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C. COULON[1*], P. VIDAL[2], C. DUPUY[3], P. BAUDIN[1], M. POPOFF[4], H. MALUSKI[5] AND D. HERMITTE[1]
[1]PÉTROLOGIE MAGMATIQUE, URA 1277, CEREGE, BP 80, 13545 AIX EN PROVENCE CEDEX 4, FRANCE
[2]CENTRE DE RECHERCHES VOLCANOLOGIQUES, URA 10, 63038 CLERMONT FERRAND CEDEX, FRANCE
[3]CENTRE GÉOLOGIQUE ET GÉOPHYSIQUE, CNRS, PLACE BATAILLON, 34095 MONTPELLIER CEDEX, FRANCE
[4]INSTITUT DE GÉODYNAMIQUE, URA 1279, UNIVERSITÉ DE NICE—SOPHIA ANTIPOLIS, AVENUE EINSTEIN, 06560 VALBONNE, FRANCE
[5]LABORATOIRE DE GÉOCHRONOLOGIE—GÉOCHIMIE, URA 1763, PLACE BATAILLON, 34095 MONTPELLIER CEDEX, FRANCE

The Mesozoic to Early Cenozoic Magmatism of the Benue Trough (Nigeria); Geochemical Evidence for the Involvement of the St Helena Plume

The Benue Trough is a continental rift related to the opening of the equatorial domain of the South Atlantic which was initiated in Late Jurassic–Early Cretaceous times. Highly diversified and volumetrically restricted Mesozoic to Cenozoic magmatic products are scattered throughout the rift. Three periods of magmatic activity have been recognized on the basis of ^{40}Ar–^{39}Ar *ages: 147–106 Ma, 97–81 Ma and 68–49 Ma. Trace element and Sr, Nd and Pb isotope determinations, performed on selected basaltic samples, allow two groups of basaltic rocks to be identified: (1) a group with a tholeiitic affinity, with* $Zr/Nb = 7–11{\cdot}1$; $La/Nb = 0{\cdot}77–1$; $^{87}Sr/^{86}Sr_i = 0{\cdot}7042–0{\cdot}7065$ $^{143}Nd/^{144}Nd_i = 0{\cdot}5125–0{\cdot}5127$; $^{206}Pb/^{204}Pb_i = 17{\cdot}59–18{\cdot}48$; *(2) a group with an alkaline affinity, with* $Zr/Nb = 3{\cdot}6–6{\cdot}8$; $La/Nb = 0{\cdot}53–0{\cdot}66$; $^{87}Sr/^{86}Sr_i = 0{\cdot}7029–0{\cdot}7037$; $^{143}Nd/^{144}Nd_i = 0{\cdot}5126–0{\cdot}5129$; $^{206}Pb/^{204}Pb_i = 18{\cdot}54–20{\cdot}42$. *The geochemical data lead to the conclusion that three types of mantle sources were involved in the genesis of the Mesozoic to Cenozoic basaltic rocks of the Benue, without significant crustal contamination: (1) an enriched subcontinental lithospheric mantle from which the tholeiitic basalts were derived; (2) a HIMU-type (plume) component from which the alkaline basaltic rocks originated; (3) a depleted asthenospheric mantle (N-MORB-type source), which was involved in the genesis of the alkaline basaltic magmas. According to (1) the postulated location of the St Helena hot spot in the Equatorial Atlantic at about 130 Ma and (2) the isotopic composition of the alkaline basaltic rocks of the Benue Trough and their geochemical similarity with the basalts of St Helena, we conclude that the St Helena plume was involved in the genesis of the alkaline magmatism of the Benue at the time of opening of the Equatorial Atlantic. Moreover, the geochemical similarity between the alkaline magmatism of the Benue Trough and that of the Cameroon Line suggests that both magmatic provinces were related to the St Helena plume. Finally, the temporal change of the mantle sources observed in the Benue Trough can be accounted for by the recent models of plume dynamics, in the general framework of opening of the Equatorial Atlantic.*

KEY WORDS: *Benue Trough; Mesozoic to Cenozoic magmatism; Equatorial Atlantic; mantle sources; St Helena plume*

