the first volcanic activity of each of the Cameroon line volcanic islands (31 Ma for Principe; $\geq$ 13 Ma for São Tomé; and 4.8 Ma for Pagalu) initiated from roughly the same sublithospheric location. This implies that the source region of the Cameroon line oceanic sector has been decoupled from the motion of the African plate and is located in the deep mantle. This is the first time such a feature has been documented for this volcanic chain, and is inconsistent with previous models for the origin of the Cameroon line.

5. Isotopic and chemical compositions

5.1 Isotopic compositions of young volcanic rocks

Initial Sr and Nd isotopic ratios of young basaltic rocks (< 10 Ma) for Principe, São Tomé and Pagalu are presented in Table 1. They are plotted along with fields for Atlantic MORB, Ascension, Madeira, Cameroon line continent/ocean boundary (c.o.b.) and two HIMU-type ocean islands, St. Helena and Mangaia, in Fig. 4. In general, Principe, São Tomé and Pagalu have a similar range of Nd isotopic compositions but distinct Sr isotopic ratios. There is an increase in $(^{87}Sr/^{86}Sr)_t$ with distance from the c.o.b. Principe has relatively a unradiogenic Sr isotopic composition, overlapping with São Tomé, and the data for both islands plot towards HIMU mantle [7]. Pagalu has the most radiogenic Sr and does not
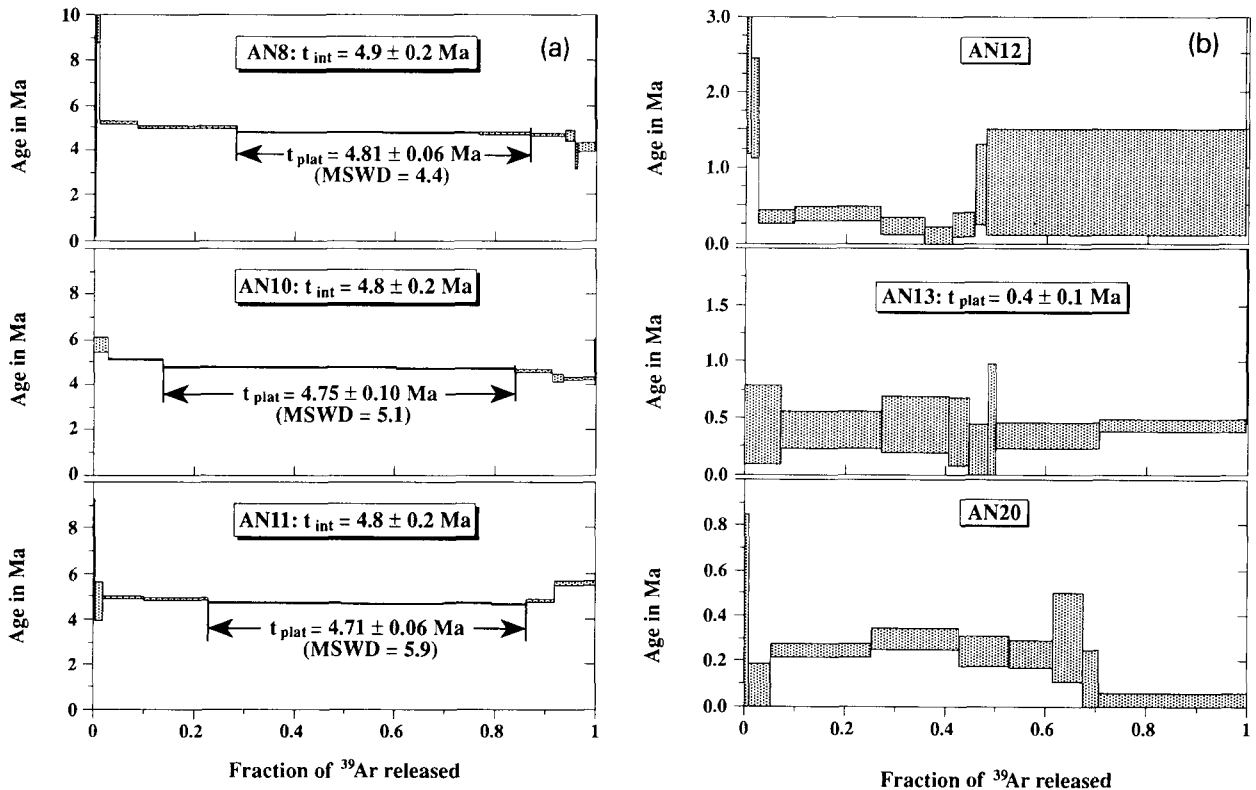

Fig. 3. $^{40}Ar-^{39}Ar$ age spectrum for Pagalu basalts. The uncertainty shown for each step is 2σ. t_{int} = integrated total gas age; t_{plat} = calculated plateau age. Three samples each from (a) the older and (b) the younger lava flows [38] are plotted.

overlap with either island. The observed variations in Sr isotopic composition among these three islands reflect either isotopic heterogeneity in the source mantle or mixing of different mantle end members. In contrast to the oceanic sector, the c.o.b. shows relatively unradiogenic Nd and radiogenic Sr. This suggests that the volcanic islands from the oceanic sector may be tapping sources that are not related to the c.o.b. volcanic centers, or that other components, for example, subcontinental lithosphere, are involved in the genesis of c.o.b. lavas.

