

The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkali basalt

J.G. Fitton¹ and H.M. Dunlop^{2,*}

¹ Grant Institute of Geology, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW (U.K.)

² Scottish Universities Research and Reactor Centre, East Kilbride, Glasgow G75 0QU (U.K.)

Received July 20, 1984

Revised version received September 27, 1984

The Cameroon line is a unique within-plate volcanic province which straddles a continental margin. It consists of a chain of Tertiary to Recent, generally alkaline volcanoes stretching from the Atlantic island of Pagalu to the interior of the African continent. It provides, therefore, an ideal area in which to compare the sub-oceanic and sub-continental mantle sources for alkali basalt.

Basaltic rocks in the oceanic and continental sectors are geochemically and isotopically indistinguishable which suggests that they have identical mantle sources. This conclusion rules out substantial lithosphere involvement in the generation of alkali basalts and therefore weakens the case for mantle metasomatism as a necessary precursor to alkaline magmatism. The convecting upper mantle is a much more likely source as it will be well-stirred and unlikely to show any ocean-continent differences. The long history of Cameroon line magmatism (65 Ma) and lack of evidence for migration of volcanism with time makes a deeper mantle source unlikely.

Mid-ocean ridge basalts (MORB) also originate within the convecting upper mantle and so must share a common source with the Cameroon line alkali basalts (and, by implication, ocean island and continental rift basalts). A grossly homogeneous mantle with a bulk composition depleted in large-ion lithophile elements (LILE), but containing streaks of old, LILE-enriched material, provides a plausible common source. Large degree, near-surface melting of such a source would produce MORB. Smaller degree melts produced at deeper levels would percolate upwards along grain boundaries and become enriched in LILE by leaching LILE-rich grain boundary films. The mixing of these liquids with melts from the LILE-rich streaks will produce magmas with the geochemical and isotopic features of ocean island basalts.

1. Introduction

Alkali basalts are strongly enriched in large-ion lithophile elements (LILE) in comparison to other basalt types. The contrast is particularly striking between alkali basalts and mid-ocean ridge basalts (MORB). MORB are generally believed to have evolved from relatively large degree (10–20%) partial melts of spinel-lherzolite [1] and so provide information on the relative abundances of trace elements in their mantle source. Alkali basalts, in

contrast, are unlikely to represent large degree partial melts and so the nature of their source is much less clear.

Alkali basalts also differ from MORB in having more radiogenic Sr and Pb and less radiogenic Nd isotope ratios. These isotopic differences have led to the suggestion [2,3] that ocean island tholeiites and alkali basalts are produced by the mixing of melts derived from plumes of undepleted lower mantle with melts from a depleted upper mantle. Other explanations have involved the recycling of lithospheric materials (e.g. [4,5]). Paradoxically the isotope ratios in alkali basalts generally indicate a mantle source which has been depleted in LILE

* Present address: B.R.G.M., Isotope Geology Unit, SGN/MGA B.P. 6009, 45060 Orléans, France.

with respect to the bulk earth for long periods even though the rocks themselves are strongly enriched in these elements.

Explanations for the LILE enrichment seen in alkali basalts fall into two categories. Either the basalts are produced by very small degrees of partial melting or the source was enriched before melting. To produce alkali basalts from a mantle source with chondritic LILE abundances would require very small degrees of partial melting ($< 1\%$). Such small amounts of melt will be difficult to extract and so zone-refining has been proposed [6] as a means of concentrating incompatible elements into a melt.

Many authors (e.g. [7-9]) have proposed that high concentrations of LILE are best explained by processes of mantle enrichment (metasomatism) shortly before partial melting. Source enrichment models receive support from metasomatised mantle xenoliths contained in kimberlites and alkali basalts [10,11]. These xenoliths are generally believed to originate within the lithosphere so a lithosphere mantle source is implicit in such models. Old, sub-continental lithosphere will have had a long tectonic, metamorphic and magmatic history and so the diversity of the xenoliths found in continental alkali basalts and kimberlites is not surprising. Young, oceanic lithosphere mantle, however, is thought to represent the refractory residue left after the formation of the ocean crust and is unlikely to be enriched to the same extent as continental lithosphere mantle. This is reflected in the scarcity of metasomatised mantle xenoliths in oceanic alkali basalts.

It should be possible to test these metasomatic enrichment models by comparing oceanic and continental within-plate alkali basalts. If the models are valid then there should be systematic chemical and isotopic differences between the two populations of alkali basalt. If, on the other hand, such differences do not exist then a source within the asthenosphere is implied. The asthenosphere is well stirred by convection and must be the same beneath oceans and continents.

The Cameroon line in West Africa (Fig. 1) provides a unique area in which to look for differences between oceanic and continental within-plate alkali basalts. It is composed of a line of

Tertiary to Recent alkaline volcanoes stretching for 1600 km from the Atlantic island of Pagalu, across the continental shelf and into the centre of Africa. Half the line lies in the ocean and half on the continent.

The purpose of this paper is to report the results of a comparative geochemical study of basic volcanic rocks from the oceanic and continental sectors of the Cameroon line. In addition to the geochemical work, a K-Ar dating programme was carried out in order to look for systematic migrations of volcanism with time. The rock samples were mostly collected by the first author and D.J. Hughes in the course of several field seasons in West Africa. The only major parts of the line not visited were the islands of Bioko and Pagalu. Samples from these islands were collected by J.D.A. Piper and A. Richardson as part of a paleomagnetic study [12]. An additional sample of basalt from Pagalu was provided by the British Museum (Natural History).

2. Analytical techniques

Major- and trace-element analyses were carried out in Edinburgh by X-ray fluorescence techniques using a Philips PW1450/20 automatic X-ray spectrometer. Major elements were determined on glass discs prepared by fusing the powdered sample with Johnson Matthey Spectroflux[®] 105. The sample preparation technique is essentially that described by Norrish and Hutton [13]. Trace elements were determined on pressed-powder samples.

Raw counts for both major and trace elements were ratioed to a monitor to correct for machine drift. Count ratios were corrected for mass absorption effects using the coefficients of Theissen and Vollach [14]. Major-element count ratios were corrected by an iterative procedure and corrections for trace elements were made using coefficients calculated from the major-element analyses. In addition, trace element count ratios were corrected for interelement interferences using a range of synthetic glass standards. Both major- and trace-element determinations were calibrated against a range of international standards using

TABLE 1

Mean and standard deviation of five analyses of basalt ST72

Oxide	Mean \pm σ (wt.%)	Trace element	Mean \pm σ (ppm)
SiO ₂	43.80 \pm 0.09	Ni	170.9 \pm 0.3
Al ₂ O ₃	14.06 \pm 0.05	Cr	380.5 \pm 2.9
Fe ₂ O ₃	12.46 \pm 0.03	V	236.6 \pm 3.5
MgO	8.31 \pm 0.03	Sc	18.2 \pm 0.3
CaO	10.62 \pm 0.03	Cu	48.4 \pm 0.4
Na ₂ O	3.61 \pm 0.04	Zn	113.9 \pm 1.1
K ₂ O	1.412 \pm 0.005	Sr	1129.7 \pm 4.0
TiO ₂	3.165 \pm 0.006	Rb	46.7 \pm 0.5
MnO	0.215 \pm 0.007	Zr	366.0 \pm 1.0
P ₂ O ₅	1.030 \pm 0.003	Nb	92.2 \pm 0.5
		Ba	718.4 \pm 5.6
		Th	16.6 \pm 1.2
		La	78.9 \pm 0.8
		Ce	156.7 \pm 1.6
		Nd	66.2 \pm 0.6
		Y	33.2 \pm 0.4

the values recommended by Abbey [15].

To assess the reproducibility of the analyses, five separate aliquots of a basalt from São Tomé (ST72) were analysed for major and trace elements. The sample was chosen because its composition is close to the mean of all the Cameroon line basic rocks. The mean and standard deviation of the five analyses of this sample are given in Table 1.

K-Ar ages and Sr-isotope ratios were determined at S.U.R.R.C, East Kilbride [16]. The techniques used have already been described elsewhere [17].