INTRODUCTION

The Benue Trough (Fig. 1) is a 1000 km long, 50–150 km wide, intraplate NE–SW rift depression, genetically related to the opening of the equatorial domain of the South Atlantic (Popoff, 1990; Fairhead & Binks, 1991). This megastructure, which was initiated in the latest Jurassic–Early Cretaceous times, is filled with continental and marine sediments (up to 6500 m in thickness). Mesozoic to Cenozoic magmatism, volumetrically restricted and scattered throughout the Benue Trough (Fig. 1) accompanied the tectonic evolution of this rift. The petrology, geochemistry (Baudin, 1991), age and geodynamic setting (Maluski *et al.*, 1995) of this magmatism have recently been re-investigated. It has been proposed that the St Helena hot spot was located beneath Western Central Africa at approximately 130 Ma (O'Connor & Duncan, 1990), and it is believed to

*Corresponding author.

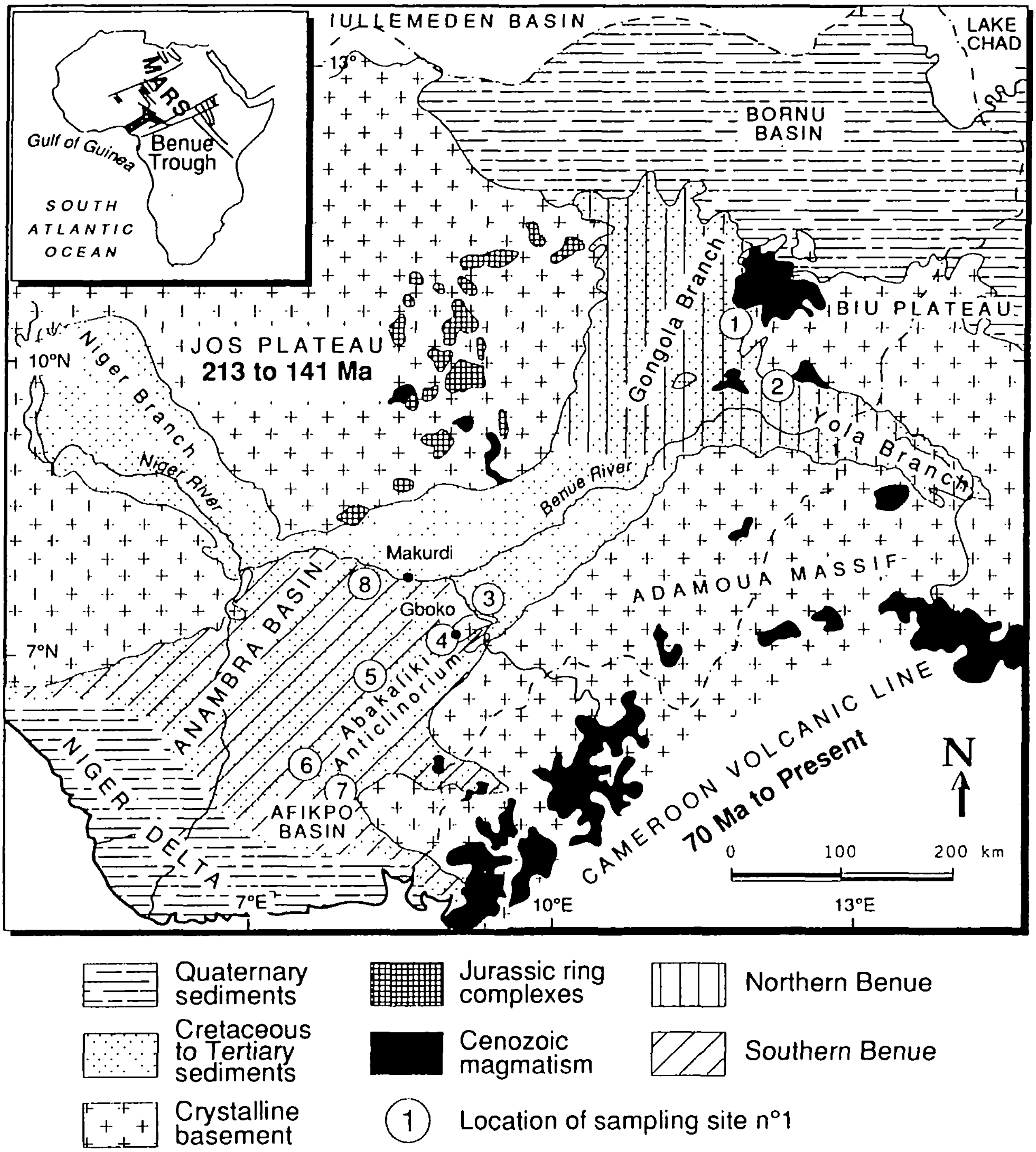

Fig. 1. Geological sketch map of the Benue Trough (after Maluski *et al.*, 1995). 1, Gwol, Shani, Guburunde, Bima Hills and Burashika volcanic areas; 2, Dumne area; 3, Gboko area; 4, Katyo area; 5, Wanakum Hills; 6, Okigwi (Uturu) area; 7, Afikpo area; 8, Makurdi and Oturkpo areas. MARS, Mid African Rift System.

have played a significant role in determining the site of Gondwana break-up (Wilson, 1992). Moreover, it has been proposed (Baudin, 1991; Wilson & Guiraud, 1992) that the magmatism of the Benue Trough might be related to the activity of the St Helena hot spot.

The aim of this paper is to test that hypothesis by using trace element geochemistry and isotopic (Sr, Nd, Pb) compositions of selected Mesozoic to Early Cenozoic basic magmatic rocks of the Benue Trough.

NATURE OF THE MAGMATIC ROCKS, AGE AND TECTONIC SETTING