The geographic control on Sr isotopic composition finds some parallels in Pb isotopic composition (Table 2). Pagalu has the most unradiogenic initial Pb isotopic compositions and plots distinctly away from the other two volcanic islands (Fig. 4), slightly overlapping with Atlantic MORB. Principe and São Tomé both have similar and more radiogenic Pb isotopic compositions relative

Table 2

U--Pb isotopic data

Sample	Rock Type	Age (Ma)	U (ppm)	Pb (ppm)	$^{238}U/^{204}Pb$ atomic	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$(^{206}Pb/^{204}Pb)_t$	$(^{207}Pb/^{204}Pb)_t$	$(^{208}Pb/^{204}Pb)_t$
Pagalu											
AN3	nb	4.8	1.16	2.86	26.0	18.955	15.598	38.80	18.935	15.597	38.78
AN4	bn	4.8	2.07	4.41	30.2	18.980	15.585	38.92	18.957	15.584	38.89
AN7	hb	4.8	1.21	3.53	22.1	19.095	15.595	39.09	19.079	15.594	39.07
AN7(d)						19.070	15.591	39.12	19.054	15.590	39.10
AN8	hb	4.8	1.09	3.32	21.4	19.272	15.640	39.26	19.257	15.639	39.24
AN8(d)						19.235	15.647	39.27	19.219	15.646	39.25
AN10	bn	4.8	1.41	3.45	26.1	18.866	15.608	38.69	18.846	15.607	38.67
AN11	hb	4.8	1.15	2.92	25.6	19.217	15.644	39.18	19.198	15.643	39.16
AN7BM	bn	<1	1.71	4.93	22.3	18.901	15.611	38.84	18.901	15.611	38.84
AN12	bn	<1	1.57	3.35	30.2	18.983	15.610	38.87	18.983	15.610	38.87
AN12(d)						18.981	15.608	38.89	18.981	15.608	38.89
AN13	bn	<1	1.40	2.64	34.3	19.049	15.580	38.80	19.049	15.580	38.80
AN13(d)						19.039	15.592	38.84	19.039	15.592	38.84
AN14	bn	<1	1.98	4.70	27.1	18.941	15.626	38.99	18.941	15.626	38.99
AN17	bn	<1	1.67	3.74	28.7	18.971	15.616	38.95	18.971	15.616	38.95
AN17(d)						18.965	15.619	38.96	18.965	15.619	38.96
AN18	bn	<1	1.62	3.72	28.0	18.895	15.618	38.89	18.895	15.618	38.89
AN18(d)						18.889	15.618	38.89	18.889	15.618	38.89
AN19	bn	<1	1.80	3.64	31.9	18.890	15.629	38.93	18.890	15.629	38.93
AN20	bn	<1	1.34	3.72	23.1	18.909	15.629	38.96	18.909	15.629	38.96
Principe											
P6	hw	19	0.991	2.64	24.8	19.859	15.676	39.73	19.786	15.672	39.63
P21	hw	19	0.884	1.70	34.3	19.836	15.673	39.71	19.734	15.668	39.58
P25	hw	19	1.00	2.14	30.8	19.637	15.675	39.51	19.547	15.670	39.39
P26	hw	19	1.23	2.33	34.6	19.760	15.662	39.57	19.658	15.657	39.44
P12*	tr	6	4.57	13.1	23.2	20.226	15.680	39.86	20.208	15.679	39.84
P13*	tr	6	4.94	13.9	23.6	20.237	15.701	39.93	20.219	15.700	39.91
P39*	ph	6	16.2	21.9	49.0	20.259	15.677	39.80	20.217	15.675	39.75
P40*	ph	6	6.71	9.07	49.1	20.285	15.673	39.82	20.243	15.671	39.77
P41*	tp	6	7.77	13.0	39.6	20.190	15.684	39.82	20.156	15.682	39.78
São Tomé											
ST57	ty	13	1.92	4.90	25.6	19.433	15.655	39.55	19.381	15.652	39.49

All Pb measurements have been corrected for fractionation and discrimination with a factor of 0.1% per a.m.u., based on measurements of NBS 981 standard.The 2σ uncertainties for the isotopic composition measurements are roughly or better than 0.1%. Some duplicate, with (d), analyses are listed for comparison.nb = ne-norm basalt, hb = hy-norm basalt, bn = basanite, hw = hawaiite, tr = tristanite, tp = trachyphonolite, ph = phonolite, ty = trachyte.* Isotopic composition data were taken from [2].

to those of Pagalu, with a few Principe samples showing higher $^{206}Pb/^{204}Pb$ than São Tomé. The $(^{207}Pb/^{204}Pb)_t$ of São Tomé, Principe and the c.o.b. are similar, although the c.o.b. has the highest $(^{206}Pb/^{204}Pb)_t$ and $(^{208}Pb/^{204}Pb)_t$.

Even though the distances from São Tomé to either Pagalu or Principe are roughly similar, there are only subtle differences between Principe and São Tomé in Sr and Pb isotopic ratios, but there are major differences between Pagalu and the other two islands, especially in Pb. Another important feature is that while the $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ increase toward the c.o.b. [2], Sr isotopic compositions of lavas from the c.o.b. are no more radiogenic than those of Pagalu.

5.2 Temporal variations in isotopic compositions

The changes in initial Sr, Nd and Pb isotopic compositions with eruption age for Principe, São

Tomé and Pagalu are illustrated in Fig. 5. Pagalu samples do not display any systematic differences in isotopic composition between the lava flows of the two age groups.