3. The age of the Cameroon line

The Cameroon line is a linear chain of volcanoes so it was tempting to speculate that it may repre-

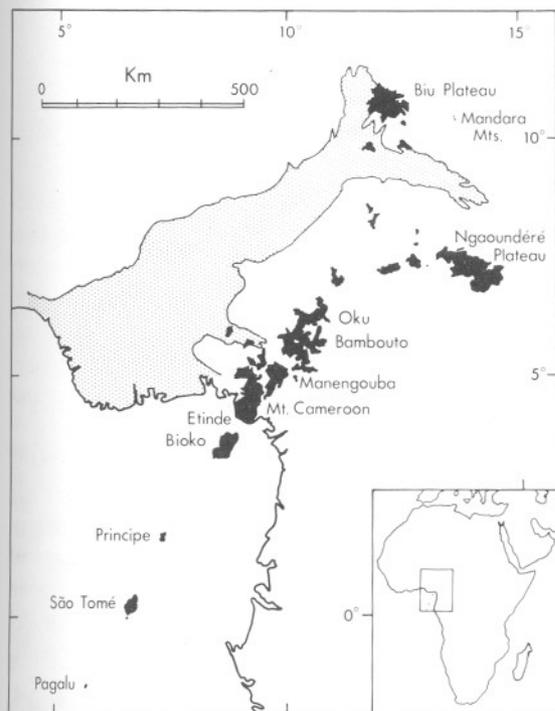


Fig. 1. Map of part of West Africa showing the outcrop of the Cameroon line volcanic rocks (black) and the Cretaceous sedimentary rocks of the Benue trough (stippled).

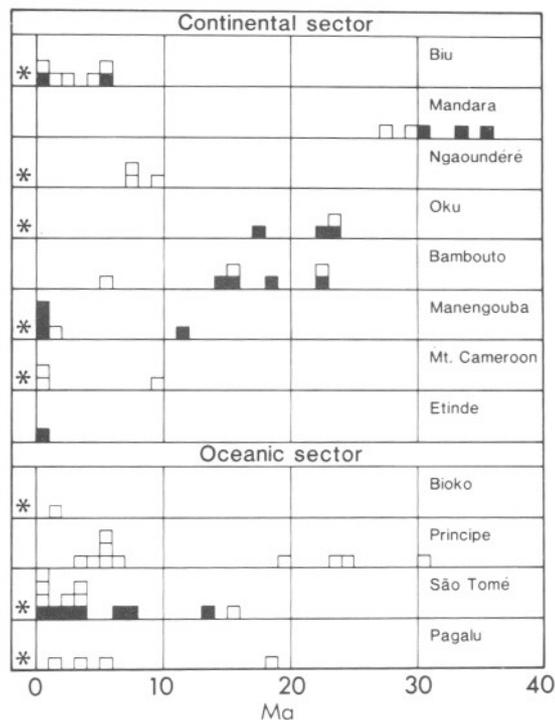


Fig. 2. Summary of available K-Ar age data for the Cameroon line volcanic rocks. Filled boxes indicate data from this paper. Open boxes represent data from the literature: Biu [18]; Mandara [19]; Ngaoundéré, Oku, Bambouto and Manengouba [20]; Mt. Cameroon and Bioko [21]; Principe [17,21]; São Tomé [21,22]; Pagalu [12,23]. Asterisks indicate the presence of morphologically recent cinder cones.

TABLE 2

New K-Ar data for Cameroon line volcanic rocks

Sample	Rock type	K (wt.%)	$^{40}\text{Ar}^*/^{40}\text{Ar}_T$	$^{40}\text{Ar}^*$ ($10^{-6} \text{ cm}^3 \text{ g}^{-1}$)	Age (Ma $\pm 1\sigma$)
<i>Biu Plateau</i>					
N2	basalt	1.062	0.194	0.215	5.20 \pm 0.33
			0.196	0.119	5.35 \pm 0.32
N38	basanite	1.185	0.119	0.039	0.84 \pm 0.09
<i>Mandara</i>					
C145	trachyte	4.425	0.182	5.906	34.00 \pm 2.27
			0.178	6.365	36.62 \pm 2.51
C146	basanite	0.834	0.307	1.062	32.46 \pm 1.33
			0.323	1.111	33.95 \pm 1.33
C147	basalt	1.305	0.732	1.574	30.75 \pm 0.69
			0.709	1.538	30.06 \pm 0.69
<i>Oku</i>					
C85	rhyolite	3.745	0.952	3.290	22.13 \pm 0.44
			0.950	3.320	22.33 \pm 0.45
C91	hawaiite	1.660	0.680	1.109	17.21 \pm 0.40
			0.750	1.145	17.71 \pm 0.39
C95	rhyolite	4.350	0.841	3.987	23.32 \pm 0.49
			0.799	3.906	23.05 \pm 0.50
<i>Bambouto</i>					
C100	rhyolite	3.436	0.937	2.501	18.71 \pm 0.38
			0.881	2.458	18.31 \pm 0.38
C107	trachyte	3.905	0.217	3.356	22.00 \pm 1.24
			0.183	3.582	23.44 \pm 1.58
C108	basalt	1.693	0.802	0.940	14.33 \pm 0.31
			0.520	0.916	13.84 \pm 0.38
C111	trachyte	4.185	0.695	2.671	16.40 \pm 0.38
			0.554	2.494	15.26 \pm 0.40
<i>Manengouba</i>					
C52	basanite	2.125	0.119	0.033	0.40 \pm 0.04
C55	basalt	1.250	0.190	0.045	0.94 \pm 0.06
C57	trachybasalt	1.680	0.029	0.031	0.48 \pm 0.29
			0.029	0.044	0.71 \pm 0.42
<i>Dome northwest of Manengouba</i>					
C54	trachyte	4.520	0.955	1.966	11.15 \pm 0.22
			0.935	2.203	12.49 \pm 0.25
<i>Etinde</i>					
C36	nephelinite	5.13	0.07	0.01512	0.082 \pm 0.3
			0.07	0.01260	0.065 \pm 0.1
<i>São Tomé</i>					
ST 43	trachyte	3.820	0.207	0.200	1.35 \pm 0.08
			0.227	0.191	1.29 \pm 0.07
ST 44	basanite	1.315	0.397	0.134	2.66 \pm 0.09
			0.304	0.121	2.39 \pm 0.10
ST 57	trachyte	3.750	0.387	1.939	13.25 \pm 0.45
			0.350	1.885	12.88 \pm 0.47
ST 60	basalt	0.785	0.111	0.016	0.51 \pm 0.06
ST 84	trachyte	4.670	0.802	1.393	7.64 \pm 0.16
			0.822	1.379	7.56 \pm 0.16
ST 90	phonolite	4.803	0.536	0.617	3.30 \pm 0.09
			0.584	0.601	3.22 \pm 0.08
ST 96	hawaiite	2.310	0.640	0.576	6.37 \pm 0.15
			0.420	0.580	6.42 \pm 0.20

 $\lambda_e = 0.581 \times 10^{-10} \text{ y}^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} \text{ y}^{-1}$; $^{40}\text{Ar}^*$ = radiogenic ^{40}Ar ; $^{40}\text{Ar}_T$ = total ^{40}Ar .

sent a hot-spot trail. In order to test this possibility, and also to allow age corrections to be applied to the Sr-isotope data, 33 of the Cameroon line samples were dated by the K-Ar method. Nine of these determinations (from Principe) have already been published [17]; the remainder are presented in Table 2.

All available K-Ar data from Cameroon line volcanic rocks are summarised in Fig. 2. The data in Fig. 2 are arranged in geographical order from

northeast to southwest and it is obvious that no systematic age progressions exist. There is no significant difference in age between the oceanic and continental volcanic rocks. All but three of the volcanic centres have morphologically recent cinder cones which implies that volcanic activity has occurred over the whole length of the line in the last million years. Mt. Cameroon, in the centre of the line, is still active with five eruptions recorded this century [24].