The composition of magmatic rocks of the Benue Trough is very diverse. In the Northern Benue, basalts (the most abundant lavas) and rhyolites are present as lava flows and dykes. The basaltic flows overlie the Pan-African basement (Dumne and Gwol areas; Fig. 1) or are interbedded in Early Cretaceous syn-rift sediments (Shani, Guburunde and Bima Hills areas). In the Burashika district (Fig. 1), volcanism is bimodal, with basalts overlain by rhyolitic flows; these lavas are spatially associated with a subvolcanic granophyric dome (Kwaba) emplaced in the crystalline basement. Basalts of the Northern Benue can be subdivided into two groups according to petrological and geochemical criteria (Baudin, 1991). Group 1 (G1) basalts (Burashika, Shani, Gwol and Bima Hills) are transitional alkaline; group 2 (G2) basalts (Guburunde, Dumne) display a transitional tholeiitic affinity. The Burashika rhyolites and the Kwaba granophyre are peralkaline.

In the Southern Benue, two main magmatic districts exist. The first one is located in the Early Cretaceous core of the Abakaliki anticlinorium; the second is associated with the Upper Cretaceous Anambra and Afikpo basins (Fig. 1). In the Abakaliki anticlinorium, magmatic rocks occur in five main areas, which are, from NE to SW, Gboko, Katyo, Wanakum Hills, Abakaliki and Okigwi. In the Gboko area, peralkaline rhyolitic dykes cross cut the Pan-African basement. In the Katyo area, peralkaline lavas (phonotephrites, tephriphonolites, phonolites and trachytes) occur as domes and necks intruding the Turonian shales. In the Wanakum Hills, magmatic rocks constitute an alkaline suite including basalts, camptonites, phonolites, and a nepheline syenite. The last of these forms a subvolcanic dome (Wanakande massif) cross-cutting the Albian shales. In the Okigwi area, small subvolcanic alkaline basaltic intrusives are observed in the Albian shales (e.g. the Uturu dolerite). In the Anambra and Afikpo basins, numerous doleritic sills are intrusive into either the Turonian shales and sandstones (Makurdi and Afikpo areas), or the Campanian to Maastrichtian shales (Oturkpo); these rocks are tholeiitic in character (Baudin, 1991).