The oldest samples from Principe and São Tomé plot close to the field defined by the Pagalu samples in Fig. 5. In each case the 31 Ma old sample from Principe deviates from the rest of the Principe samples and plots within the field of Pagalu. Similarly, the 13 Ma trachyte from São Tomé deviates from the younger samples and plots toward the field of Pagalu. There is little doubt that the earliest Principe and São Tomé magmas originated from a mantle source similar to that of the Pagalu magmas. The youngest samples for both Principe and São Tomé have the most radiogenic Pb (Fig. 5). The difference in Pb isotopic ratios among each group of samples cannot be reconciled by the time-integrated effect of
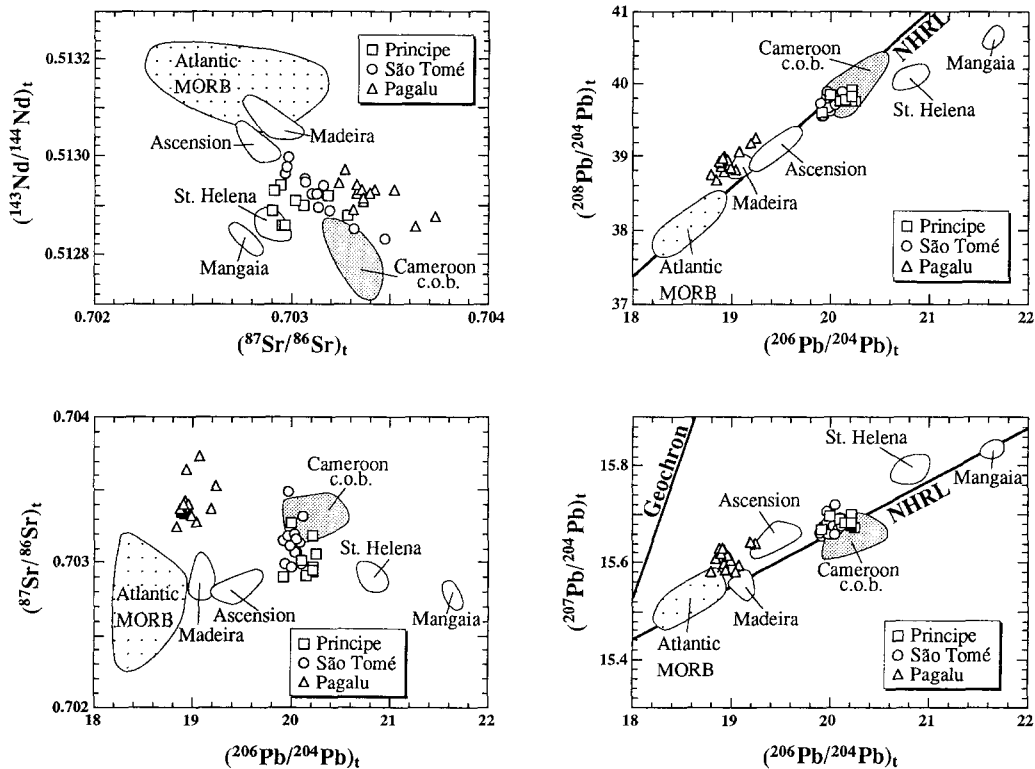

Fig. 4. Plots of initial Sr versus Nd and Pb for the young (< 10 Ma) samples from Principe, São Tomé and Pagalu, along with the data of the Atlantic MORB [53], Madeira and Ascension [31], Cameroon line c.o.b. [2,32] and two HIMU-type ocean islands, St. Helena [54] and Mangaia [43].

radioactive decay, given the range in $^{207}Pb/^{204}Pb$ and small measured μ ($^{238}U/^{204}Pb$) values (Table 2), which should be a maximum for their sources.

5.3 Major and trace elements

Both Principe and São Tomé display considerable variation in SiO_2 and MgO (Table 3), but reveal no systematic relationship with isotopic compositions (Fig. 6). However, samples from Pagalu show slight negative and positive correlation between MgO and Sr and Nd isotopic ratios, respectively. The implication is that some magmas incorporated Sr and Nd in the lithosphere, through assimilation of a slightly enriched source, while undergoing differentiation (AFC), as reported for the Canary Islands [17,18]. However, the effect, even in Pagalu, is small and does not affect the conclusions regarding the fundamental magma sources.

Despite the large differences in Sr and Pb isotopic ratio, the < 10 Ma basaltic lavas from these three islands have similar primitive mantle-normalized trace element patterns. This is illustrated in Fig. 7, where the average compositions of all < 10 Ma samples with $\geqslant 4\%$ MgO are plotted from the data in Tables 1–3 and [1,20]. In general, the patterns display enrichment in highly incompatible elements, such as Ba and Nb, and the degree of enrichment decreases for less incompatible elements, such as Sm and Y, as is typical for small degrees of partial melting. The lavas also have distinct negative K anomalies. Similar patterns have been found throughout the entire volcanic chain [1]. The similar trace element compositions in < 10 Ma basalts, but very different Sr and Pb isotopic ratios, between Pa-

Table 3
Whole rock XRF data for Pagalu basalts

Sample	AN3	AN4	AN7	AN7BM	AN8	AN10	AN11	AN12	AN13	AN14	AN17	AN18	AN19	AN20
Major elements (wt%)														
SiO_2	45.99	44.51	47.38	43.12	47.65	42.38	45.92	43.41	42.21	41.79	43.16	43.00	43.41	43.57
TiO_2	3.44	3.97	3.61	3.26	3.84	3.12	3.81	3.07	3.08	2.95	3.06	3.06	2.74	2.94
Al_2O_3	12.55	12.48	13.95	12.36	15.41	10.80	13.20	11.36	10.62	12.61	12.49	12.46	12.29	12.41
FeO	13.09	13.72	12.79	14.31	12.71	13.84	12.82	14.15	13.81	14.46	14.34	14.46	13.78	14.08
MgO	8.48	8.16	6.38	10.62	4.55	14.50	8.08	12.85	14.81	10.47	9.26	9.39	10.82	10.63
CaO	10.58	10.94	9.46	9.99	9.06	9.95	9.96	10.08	9.98	11.00	10.98	11.17	10.53	10.66
Na_2O	2.57	2.79	2.49	3.00	3.21	3.08	2.57	2.10	3.08	2.70	2.76	2.91	3.00	2.75
K_2O	1.54	1.19	1.77	1.73	1.85	0.65	1.77	1.30	0.64	0.67	0.96	0.63	1.17	1.30
MnO	0.17	0.18	0.14	0.18	0.15	0.19	0.17	0.18	0.19	0.21	0.20	0.20	0.20	0.23
P_2O_5	0.64	0.90	0.75	0.82	0.80	0.87	0.85	0.90	0.85	1.47	1.10	1.05	0.95	1.01
Total	99.05	98.84	98.71	99.38	99.22	99.38	99.13	99.40	99.25	98.32	98.31	98.33	98.89	99.59
Trace elements (ppm)														
V	302	311	316	274	321	272	300	265	266	279	300	307	251	275
Ba	526	725	675	669	579	544	606	571	516	743	648	618	640	665
Sc	24	27	26	26	21	26	24	26	25	29	28	29	29	25
La	41	61	51	50	51	50	47	50	47	75	61	62	67	58
Ce	87	136	119	106	120	101	109	107	100	152	125	122	136	119
Cr	561	396	338	246	137	710	335	514	541	299	376	379	345	348
Ni	256	229	180	204	104	505	225	406	506	252	267	252	245	269
Cu	65	52	44	48	41	46	60	38	41	37	56	52	49	60
Zn	110	123	114	142	110	126	118	142	123	163	136	137	142	134
Th	4	6	5	7	5	6	4	6	5	9	7	7	9	7
Y	29	34	32	33	36	32	32	32	31	41	35	36	37	35
Zr	291	474	405	339	404	278	365	305	275	352	322	311	312	313
Nb	52	63	53	71	54	62	52	65	61	77	68	65	67	68