TABLE 3

Average compositions of Cameroon line basic volcanic rocks (MgO > 4%)

	Continental sector (n = 134)		Oceanic sector (n = 144)		Hypersthene-normative (n = 65)		Nepheline-normative (n = 213)		Etinde nephelinite (n = 15)	
	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ
<i>Major elements (wt.%)</i>										
SiO ₂	45.71	2.48	44.57	2.01	47.20	1.98	44.49	2.03	39.98	0.69
Al ₂ O ₃	14.18	1.64	13.32	1.82	14.37	1.54	13.54	1.81	14.81	0.99
Fe ₂ O ₃ ^a	12.40	1.25	13.11	1.08	12.21	1.21	12.94	1.17	12.24	0.72
MgO	8.18	2.48	8.49	2.82	7.37	2.25	8.64	2.72	5.29	1.16
CaO	9.84	1.45	10.48	1.42	9.18	1.31	10.47	1.38	13.49	1.11
Na ₂ O	3.36	0.72	3.02	0.76	2.96	0.63	3.26	0.78	3.90	0.83
K ₂ O	1.47	0.42	1.36	0.51	1.41	0.44	1.41	0.48	2.15	0.95
TiO ₂	2.98	0.55	3.36	0.44	2.96	0.63	3.24	0.48	3.85	0.34
MnO	0.18	0.03	0.18	0.02	0.17	0.02	0.18	0.02	0.30	0.05
P ₂ O ₅	0.73	0.27	0.84	0.23	0.68	0.22	0.82	0.25	1.08	0.19
Total	99.03		98.73		98.51		98.99		97.77 ^b	
<i>Trace elements (ppm)</i>										
Ni	141	89	165	113	142	95	157	105	17	11
Cr	237	174	268	187	221	155	263	188	26	37
V	264	77	263	50	254	71	266	62	430	44
Sc	21.8	6.3	22.6	6.4	20.9	5.6	22.6	6.6	15.2	11.5
Cu	46	18	50	20	44	19	49	19	79	22
Zn	107	12	118	12	111	13	113	14	137	27
Sr	919	272	918	248	811	314	951	231	2801	1280
Rb	39.0	16.2	35.4	18.8	31.4	13.8	38.9	18.4	103.5	55.5
Zr	302	91	322	81	288	98	321	81	636	135
Nb	72	23	71	21	58	19	76	21	231	62
Ba	583	185	577	174	519	178	599	176	1299	739
Th	4.6	3.0	5.4	2.8	3.8	2.2	5.4	3.0	16.1	5.9
La	58	20	61	19	48	16	63	19	205	46
Ca	111	41	123	37	96	35	124	38	406	94
Nd	49	16	56	14	45	15	55	15	148	31
Y	29.2	4.6	31.3	4.5	29.5	4.8	30.5	4.6	46.3	8.3
(⁸⁷ Sr/ ⁸⁶ Sr) ₀	0.70324	20 ^c	0.70319	21 ^c	0.70332	22 ^c	0.70317	18 ^c	0.70325	12 ^c
	(n = 66)		(n = 40)		(n = 35)		(n = 71)		(n = 12)	

^a Total Fe as Fe₂O₃.^b Includes SrO 0.33, BaO 0.14, SO₃ 0.14 and Cl 0.07.^c × 10⁻⁵.

In addition to extrusive rocks, the continental sector of the Cameroon line also includes intrusive ring complexes composed of granite and syenite with less abundant gabbro and occasional remnants of rhyolite and trachyte. These stretch from Mt. Koupé in the south (30 km southwest of Manengouba) to Golda Zuelva in the north (60 km northeast of the Mandara Mts.). The ages of these complexes, determined by K-Ar and Rb-Sr methods [25–27], range from 30 to 66 Ma and so overlap with those of the extrusive centres. As with the extrusive centres, there is no clear progression of ages along the line.

It must be concluded, therefore, that the Cameroon line has been intermittently active along its whole length at least since the Oligocene and in the continental sector since the Palaeocene. The submarine basements of the oceanic islands may well be contemporaneous with the continental ring complexes [22]. The Cameroon line is clearly not a hot-spot trail but is more likely an incipient rift associated with the Cretaceous Benue trough [28,29].

4. Geochemistry of basic volcanic rocks from the Cameroon line

423 rock samples, collected from all parts of the Cameroon line, were analysed for major and trace elements. These rocks range in composition from alkali basalt, basanite and nephelinite to rhyolite and phonolite. The present paper will be concerned

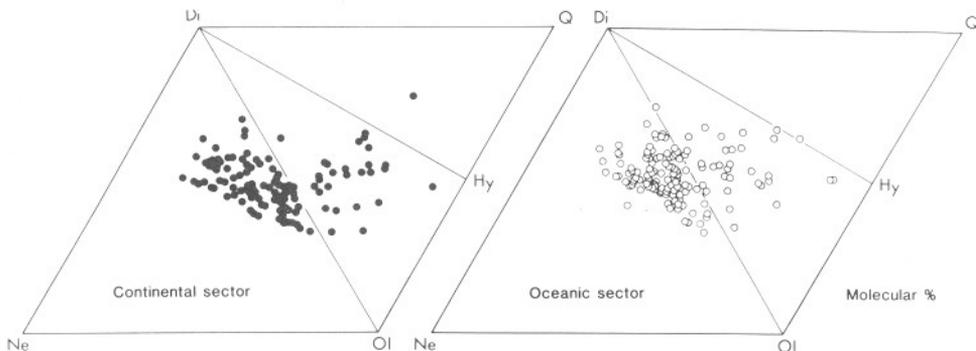


Fig. 3. Normative composition of Cameroon line basic volcanic rocks ($MgO > 4\%$; Etinde nephelinite data excluded). $Fe_2O_3/(FeO + Fe_2O_3)$ normalised to 0.3 for all normative calculations.

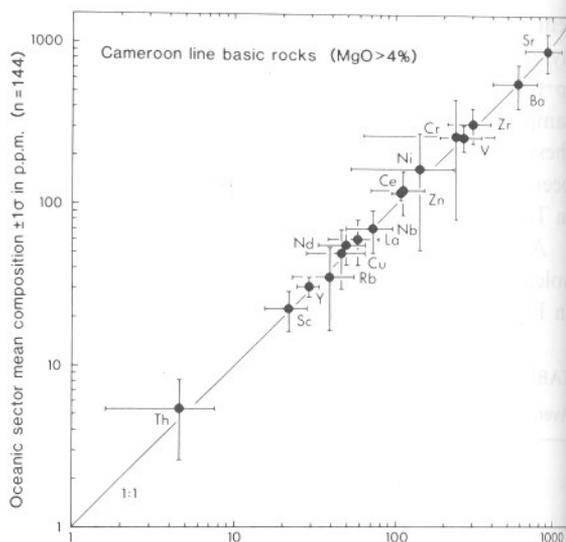


Fig. 4. Comparison of mean trace element concentrations in oceanic and continental Cameroon line basic volcanic rocks. Data from the Etinde nephelinites have been excluded.

with the 293 basic rocks (here defined as those with $MgO > 4\%$); the more evolved rocks will form the subject of a later paper. $^{87}Sr/^{86}Sr$ ratios were measured on 111 of the basic rocks used in this study. These were supplemented by 8 additional $^{87}Sr/^{86}Sr$ determinations on rocks from Manengouba carried out by C.A. Hirst at S.U.R.R.C.

Mean compositions of the basic rocks are given in Table 3. The nephelinites from Etinde are so unlike everything else from the Cameroon line that

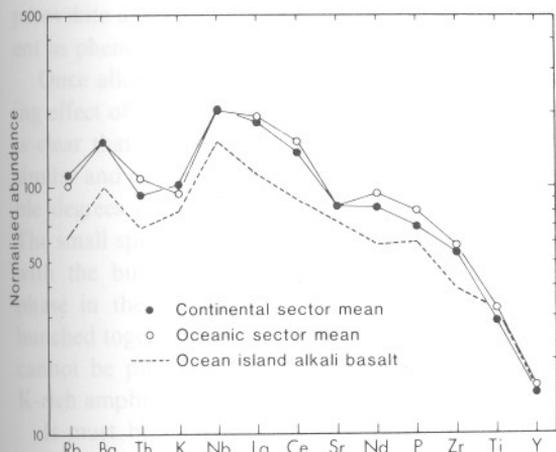


Fig. 5. Normalised abundance patterns for incompatible element concentrations in average oceanic and continental Cameroon line basic rocks ($\text{MgO} > 4\%$; Etinde nephelinite data excluded). Normalising values and average ocean island alkali basalt pattern (shown for comparison) are taken from Sun [30].

they are not included in the means but will be considered separately. Copies of the individual analyses used in this study may be obtained from the first author.