A detailed study concerning the age of this magmatism has recently been carried out using the ^{40}Ar–^{39}Ar method (Maluski *et al.*, 1995). Three periods of magmatic activity have been identified. The first magmatic period (147–106 Ma; Late Jurassic to Albian) is mainly expressed in the Northern Benue. It corresponds to the eruption of: (1) the alkaline transitional G1 basalts (and the spatially associated peralkaline rhyolites in the Burashika area) and (2) the tholeiitic transitional G2 basalts. However, during this period, magmatism was probably active throughout the Benue Trough: in the Southern Benue, a rhyolitic dome (Gboko area) has been dated at 113 Ma by the Rb–Sr method (Umeji & Caen-Vachette, 1983); in the Abakaliki area, highly altered submarine basaltic pyroclastics are thought to be Upper Albian in age, according to stratigraphy (Ojoh, 1988). This 147–106 Ma magmatism occurred before the onset of sea-floor spreading, when the Equatorial Atlantic was still closed, and it has been interpreted as the forerunner of the opening of this oceanic equatorial domain (Maluski *et al.*, 1995). It is relevant to note that this magmatism is broadly contemporaneous with the eruption, between 137 and 127 Ma, of the voluminous tholeiitic flood basalts of the Parana (Brazil) and Etendeka (Namibia) (Renne *et al.*, 1992; Turner *et al.* 1994). The Late Jurassic to Albian volcanism of the Benue Trough was emplaced during an ENE–WSW extensional regime (Popoff, 1988a, 1990).

The second magmatic period (97–81 Ma; Cenomanian to Santonian) was restricted to the Southern Benue (Gboko, Wanakum Hills, Okigwi); it postdates the break-up of the South American and African continents which started, in this region, at about 105–100 Ma (Mascle *et al.*, 1986; Popoff *et al.*, 1989; Nürnberg & Müller, 1991). Magmatism of this period is represented by alkaline rocks, mainly intrusive, emplaced during a decreasing extensional regime, following the major Late Jurassic–Albian rifting phase. Subsiding sedimentary basins continued to deepen along NNE–SSW rift faults and along ENE–WSW shear zones which represent the extension of the transform fracture zones of the Gulf of Guinea proto-ocean (Popoff, 1988*b*). These strike-slip movements occurred in response to the differential opening between the Central and South Atlantic Ocean (Fairhead & Binks, 1991). At about

80 Ma, magmatism ceased as a result of the Santonian compressional episode (Benkhelil, 1986).

The third magmatic period (68–49 Ma; Late Maastrichtian to Eocene) is also restricted to the Southern Benue. Subvolcanic rocks are predominant. They are first alkaline (Katyo: 68 Ma) and then tholeiitic (Oturkpo: 60 Ma; Afikpo: 55 Ma; Makurdi: 49 Ma). This period corresponds to a subsidence regime interpreted as the isostatic response to the post-rift thermal relaxation of the lithosphere (Binks & Fairhead, 1992).

To summarize, the following main points emerge from the radiometric data: (1) during the Late Jurassic to Albian period (147–106 Ma), magmatism probably occurred in the whole Benue Trough. It is particularly expressed in the northern extremity of the trough, where it is represented by alkaline transitional basalts and associated peralkaline rhyolites (bimodal volcanism), and by tholeiitic transitional basalts; (2) after the emplacement of the 106 Ma basalts of the Northern Benue, magmatism was concentrated only in the southern part of the trough; (3) between 97 and 81 Ma, magmatism was exclusively alkaline and predominantly intrusive; (4) during the period 68–49 Ma, the first magmatic products were alkaline and the last ones, tholeiitic; (5) when considered on a large scale, the Mesozoic to Early Cenozoic magmatism of the Benue Trough constitutes a step, in time and space, in a general north to south migration of magmatism, from the magmatic province of the Jos Plateau to the Cameroon Volcanic Line (Fig. 1). In the Jos Plateau, the alkaline ring complexes were emplaced along a north–south axis with ages decreasing from 213 Ma in the north, to 141 Ma in the south (Van Breemen & Bowden, 1973; Van Breemen *et al.*, 1975; Rahaman *et al.*, 1984). In the Cameroon Line, magmatic activity started at about 70 Ma and lasted to the present (Cantagrel *et al.*, 1978; Dunlop & Fitton, 1979; Dunlop, 1983; Fitton, 1987). This temporal and spatial migration suggests that these three magmatic provinces (Jos, Benue, Cameroon) are related to the dynamics of the lithosphere–asthenosphere closely linked to the opening of the Equatorial Atlantic and the drifting of Africa (Maluski *et al.*, 1995).