Total Fe as FeO. The concentrations of Rb, Sr, Sm, Nd, U and Pb are shown in Table 1 and 2.

galu and Principe suggest that the source region components should have roughly the same trace element compositions. In addition, the degrees, and hence integrated depths, of partial melting should be approximately the same for these three islands.

Sun and McDonough [42] suggested that the Ba/Nb and La/Nb ratios of OIB are correlated with the HIMU type (low $^{87}Sr/^{86}Sr$), having low Ba/Nb, and EM type (high $^{87}Sr/^{86}Sr$), having high Ba/Nb. Pagalu has the highest Ba/Nb and $^{87}Sr/^{86}Sr$ ratios, even though the difference is small (Fig. 8). The low Ba/Nb and Sr isotopic ratios in Principe and São Tomé are consistent with the isotopic evidence for the influence of a HIMU component in the mantle source for these two islands. This is supported by a negative correlation between the Ba/Nb and $^{206}Pb/^{204}Pb$ ratios among these three islands and some HIMU type OIBs (Fig. 8). The HIMU type OIBs have

the most radiogenic $^{206}Pb/^{204}Pb$ and the lowest Ba/Nb ratios [42–45], while Pagalu has the exact opposite. Principe and São Tomé plot in between HIMU type OIBs and the island of Pagalu, and the trace elements and isotopic compositions of these two islands can be generated through admixing HIMU component to the 'Pagalu source'.

6. Discussion

All three volcanic islands in this study have a substantial history of volcanic activity. Principe has had the longest eruption history (ca. 30 myr). Given the small size of the island (roughly 15 × 20 km), the magma conduits supplying Principe must have been capable of rejuvenation, despite long periods of apparent quiescence and the tapping of distinct heterogeneities in the mantle, since the movement of the African plate has locally
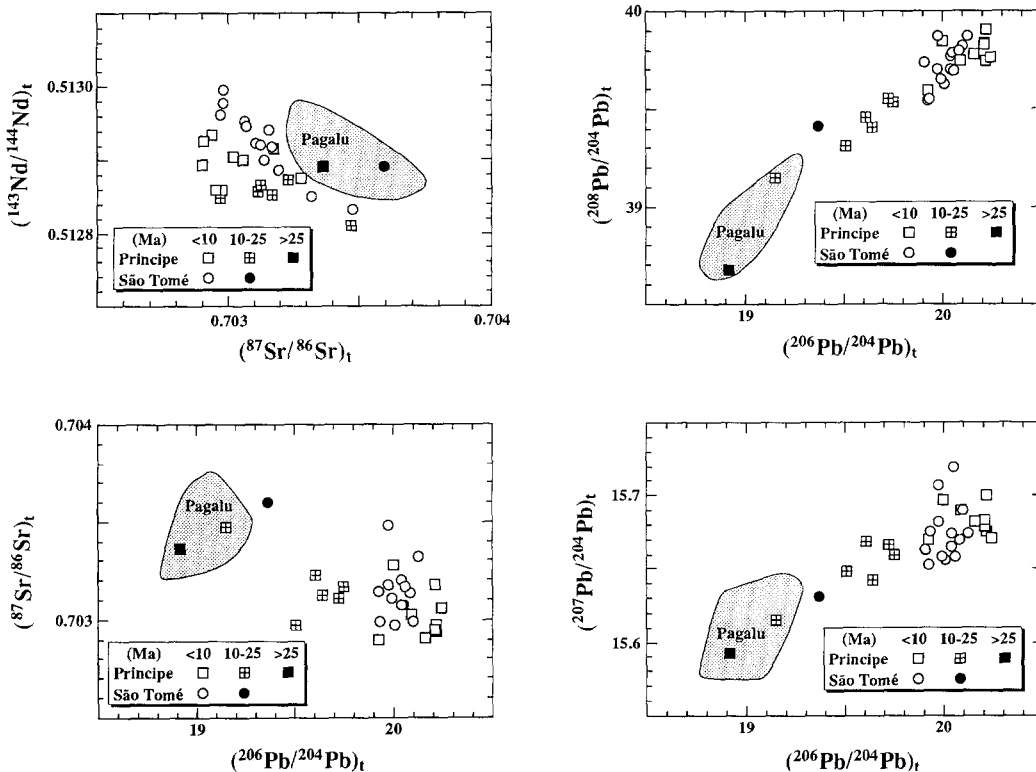

Fig. 5. Plots of initial Sr versus Nd and Pb for samples from Principe, São Tomé and Pagalu. The samples from Principe and São Tomé are divided into < 10 Ma, 10–25 Ma and > 25 Ma, while the samples from Pagalu are shown with the shaded area.

exceeded 500 km over the same period of time [40]. Similar arguments can be made for São Tomé.