The normative composition of the basic rocks (excluding the Etinde samples) is illustrated in Fig. 3. Rocks from both the continental and the oceanic sector of the Cameroon line show the same range from strongly nepheline-normative to quartz-normative and, in terms of their major element composition, are indistinguishable from one another (see Table 3). The same is true for trace elements. Mean compositions of oceanic and continental basic rocks (again excluding the Etinde samples) are compared in Figs. 4 and 5. In Fig. 5, the incompatible element concentrations are normalised to chondrite abundances [30] and compared with Sun's [30] average ocean island alkali basalt. The oceanic and continental sector basic rocks and the average ocean island alkali basalt all show remarkably similar patterns.

The compositional similarity between oceanic and continental alkali basalts in the Cameroon line is also reflected in their isotope ratios. This will be illustrated here using only Sr isotopes although the few Nd and Pb isotope data available [31] show the same pattern. All the Sr-isotope data

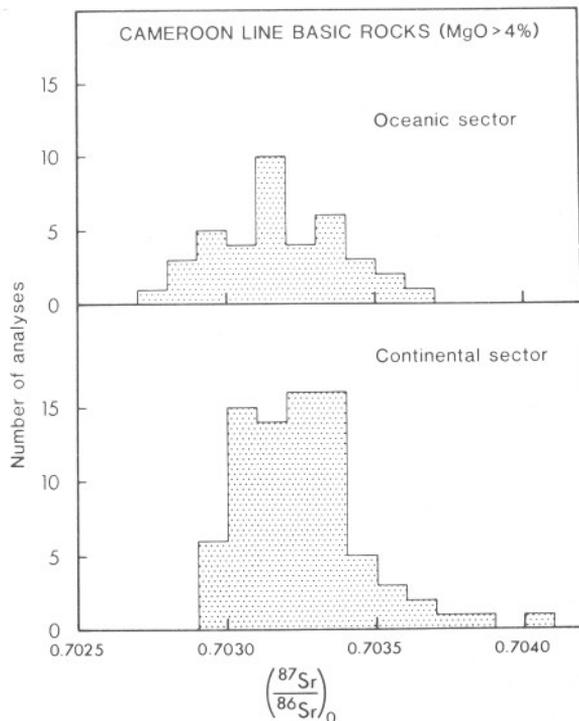


Fig. 6. Distribution of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in oceanic and continental Cameroon line basic volcanic rocks.

obtained in this study are plotted as histograms in Fig. 6. In this plot, the Etinde data have been included with the continental sector data. The bulk of the data from both sectors fall in the range 0.7030 to 0.7035. The few high values in rocks from the continental sector are almost certainly the result of small amounts of crustal contamination. The sample with $^{87}\text{Sr}/^{86}\text{Sr} > 0.7040$ (C74 from Bambouto) contains partly digested granulite xenoliths and has been excluded from the mean compositions given in Table 3.

The oceanic and continental basic rocks are indistinguishable even in the fine detail of their Sr-isotope variation. Several authors [32–34] have noted that $^{87}\text{Sr}/^{86}\text{Sr}$ in volcanic rocks from the Hawaiian chain varies inversely with degree of silica-undersaturation. Strongly alkaline basalts erupted after a period of quiescence often have lower $^{87}\text{Sr}/^{86}\text{Sr}$ than do the underlying tholeiitic rocks. A similar relationship is seen in the volcanic rocks of Principe [17]. Fig. 7 shows a crude correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and degree of silica

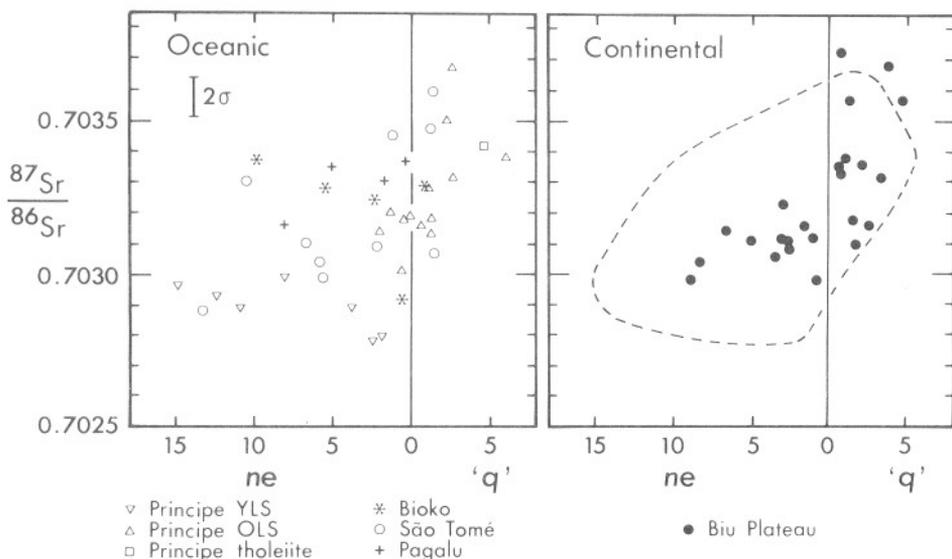


Fig. 7. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ plotted against degree of silica saturation for Cameroon line basic volcanic rocks. *ne* is wt.% normative nepheline; "*q*" is wt.% SiO_2 equivalent to normative hypersthene. Biu Plateau data have been used to represent the continental sector since basalts from this area frequently contain abundant peridotite xenoliths and cannot, therefore, have interacted with continental crust. The broken line encloses the field of data from the oceanic sector.

saturation in the basic rocks from the oceanic sector of the Cameroon line. A similar correlation in the continental sector rocks could result from crustal contamination and so, to exclude this possibility, the Biu Plateau lavas have been taken as representative. These frequently contain peridotite xenoliths (even in hypersthene-normative lavas) and so cannot have suffered significant amounts of crustal contamination. The clear correlation shown by these samples emphasises the striking similarity between oceanic and continental alkali basalts in the Cameroon line. This confirms the conclusion reached by Allègre et al. [35] that oceanic and continental alkali basalts have isotopically similar sources.

The data set used in this study has also been divided on a normative basis (Table 3) and the results plotted in Fig. 8. From this diagram it is apparent that the nepheline-normative rocks are more enriched in incompatible elements than are those with hypersthene in the norm. The Etinde nephelinites are more enriched still although these rocks are generally more evolved than the alkali basalts as can be seen from their lower concentra-

tions of MgO, Ni and Cr (Table 3). The relatively low concentrations of P and Ti in the Etinde rock (Fig. 8) is consistent with fractionation of apatite

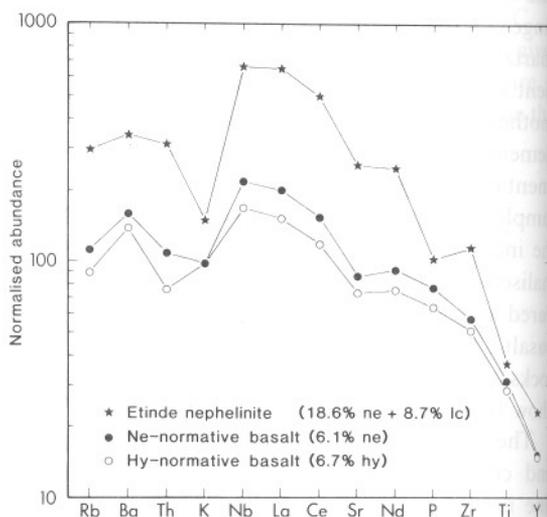


Fig. 8. Normalised abundance patterns for incompatible element concentrations in average basic ($\text{MgO} > 4\%$) Cameroon line volcanic rocks.

perovskite and Ti-magnetite, all of which are present as phenocrysts.

Once allowance has been made for the distorting effect of fractionation on the Etinde samples it is clear that the three patterns in Fig. 8 are very similar and could easily be accounted for by variable degrees of melting of a *single mantle source*. The small spread of K concentrations is consistent with the buffering of this element by a K-rich phase in the mantle. Since Rb and Ba are not bunched together in the same way as K, this phase cannot be phlogopite but is more likely to be a K-rich amphibole.

It must be concluded that variable degrees of melting of a common mantle source can account for the geochemical features of all the Cameroon line basic magmas. The same source must be present beneath both the oceanic and continental sectors.