The space–time variations in isotopic ratios observed in the oceanic sector of the Cameroon line indicate the gradual incorporation of HIMU components. The source from which the islands are initiated has slightly enriched isotopic compositions relative to that of the Atlantic MORB, as

shown by the island of Pagalu. However, instead of displaying mixing trends towards a HIMU component, < 10 Ma samples from each island show subparallel linear correlations in Sr–Nd and Pb–Sr isotopic diagrams that are explicable by mixing between a depleted MORB mantle (DMM) and an enriched mantle (EMI) component (Fig. 9). The implication is that, despite the general mixing scheme between HIMU and the
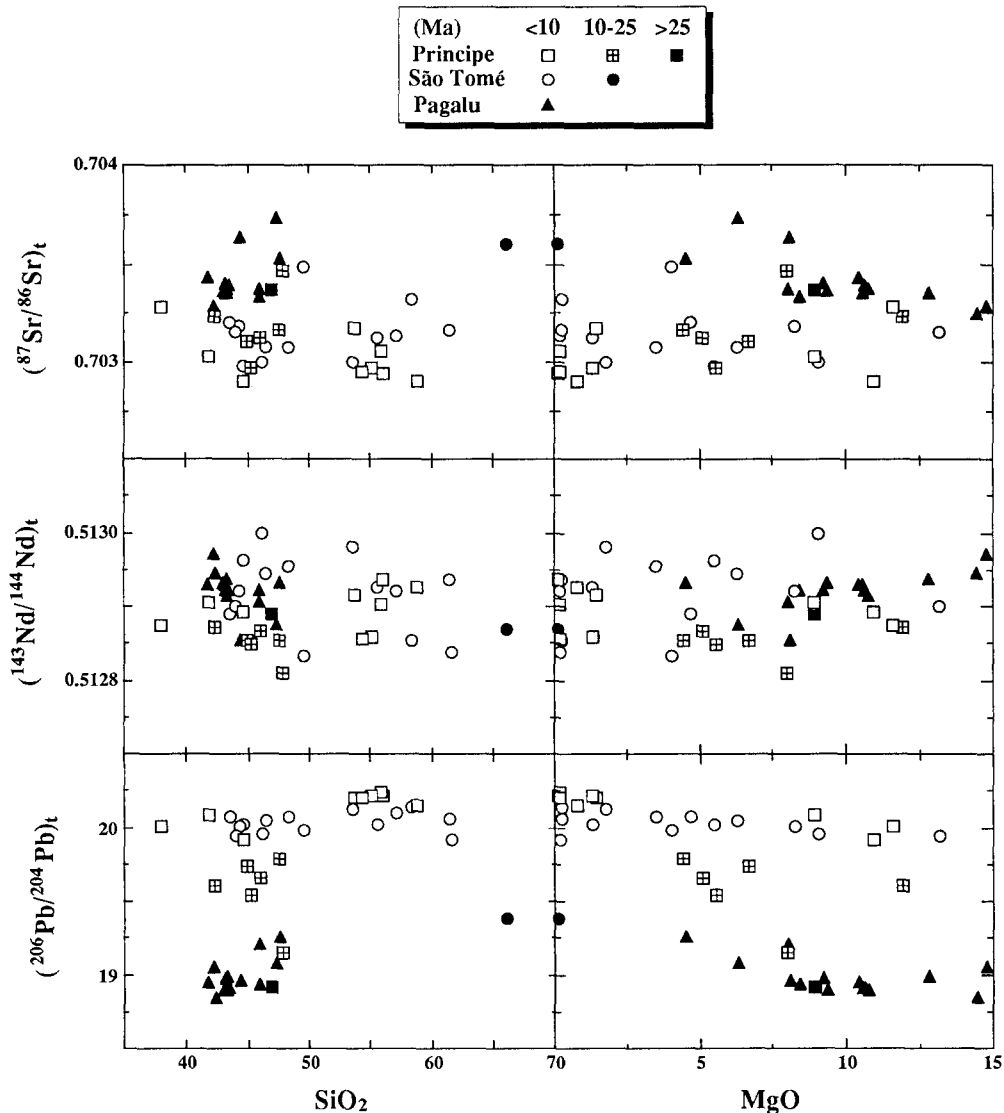
Fig. 6. Plots of SiO_2 and MgO versus initial Sr, Nd and Pb isotopic ratios for samples from the oceanic sector of the Cameroon line. Additional data are taken from [2,32].
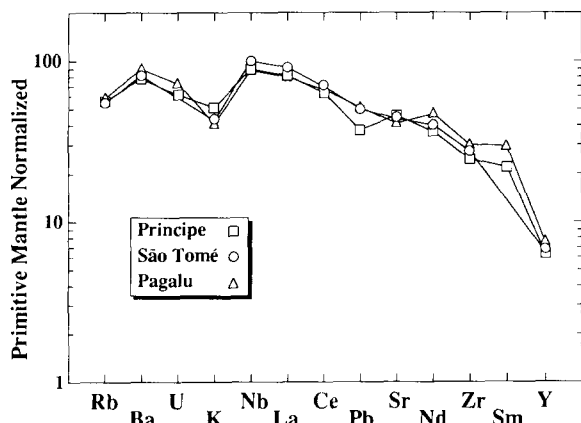
Fig. 7. Primitive mantle normalized trace element plot for selected samples (< 10 Ma and $\geqslant$ 4 wt% MgO) from Principe, São Tomé and Pagalu. The normalizing values are taken from [42].