5. Nature of the mantle source

Since the sub-oceanic and sub-continental mantle sources for the Cameroon line basic magmas are identical, significant involvement of lithosphere mantle can be ruled out. The lithosphere mantle beneath the oceanic sector is less than 120 Ma old and almost certainly depleted in LILE. In contrast the sub-continental lithosphere mantle has had a long and complex history and may well be enriched in LILE. Furthermore it is possible to account for the whole compositional range of the basic rocks, from hypersthene-normative to very undersaturated, by variable melting of a common mantle source.

The Cameroon line has been almost continuously active for the past 65Ma and shows no consistent migration of volcanism with time. It is not very likely, therefore, that the magma source is a *deep* mantle plume originating below the 670-km discontinuity. If it is, it would require a remarkable coincidence for lower mantle convective motion to have kept pace exactly, in velocity and direction, with the movement of the African plate over the past 65 Ma. Clearly, the mantle source must be coupled to the lithosphere. The only plausible source for the Cameroon line magmas,

therefore, is the convecting upper mantle.

This poses a problem since the convecting upper mantle must also be the source of MORB. Convection will ensure that the upper mantle is well stirred and therefore homogeneous on the scale of individual convection cells. Homogeneity on a scale of 1000 km or more is implied by the geochemical similarity between alkali basalts erupted in the oceanic and continental sectors of the Cameroon line. On the other hand, small-scale heterogeneity may persist for long periods in a convecting mantle [36]. In the next section we will explore the possibility of deriving both MORB and alkali basalt from a grossly homogeneous mantle with small-scale heterogeneity. The need to generate both from a common mantle source follows inevitably from the conclusion that the Cameroon line magmas originate within the convecting upper mantle.

6. Derivation of alkali basalt from the MORB source

6.1. Incompatible-element modelling

For the purposes of modelling the generation of the Cameroon line magmas from a MORB source we have taken a mean composition of the most basic basalts ($\text{MgO} > 10\%$) as a close approximation to the primary melt. The justification for this is shown in Fig. 9 which shows chondrite-normalised incompatible-element abundance patterns for average Cameroon line rocks with various MgO contents. As expected, the overall level of abundance falls with increasing MgO content but the pattern remains the same. Adding a few percent of olivine to the least fractionated composition would reduce the abundances further but would not disturb the relative concentrations. This would not significantly affect the outcome of attempts to model the incompatible-element abundance patterns.

The model parameters used are given in Table 4 and illustrated in Fig. 10. The composition of the MORB source was calculated by assuming that Sun's [30] average N-type MORB was generated by 15% equilibrium partial melting of the mantle,

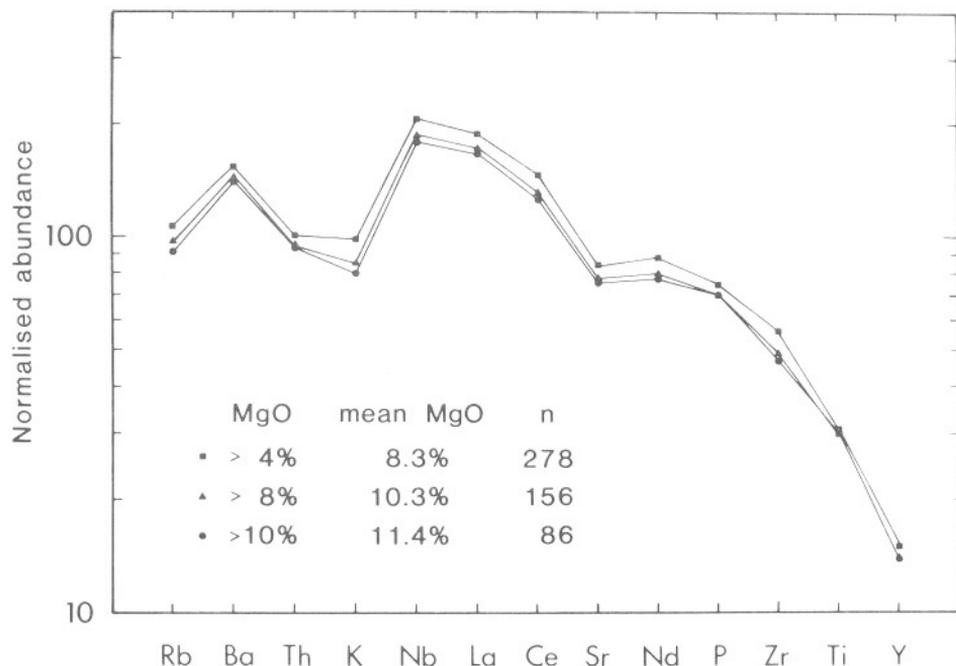


Fig. 9. Normalised abundance patterns for average Cameroon line basic volcanic rocks of various MgO content.

leaving a residue composed of 70% olivine, 23% orthopyroxene and 7% clinopyroxene. Partition coefficients (D) were taken from Frey et al. [7]

(their set 1 coefficients were used for rare earth elements) although the choice of coefficients is not critical at large degrees of partial melting. This was

TABLE 4

Bulk distribution coefficients (D) required to produce the most basic Cameroon line magmas from a MORB source at various degrees of melting (F)

	MORB ^a (ppm)	MORB source ^b (ppm)	Cameroon line (> 10% MgO) (ppm)	D ($F = 0$)	D ($F = 0.002$)	D ($F = 0.003$)
Rb	1.0	0.15	31.7	0.0047	0.0027	0.0017
Ba	12	1.8	531	0.0034	0.0014	0.0004
K	1060	159	9444	0.017	0.015	0.014
Nb	3.1	0.48	62.7	0.0077	0.0057	0.0047
La	3.0	0.47	51.9	0.0091	0.0071	0.0061
Ce	9.0	1.4	101.8	0.014	0.012	0.011
Sr	124	19.4	830	0.023	0.021	0.020
Nd	7.7	1.2	43.6	0.026	0.024	0.023
P	600	95	3234	0.029	0.027	0.026
Zr	85	13.5	263	0.051	0.049	0.048
Ti	9300	1632	18,600	0.088	0.086	0.085
Y	29	5.1	27.7	0.184	0.183	0.182

^a From Sun [30].

^b Calculated by assuming that MORB is produced by 15% melting leaving a residue of 70% olivine, 23% orthopyroxene and 7% clinopyroxene.

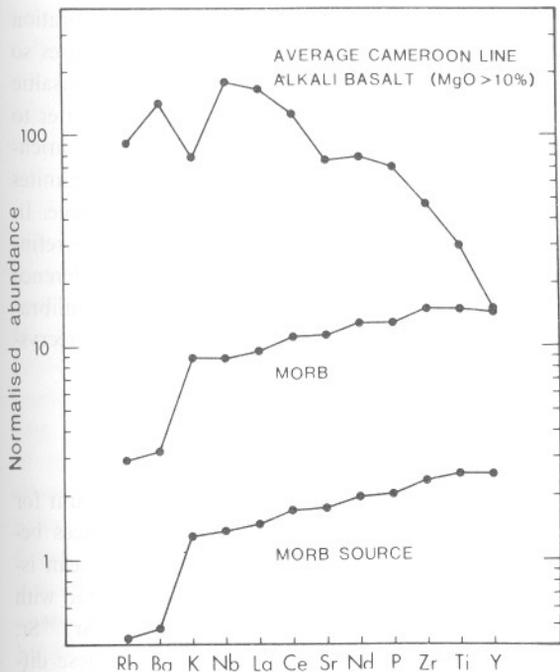


Fig. 10. Comparison of incompatible element concentrations in the most basic Cameroon line lavas, MORB [30] and a calculated MORB source.

omitted from the calculations because it could not be determined with very high precision in the Cameroon line samples.