the overall mixing between HIMU and the Pagalu source, and the parallel DMM–EMI mixing trends. Partial melting of an active plume head with HIMU signatures and entrained DMM–EMI ambient mantle may account for the observed isotopic variations in these islands. An active plume origin is consistent with the space–time distribution of the earliest magmatism in the oceanic sector of the Cameroon line. However, these islands are unlikely to originate from the same mantle plume, since each island seems to record different degrees of DMM–EMI homogeneity. This problem can be resolved if each island is supplied by an individual plume that shares a common origin. A single active plume model also encounters other difficulties, as is discussed further below.
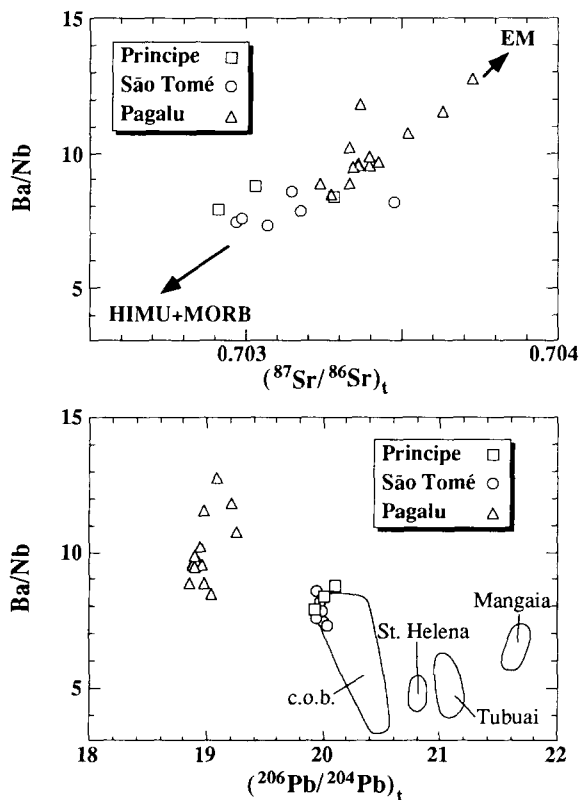
Pagalu source, which is responsible for the overall isotopic variations in the oceanic sector of the Cameroon line (Figs. 4 and 5), the plume head or its derivative magmas interacted with both a depleted MORB mantle and an enriched mantle component during ascent. This process of admixing is probably caused by plume entrainment or is a diffusion-dominated chromatographic effect [46] and affects only trace elements, since there is a lack of systematic relationship between major elements and isotopic compositions (Fig. 6). Mixing processes at shallow depths, as proposed for the Canary Islands [17], where a correlation between isotope geochemistry and major element composition is observed, appear to be irrelevant in the case of the Cameroon line.

The observed mixing trends in Fig. 9 can be modeled by melting different proportions of two principle 'components', a HIMU and a second 'component' consisting of DMM–EMI mixtures. The average proportion of DMM to EMI in the second component does not appear to vary with time or between different islands, as can be seen from Fig. 9. However, the degree of homogeneity of the DMM–EMI mix does vary. Furthermore, the Pb in this DMM–EMI mixture appears to be more thoroughly homogenized than the Nd and Sr. Mixing variable amounts of HIMU and this mixed DMM–EMI component may account for

Fig. 8. Plots of initial $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ ratios versus Ba/Nb ratios for the same samples used in Fig. 7. Additional data are taken from [1,2,32,43–45].

Regardless of the complexity of these mixing schemes, the isotopic variations in the oceanic sector of the Cameroon line fall within an area explicable through mixing of a depleted MORB mantle (DMM), an enriched mantle (EMI) and a HIMU mantle component (Fig. 9). The origin of DMM is most obvious, and probably reflects ambient MORB source upper mantle entrained with the rising plume [47–50]. The origin of EMI can be attributed to incorporation of ancient pelagic sediments in the source [44,45] or delaminated subcontinental lithosphere [17,18]. The origin of HIMU mantle [7,43–45] is generally considered to involve sources with elevated U/Pb ratios, relative to the bulk Earth, that have been isolated for a long period of time (e.g. 2 Ga). Therefore, the HIMU component is likely to originate in

deeper mantle (e.g., the 670 km boundary layer), or deeper.