At the very low degrees of melting required to generate alkali basalt from a MORB source, the values of D used in calculations become critical. It is possible to generate a very wide range of compositions simply by varying the bulk D values over a factor of 2 or so. Since most partition coefficients are not known to better than an order of magnitude it would be pointless trying to model our alkali basalt composition using published D values. Instead we have *assumed* a low-degree partial melting model and calculated the required bulk D values using the equation:

$$C_L/C_0 = 1/(D + F - DF)$$

where C_L and C_0 are concentrations in the partial melt and source respectively, D is the bulk partition coefficient and F the degree of melting. The resulting D values, calculated for a range of F , are given in Table 4. Values of $F > 0.0034$ (= 0.34% melting) would result in negative values of D for

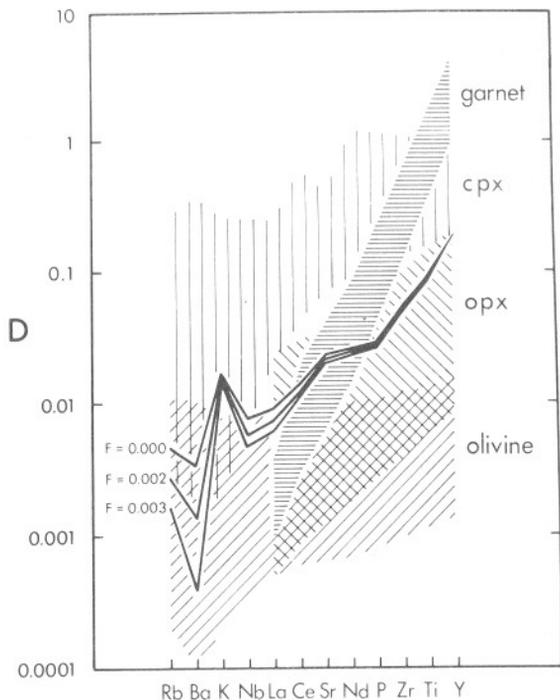


Fig. 11. Calculated bulk distribution coefficients (D) required to generate the most basic Cameroon line magmas from a MORB source for a range of degrees of partial melting (F). The range of published D values (summarised in [7] and [37]) for mantle phases is shown for comparison.

Ba. The permitted range of D values is quite consistent with the range of measured values [7,37] for likely mantle phases (Fig. 11). A striking feature of this diagram is the relatively high values of D for K which implies the presence of a K-rich phase in the mantle. It was noted above that the presence of a K-rich (but not Rb- and Ba-rich) mantle phase is implied by the data in Fig. 8.

The D values shown in Fig. 11 are clearly appropriate for a garnet-lherzolite mantle source containing a small amount of a K-rich phase such as a potassic amphibole. The least fractionated Cameroon line magmas could, therefore, be generated by small degree (< 0.34%) partial melting of such a source provided that the melts can be extracted. Larger degree melting of the same source could produce liquids of MORB composition. Degree of melting cannot, of course, account for the isotopic differences between MORB and alkali

basalts. These will be considered later.

Watson [38] has shown, from surface-energy considerations and experiment, that a body of magma in equilibrium with its surroundings will tend to infiltrate the dry grain boundaries of its host at a relatively rapid rate of 1–2 mm per day. Similar rates of melt migration along grain boundaries have been predicted by Turcotte and Ahern [39] on the basis of buoyancy. McKenzie [40] has derived a set of equations describing the behaviour of partially melted rock. He concludes that melt migration will be sufficiently rapid to restrict the amount of melt present in the mantle to less than 3% even for large degrees of melting. Magma is therefore more likely to move towards the surface along mantle grain boundaries than in large conduits, provided the mantle is at or close to its solidus temperature. Since the melt moves rapidly in comparison with diffusion rates it will only be able to equilibrate with the outer parts of the mantle phases in contact with it. Elements concentrated at mantle grain boundaries will be selectively incorporated into the melt.

It has long been known that uranium is concentrated at grain boundaries in mantle xenoliths [41]. More recently it has become apparent that Rb and Sr [42] and light rare earth elements (LREE) [43] are likewise concentrated. Fluid inclusions in mantle xenoliths are also strongly enriched in alkali elements [44] and LREE [45] relative to their host silicates. It is concluded that a major part of the LILE content of mantle xenoliths is present as grain surface films and fluid inclusions. These xenoliths are derived from the relatively cool lithosphere mantle but it seems likely that similarly enriched grain boundary films will be present in the deeper convecting mantle. Magmas rising to the surface along grain boundaries will effectively leach these films and therefore become strongly LILE-enriched.

Consider a magma produced by say 10% partial melting of a depleted mantle source and allowed to percolate through 100 times the volume of mantle from which it was originally derived. If such a magma leaches half the LILE content out of the mantle through which it passes it will assume the trace element characteristics of a liquid derived by 0.2% equilibrium partial melting. Its

major elements will be buffered by equilibration with the surfaces of the silicate mantle phases so that it will still arrive at the surface as a basaltic liquid. There is therefore no theoretical barrier to producing the very large degrees of LILE enrichment seen in alkali basalts and even nephelinites and melilitites from a depleted mantle source. In this respect the model is analogous to zone-refining [6] and wall-rock reaction [46]. The difference is that these processes require complete equilibration with the mantle through melting and recrystallisation rather than surface equilibration.

6.2. Isotopic considerations

To be viable, this model must also account for the small but consistent isotopic differences between MORB and LILE-enriched (e.g. ocean island and continental rift) basalts. Compared with MORB, these basalts have higher $^{87}\text{Sr}/^{86}\text{Sr}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$. These differences require that the respective sources have remained separate for 1–2 Ga [47,48]. At the

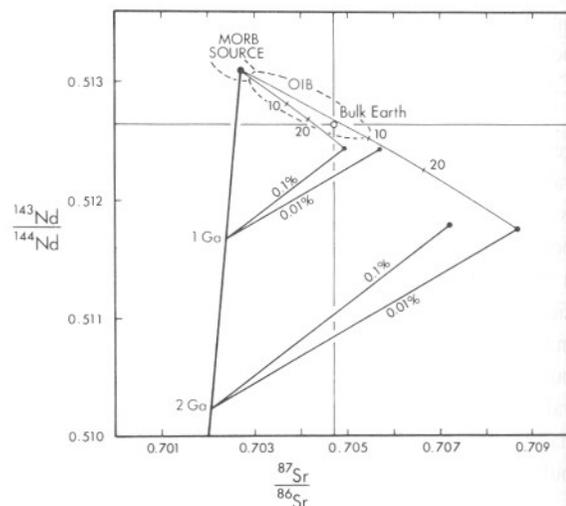


Fig. 12. Sr-Nd isotopic evolution of a MORB source ($\text{Rb}/\text{Sr} = 0.008$, $\text{Sm}/\text{Nd} = 0.365$) and partial melts (0.01 and 0.1%) derived from it 1 and 2 Ga ago. Solid circles represent present-day isotopic ratios. Present-day mixing lines (curved) between the ancient enriched melts and MORB-like magma are shown. Numbers on these curves represent % enriched material in the mixture. Fields of typical MORB and ocean island basalt (OIB) are shown for comparison.

temperatures expected in the source regions, it is unlikely that grain boundary films would remain isotopically distinct from the bulk mantle for such long periods [49]. We must, therefore, appeal to larger-scale heterogeneity to account for the isotopic differences.

In the course of within-plate magmatic episodes (e.g. the growth of an ocean island) by no means all of the magma generated in the mantle will reach the surface. A proportion of it will remain in the asthenosphere after the cessation of volcanic activity. Within-plate volcanism is unlikely to be a recent phenomenon but has probably been occurring, at least at the present rate, throughout most of the earth's history. The convecting mantle should, therefore, contain numerous patches enriched in basaltic components (including LILE). Convection will transform these patches into streaks [36] which may remain large enough to escape rehomogenisation by diffusion. These LILE-enriched streaks will have higher Rb/Sr, U/Pb and Nd/Sm ratios than the bulk mantle and will, therefore, evolve over geological time to higher $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ ratios.

In this model, the 1–2 Ga age for the separation of mantle reservoirs [47,48] represents the average age of the streaks. The isotopic evolution of the streaks is illustrated in Fig. 12. In this diagram, small-degree partial melts are generated from a MORB source 1 and 2 Ga ago and allowed to age to the present day. The D values used are those calculated for the generation of the Cameroon line magmas by 0.2% partial melting (Table 4). D_{Sm} has been estimated from D_{Nd} and the partition coefficient data compiled by Frey et al. [7]. It is clear from Fig. 12 that the “mantle array” defined by oceanic basalts could be explained as a family of mixing lines between the MORB source (= bulk mantle) and melts from enriched streaks. The enrichment in basaltic components will mean that these streaks will have lower solidus temperatures than the surrounding mantle and will therefore contribute a greater proportion of melt during a low-degree partial melting event.