Halliday et al. [2,31] proposed that a plume was emplaced beneath the c.o.b. of the Cameroon line and coupled with the lithosphere at 125 Ma. The observed spatial variations in Pb isotopic ratios in the c.o.b. resulted from fractionation of U/Pb during compaction and melting of the enriched plume head, increasing laterally toward the center of the plume head. According to the model, Principe, which is closer to the c.o.b., should be more radiogenic than Pagalu. This is true for the young lavas, but the 31 Ma Principe sample has the same isotopic compositions as the Pagalu samples. The difficulty with this fossil plume model is that it provides no mechanism for melting, no explanation for why the earliest vol-
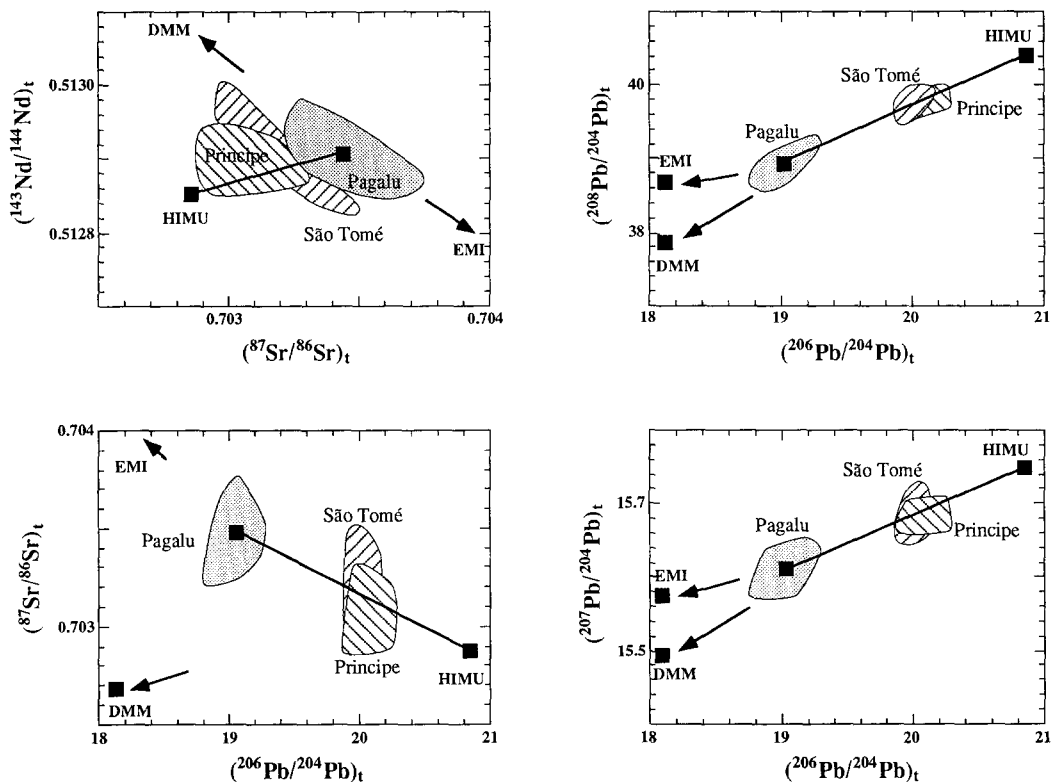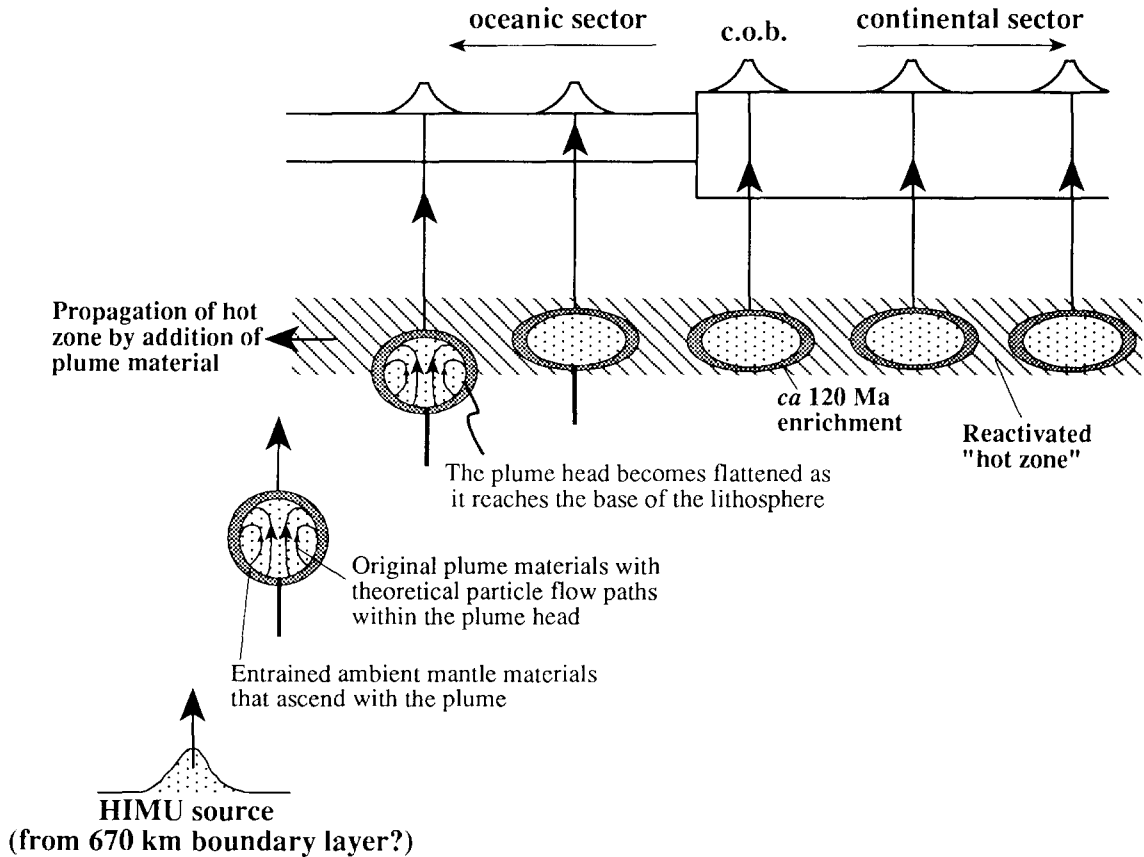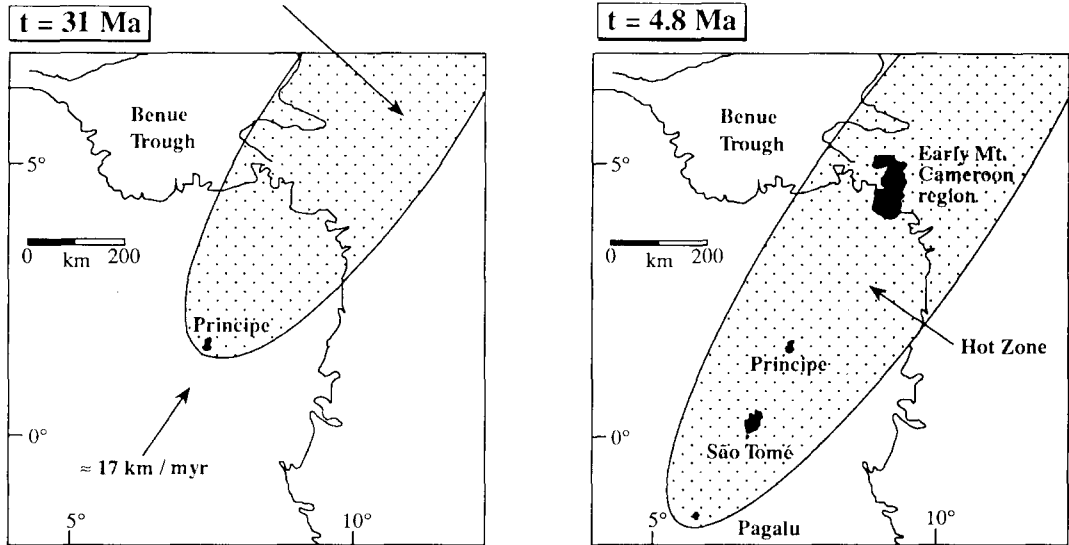

Fig. 9. Three-component mixing schemes for < 10 Ma samples from each volcanic island. The solid lines connecting HIMU and Pagalu represent the overall mixing schemes found in these islands. The arrows, however, reflect the isotopic variations within individual island that can be modeled by incomplete mixing of DMM and EMI. Note that the Pb is more thoroughly mixed than Sr and Nd.