The factors most important in determining the character of the magma arriving at the surface are

depth and degree of initial melting, and rate of magma ascent. Extensive, near-surface melting of depleted mantle at mid-ocean ridges will produce tholeiitic magma (MORB) whose isotope and trace-element ratios are very close to those in the bulk mantle. More restricted melting of the same mantle at depth will produce tholeiitic to alkaline magma which will percolate and leach the overlying mantle and result in magmas of ocean island basalt (OIB) composition in oceanic or continental environments. Magma types transitional between MORB and OIB can be produced where a site of deep melting (hot spot) is located beneath a mid-ocean ridge as in Iceland [2]. The complete restriction of MORB to ridges is easily explained by this model since ridges are the only places on earth where depleted, mobile mantle is melted at sufficiently shallow depths to prevent significant leaching of the overlying mantle. The continental analogue of MORB is flood tholeiite which may also be produced by extensive shallow melting. In this case, though, the source is probably old lithosphere mantle which may have undergone a long history of enrichment. This source enrichment is reflected in the isotope geochemistry of continental flood tholeiites [50].

The rate at which magma percolates upwards will affect this isotopic composition. Rapid ascent will preserve the “age” of the enriched streaks and may account for the 1.5-Ga “isochron” [47] obtained from ocean island tholeiites. On the other hand slow ascent will result in partial isotopic equilibration with the bulk mantle and may produce “mantle isochrons” with lower ages. In extreme cases, where a magma batch is for some reason halted in its ascent for a few million years, isotopic equilibration may be almost complete and produce alkali basalts with isotope ratios close to those in MORB. This may account for the low $^{87}\text{Sr}/^{86}\text{Sr}$ measured in highly undersaturated lavas erupted on some ocean islands following a period of quiescence. Examples of this are found on Oahu [33], Maui [34] and Principe [17]. Chen and Frey [34] have explained the Maui data by mixing small-degree melts derived from a depleted (MORB) mantle source with larger-degree melts from an undepleted mantle. This explanation is compatible with the model presented here.

Alkali basalts are likely to be produced by smaller degree and/or deeper initial melting than are tholeiites [7]. Since both degree of melting and the volume of mantle through which a magma can percolate will affect LILE enrichment, it follows that LILE enrichment should correlate with degree of undersaturation. Such a correlation is shown by the Cameroon line data (Fig. 8). Magmas produced by small degrees of initial melting will tend to rise to the surface more slowly, and therefore approach isotopic equilibration with the mantle more closely, than will those produced by larger degree initial melting. We would therefore expect that the more undersaturated magmas will tend to have lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than will less undersaturated or saturated types. This explains the crude correlation between Sr-isotope ratios and degree of silica saturation shown by the Cameroon line (Fig. 7) and Hawaiian data.

Support for our model is provided by Sr-isotope data from MORB. Batiza [51] has recently demonstrated that the diversity in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of MORB samples varies inversely with the spreading rate and hence the rate of magma production. He interprets this observation to imply a "plum pudding" mantle which is homogenised more efficiently at high rates of magma production. The greatest diversity in $^{87}\text{Sr}/^{86}\text{Sr}$ is shown by basalts from ocean islands where magma production rates are low in comparison with mid-ocean ridges. The model is also consistent with Gill's [52] observation that the isotope geochemistry of lavas from Fiji require the presence of both MORB and OIB sources in the mantle above the subduction zone.

7. Conclusions

(1) K-Ar dating of volcanic rocks from the Cameroon line show no consistent migration of volcanism with time and so the line is not a hot-spot trail. The longevity of activity (65 Ma) rules out a deep mantle source for the magma.

(2) Basalts erupted in the oceanic and continental sectors of the line are chemically and isotopically indistinguishable. The magmas must, therefore, have originated in the convecting upper man-

tle and cannot have interacted to any significant extent with the lithosphere mantle.

(3) Since the convecting upper mantle is also the source for MORB, a grossly homogeneous upper mantle with small-scale heterogeneity is implied.

(4) Partition coefficients (D) needed to derive the Cameroon line alkali basalts from a MORB source are consistent with published values for mantle phases. The small-degree ($< 0.34\%$) melting implied can be achieved by a leaching process in which MORB-like percolating along grain boundaries incorporates LILE-enriched grain boundary films.

(5) Isotopic differences between MORB and alkali basalts (and ocean island tholeiites) can be explained by the incorporation of melts from old, LILE-enriched streaks in the mantle. These streaks are the remnants of ancient enriched magmas left behind in the convecting upper mantle.

Acknowledgements

Fieldwork in West Africa and isotope facilities at S.U.R.R.C. were supported by research grants from the U.K. Natural Environment Research Council. The isotopic work was carried out during the tenure of a NERC research studentship (H.M.D.).

We are grateful to Mrs D.E. James and Mr G.R. Angell for assistance with the chemical analyses and to Dr R.M. MacIntyre, Mr T. McMenamin and Mr J. Hutchinson for help with the K-Ar and Sr-isotope work. We also thank Miss C.A. Hirst for permission to use her unpublished Sr-isotope data and Dr J.D.A. Piper for supplying rock samples from Bioko and Pagalu.

Appendix 1—Location of samples used for K-Ar dating

All distances are measured in a straight line.

N2	near base of lava plateau; roadside exposure 24 km south of Biu
N38	northern limit of Biu Plateau on road to Damaturu
C145	Ontemale (plug) north of Mogode

- C146 side of track mid-way between Jiri and Kila
 C147 hillside to south of Kila
 C85 Sabga Pass, 16 km ENE of Bamenda
 C91 roadside 6 km SW of Kumbo
 C95 roadside at Mbingo, 28 km NNE of Bamenda
 C100 Ashong, 28 km SW of Bamenda
 C107 by track to Santa coffee factory, 2 km E of Santa
 C108 roadside quarry, 3 km NE of Dschang
 C111 2.5 km SW of peak (Lekwé Leloé) on south slopes of Bambouto
 C52 Njinjo, 11 km NNE of Manengouba summit
 C55 roadside by railway crossing at Ndoungué, 6 km SW of Nkongsamba
 C57 in stream 1 km SE of Manengouba village
 C54 roadside ca. 4 km N of Bangem
 C36 loose block in river at Batoke
 ST43 northeast slope of São José, Monte Café plantation
 ST44 quarry at Palmar
 ST57 northeast peak of Ilhéu das Cabras
 ST60 coastal exposure near Água Izé
 ST84 south side of Mizambu (plug)
 ST90 northeast side of Maria Fernandez (plug)
 ST96 dyke on coast southwest of Ribeira Peixe, south coast of São Tomé

References

- J.-G. Schilling, Rare-earth variations across "normal segments" of the Reykjanes Ridge, 60°–53°N, Mid-Atlantic Ridge, 29°S, and East Pacific Rise, 2°–19°S, and evidence on the composition of the underlying low-velocity layer. *J. Geophys. Res.* 80, 1459–1473, 1975.
- J.-G. Schilling, Iceland mantle plume: geochemical evidence along Reykjanes Ridge, *Nature* 242, 565–571, 1973.
- C.J. Allègre, Chemical geodynamics, *Tectonophysics* 81, 109–132, 1982.
- A.W. Hofmann and W.M. White, Mantle plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.* 57, 421–436, 1982.
- D. McKenzie and R.K. O'Nions, Mantle reservoirs and ocean island basalts, *Nature* 301, 229–231, 1983.
- P.G. Harris, Zone refining and the origin of potassic basalts, *Geochim. Cosmochim. Acta* 12, 195–208, 1957.
- F.A. Frey, D.H. Green and S.D. Roy, Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from south-eastern Australia utilising geochemical and experimental petrological data, *J. Petrol.* 19, 463–513, 1978.
- M.A. Menzies and V.R. Murthy, Nd and Sr isotope geochemistry of hydrous mantle nodules and their host alkali basalts: implications for local heterogeneities in metasomatically veined mantle, *Earth Planet. Sci. Lett.* 46, 323–334, 1980.
- D.K. Bailey, Mantle metasomatism—continuing chemical change within the Earth, *Nature* 296, 525–530, 1982.
- B. Harte, Mantle peridotites and processes—the kimberlite sample, in: *Continental Basalts and Mantle Xenoliths*, C.J. Hawkesworth and M.J. Norry, eds., pp. 46–91, Shiva, 1983.
- M.A. Menzies, Mantle ultramafic xenoliths in alkaline magmas: evidence for mantle heterogeneity modified by magmatic activity, in: *Continental Basalts and Mantle Xenoliths*, C.J. Hawkesworth and M.J. Norry, eds., pp. 92–110, Shiva, 1983.
- J.D.A. Piper and A. Richardson, The palaeomagnetism of the Gulf of Guinea volcanic province, West Africa, *Geophys. J. R. Astron. Soc.* 29, 147–171, 1972.
- K. Norrish and J.T. Hutton, An accurate X-ray spectrographic method for the analysis of a wide range of geological samples, *Geochim. Cosmochim. Acta* 33, 431–453, 1969.
- R. Theissen and D. Vollach, *Tables of X-ray Mass Absorption Coefficients*, Verlag Stahleisen M.B.H., Dusseldorf, 1967.
- S. Abbey, Studies in "standard samples" of silicate rocks and minerals, *Geol. Surv. Can. Pap.* 83-15, 1983.
- H.M. Dunlop, Strontium isotope geochemistry and potassium-argon studies on volcanic rocks from the Cameroon line, West Africa, unpublished Ph.D. Thesis, University of Edinburgh, 1983.
- H.M. Dunlop and J.G. Fitton, A K-Ar and Sr-isotopic study of the volcanic island of Principe, West Africa—evidence for mantle heterogeneity beneath the Gulf of Guinea, *Contrib. Mineral. Petrol.* 71, 125–131, 1979.
- N.K. Grant, D.C. Rex and S.J. Freeth, Potassium-argon ages and strontium isotope ratio measurements from volcanic rocks in northeastern Nigeria, *Contrib. Mineral. Petrol.* 35, 277–292, 1972.
- P.M. Vincent and R.L. Armstrong, Le volcanisme du plateau Kapsiki (Nord Cameroun) et les formations sédimentaires sous-jacentes (abstract), 7th Colloq. African Geology, Florence, 1973.
- J. Gouhier, J. Nougier and D. Nougier, Contribution à l'étude volcanologique du Cameroun ("Ligne du Cameroun"—Adamaoua), *Ann. Fac. Sci. Cameroun* 17, 3–48, 1974.
- J.D. Hedberg, A geological analysis of the Cameroun trend, unpublished Ph.D. Thesis, University of Princeton, Princeton, N.J., 1968.
- H.R. Grunau, P. Lehner, M.R. Cleintuar, P. Allenbach and G. Bakker, New radiometric ages and seismic data from Fuerteventura (Canary Islands), Maio (Cape Verde Islands) and São Tomé (Gulf of Guinea), in: *Progress in Geodynamics*, G.J. Borradaile et al., eds., pp. 90–118, North-Holland, Amsterdam, 1975.
- G. Cornen and R.C. Maury, Petrology of the volcanic island of Annobon, Gulf of Guinea, *Mar. Geol.* 36, 253–267, 1980.
- J.G. Fitton, C.R.J. Kilburn, M.F. Thirlwall and D.J. Hughes, 1982 eruption of Mt. Cameroon, West Africa, *Nature* 306, 327–332, 1983.
- J.-M. Cantagrel, C. Jamond and M. Lasserre, Le magmatisme alcalin de la ligne du Cameroun au Tertiaire inférieur: données géochronologiques K-Ar, *C.R. Somm. Soc. Géol. Fr.* 6, 300–303, 1978.

- 26 M. Lasserre, Mise au point sur les granitoïdes dits "ultimes" du Cameroun: gisement, pétrographie et géochronologie, *Bull. B.R.G.M.*, 2e Sér. Sect. IV, 143–159, 1978.
- 27 H. Jacquemin, S.M.F. Sheppard and P. Vidal, Isotopic geochemistry (O, Sr, Pb) of the Golda Zuelva and Mboutou anorogenic complexes, North Cameroun: mantle origin with evidence for crustal contamination, *Earth Planet. Sci. Lett.* 61, 97–111, 1982.
- 28 J.G. Fitton, The Benue trough and Cameroon line—a migrating rift system in West Africa, *Earth Planet. Sci. Lett.* 51, 132–138, 1980.
- 29 J.G. Fitton, Active versus passive continental rifting: evidence from the West African rift system, *Tectonophysics* 94, 473–481, 1983.
- 30 S.-S. Sun, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs, *Philos. Trans. R. Soc. London, Ser. A* 297, 409–445, 1980.
- 31 A.N. Halliday, A.P. Dickin and J.G. Fitton, A Nd, Sr and Pb isotopic study of the Cameroon line volcanics and a comparison of the chemical structure of sub-continental and sub-oceanic mantle, in preparation.
- 32 M.A. Lanphere and G.B. Dalrymple, Age and strontium isotopic composition of the Honolulu volcanic series, Oahu, Hawaii, *Am. J. Sci.* 280A, 736–751, 1980.
- 33 P. Stille, D.M. Unruh and M. Tatsumoto, Pb, Sr, Nd and Hf isotopic evidence of multiple sources for Oahu, Hawaii basalts, *Nature* 304, 25–29, 1983.
- 34 C.-Y. Chen and F.A. Frey, Origin of Hawaiian tholeiite and alkalic basalt, *Nature* 302, 785–789, 1983.
- 35 C.J. Allègre, B. Dupré, B. Lambret and P. Richard, The sub-continental versus sub-oceanic debate, I. Lead-neodymium-strontium isotopes in primary alkali basalts from a shield area: Ahaggar volcanic suite, *Earth Planet. Sci. Lett.* 52, 85–92, 1981.
- 36 P. Olsen, D.A. Yuen and D. Balsiger, Mixing of passive heterogeneities by mantle convection, *J. Geophys. Res.* 89, 425–436, 1984.
- 37 P. Henderson, *Inorganic Geochemistry*, Pergamon, Oxford, 1982.
- 38 E.B. Watson, Melt infiltration and magma evolution, *Geology* 10, 236–240, 1982.
- 39 D.L. Turcotte and J.L. Ahern, A porous flow model for magma migration in the asthenosphere, *J. Geophys. Res.* 83, 767–772, 1978.
- 40 D. McKenzie, The generation and compaction of partially molten rock, *J. Petrol.* 25, 713–765, 1984.
- 41 J.D. Kleeman, D.H. Green and J.F. Lovering, Uranium distribution in ultramafic inclusions from Victoria basalts, *Earth Planet. Sci. Lett.* 5, 449–458, 1969.
- 42 A.R. Basu and V.R. Murthy, Ancient lithospheric lherzolite xenoliths in alkali basalt from Baja California, *Earth Planet. Sci. Lett.* 34, 246–253, 1977.
- 43 H.-G. Stosch and H.A. Seck, Geochemistry and mineralogy of two spinel peridotite suites from Dreiser Weiher, West Germany, *Geochim. Cosmochim. Acta* 44, 457–470, 1980.
- 44 A. Zindler and E. Jagoutz, Isotope and trace element systematics in mantle-derived peridotite nodules from San Carlos, *EOS* 61, 374, 1980.
- 45 H.-G. Stosch, Rare earth element partitioning between minerals from anhydrous spinel peridotite xenoliths, *Geochim. Cosmochim. Acta* 46, 793–811, 1982.
- 46 D.H. Green and A.E. Ringwood, The genesis of basalt magmas, *Contrib. Mineral. Petrol.* 15, 103–190, 1967.
- 47 C. Brooks, S.R. Hart, A.W. Hofmann and D.E. James, Rb-Sr mantle isochrons from oceanic regions, *Earth Planet. Sci. Lett.* 32, 51–61, 1976.
- 48 M. Tatsumoto, Isotopic composition of lead in oceanic basalts and its implication to mantle evolution, *Earth Planet. Sci. Lett.* 38, 63–87, 1978.
- 49 A.W. Hofmann and S.R. Hart, An assessment of local and regional isotopic equilibrium in the mantle, *Earth Planet. Sci. Lett.* 38, 44–62, 1978.
- 50 M.A. Menzies, W.P. Leeman and C.J. Hawkesworth, Isotope geochemistry of Cenozoic volcanic rocks reveals mantle heterogeneity below western U.S.A., *Nature* 303, 205–209, 1983.
- 51 R. Batiza, Inverse relationship between Sr isotope diversity and rate of oceanic volcanism has implications for mantle heterogeneity, *Nature* 309, 440–441, 1984.
- 52 J.B. Gill, Sr-Pb-Nd isotopic evidence that both MORB and OIB sources contribute to oceanic island arc magmas in Fiji, *Earth Planet. Sci. Lett.* 68, 443–458, 1984.