Sub-lithospheric"hot zone", the actual
size and shape of which is unknown.

| t = 31 Ma |

Benue
Trough
—5°

0   km   200

Principe

—0°

≈ 17 km / myr

5°   10°

| t = 4.8 Ma |

Benue
Trough
—5°

0   km   200

Early Mt.
Cameroon
region.

Hot Zone

Principe

—0°

São Tomé

5°   10°

Pagalu

oceanic sector   c.o.b.   continental sector

Propagation of hot
zone by addition of
plume material

ca 120 Ma
enrichment

Reactivated
"hot zone"

The plume head becomes flattened as
it reaches the base of the lithosphere

Original plume materials with
theoretical particle flow paths
within the plume head

Entrained ambient mantle materials
that ascend with the plume

**HIMU source
(from 670 km boundary layer?)**

canism should always be associated with the most depleted source compositions and no prediction that the earliest volcanism should migrate from Principe to São Tomé to Pagalu. The temporal variations in isotopic composition observed in Principe and São Tomé, however, could suggest that the fossil plume head was zoned vertically and is being tapped at different depths with time.

An alternative model is that an active plume, initiated in the deep mantle, with isotopic signatures of HIMU mantle, is currently expanding and extending its influence away from the c.o.b. This is consistent with the space–time distribution of the earliest volcanic activity in these volcanic islands. The plume head gradually flattened out when it reached the lithosphere and entrained some ambient mantle during its ascent [47–50]. Since this ambient mantle component, a mixture of DMM and EMI in this case, is concentrated around the margin of this plume head, early magmas that are produced due to decompression partial melting should mainly feature this ambient mantle component. As the plume rises further, original plume materials gradually become dominant in subsequent magmas. Although this active plume model offers a simple explanation for the data, it is in conflict with other observations. There is no systematic progression in the ages of volcanism for the rest of the Cameroon line [1] and the magma conduits must somehow remain coupled with the lithosphere for the past 30 myr. The Cameroon line is linear rather than circular in outline, as might be expected from a very large active plume head. In addition, this model cannot explain the relative enrichment of ^{206}Pb/^{204}Pb but not ^{207}Pb/^{204}Pb in the basaltic lavas from the c.o.b., which is explained by the source region evolving with high U/Pb for ca. 125 myr [2]. Furthermore, the model

does not explain the older (30–65 Ma) plutonic activity in the continental sector. Finally, the model does not predict the relationship between the locus of magmatism and African plate motion.

A new model is proposed which attempts to accommodate all of these features of the Cameroon line. We propose that the Cameroon line originates from a sublithospheric enriched 'hot zone', periodically fed and melted by deep mantle plumes (Fig. 10). Part of this zone of hotter mantle represents reactivated mantle previously enriched during the breakup of the South Atlantic in the Mesozoic. The observed Pb isotope anomaly of the basaltic lavas at the c.o.b. provide a record of this enrichment event. The earliest erupted magmas were in the continental sector (> 35 Ma) and we suggest that the Cameroon line has been gradually expanding oceanward with time, while remaining active over considerable periods of time at any individual volcanic center. The focus of magmatism is, therefore, partly controlled tectonically; that is, by preferential flow paths through the lithosphere. As pointed out earlier, reconstructing the motion of the African plate indicates that the earliest volcanism of the Cameroon line volcanic islands (31 Ma for Principe; ≥ 13 Ma for São Tomé; and 4.8 Ma for Pagalu) were all initiated from roughly the same location. In other words, the source region of the Cameroon line magmas in this region has been decoupled from the motion of the African plate and is located in the deep mantle. The observed spatial and temporal isotopic variations therefore reflect a combination of the horizontal heterogeneities within this hot zone and new plume material added from the deep mantle. The best way to reconcile the Pb isotope anomaly at the c.o.b. with an enrichment

Fig. 10. Sublithospheric 'hot zone' model. A sublithospheric hot zone, enriched since the late Mesozoic, has been periodically fed and melted by the addition of deep mantle plumes. A plume triggered the first eruption in Principe at ca. 31 Ma. Since then, the African plate has rotated counter-clockwise about a pole near the Azores [40]. The first eruptions of São Tomé (≥ 13 Ma) and Pagalu (4.8 Ma) were produced by partial melting of plume material from the same source as formed the lavas of Principe at 31 Ma, due to the rotation of the African plate. These first eruptions in each island featured partial melting of entrained ambient mantle with isotopic signatures similar to Pagalu. The later magmas from the islands of Principe and São Tomé featured melting of original plume materials, dominated by HIMU isotopic signatures.

that is roughly correlated to the earlier formation of the continental margin and the extended volcanic eruptions within each volcanic center, is if the Cameroon line is tapping sources that are both coupled and decoupled from the lithosphere (Fig. 10). This cannot be explained by the lithosphere controlling the nature of heterogeneities being sampled from the asthenosphere, for the alkali basalts at the c.o.b. are no more enriched, chemically, than other parts of the Cameroon line. It is still unclear how a plume becomes coupled with the lithosphere and remains active for as long as 30 myr. However, we speculate that the original plume component, HIMU, is probably the only part of this gradually rising, flattening and cooling plume head that is still hot enough to generate partial melting after long periods (10^7 yr) of apparent quiescence.

Ascending mantle plumes are often driven by buoyancy, resulting from viscosity contrast. Therefore, they most likely originate from thermal boundary layers, for example, the core–mantle boundary or 670 km transition zone. Plumes originating from the core–mantle boundary are thought to be more voluminous, over 500 km in diameter, having ascended a much greater distance [47–49]. This is inconsistent with the small scales required for the Cameroon line. The more plausible plume source for the Cameroon line is, therefore, the 670 km transition zone. Our model differs significantly from those proposed for large systems such as Hawaii, in that several small plumes are involved. Furthermore, the concept of a buoyant, continuously replenished sublithospheric hot zone finds no parallel in the Hawaiian chain, where successive islands become dormant rapidly without reactivation. Therefore, the degree to which 'Cameroon line type' plume tectonics can be applied to other systems is unclear.

Acknowledgments

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