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Twelve basaltic samples, on which ^{40}Ar–^{39}Ar analyses have been performed, were selected for the present study from a data set of 133 analyses; these selected samples are representative of (1) the different magmatic episodes of the Northern and Southern Benue, and (2) the two magmatic groups displaying either an alkaline or a tholeiitic affinity. Major elements and some trace elements (Cr, Ni, Co, V, Zn, Cu) were determined by inductively coupled plasma optical emission spectrometry (ICP–OES) [analytical precisions have been given by Baudin (1991)]; the other elements were analysed by inductively coupled plasma mass spectrometry (ICP–MS) [accuracy of the method has been discussed by Ionov *et al.* (1992)]. Major and trace element data are reported in Table 1. According to the low and variable *mg*-numbers (*mg*-number 36 to 66), none of the samples considered in this study represent primary mantle-derived melts; this is a general feature observed in all the basaltic rocks of the Benue Trough (Baudin, 1991). Tholeiitic and tholeiitic transitional (G2 basalts) samples are uniformly *Qz*-normative, whereas alkaline and alkaline transitional G1 basalts (with the exception of sample 104 P1) are *Ne*- or *Ol–Hy* normative (with high *Ol/Hy* ratios). Chondrite-normalized rare-earth element (REE) diagrams (Fig. 2) discriminate clearly between the alkaline and tholeiitic rocks. The alkaline rocks are enriched in light REE (LREE), with $(La/Yb)_N$ varying between 6·9 and 14·9, compared with the tholeiitic rocks (La/Yb_N = 2·4–6·3). The two groups have similar heavy REE (HREE) abundances. In the tholeiitic group, one sample (152 B1) is characterized by higher abundances of all the REE, the distribution pattern being subparallel to those of the other samples; this is indicative of the evolved nature of this basalt, in agreement with its *mg*-number (36·4). Spiderdiagrams (Fig. 3) show a regular distribution of the more mobile incompatible trace elements which is indicative of the lack of meteoric alteration; one exception is a tholeiitic sample from the Southern Benue (153 B1), in which a moderate depletion in Rb and K is observed. A distinct difference between the alkaline and tholeiitic groups is also apparent in Figs 3a and b. The alkaline rocks, enriched in incompatible elements, with a peak in Nb and Ta, have a trace-element pattern typical of alkaline oceanic-island basalts, as illustrated by a comparison with the basalts from St Helena (Fig. 3c). Basalts from the Cameroon Line also exhibit a similar general pattern with, however, a more pronounced enrichment in Nb to Ce and a depletion in P which has been interpreted as reflecting a small amount of apatite in the source (Halliday *et al.*, 1995). Within the alkaline group it must be noted that the G1 alkaline transitional basalts (Northern Benue) are, on average, less enriched than the alkaline samples from the Southern Benue. Compared with the alkaline group, the tholeiitic rocks are depleted in a wide spectrum of elements, espec-

Table 1: Analyses of selected basaltic magmatic rocks from the Benue Trough

	Northern Benue						Southern Benue					
	G1 basalts				G2 basalts		Alkaline			Tholeiitic		
Samples:	53 B1	143 B1	106 P6	104 P1	153 B1	152 B1	46 B1	111 B1	804 P1	86 B1	150 B4	113 B
SiO_2	47·22	47·74	46·25	52·33	50·56	51·75	49·03	47·44	45·97	52·06	54·08	53·54
TiO_2	2·69	2·99	2·68	1·53	1·44	3·21	1·48	2·24	2·38	1·56	1·54	1·65
Al_2O_3	16·22	17·21	15·80	14·59	14·64	14·58	20·25	16·34	17·36	15·18	14·44	14·96
Fe_2O_3	4·40	2·54	3·53	3·99	3·89	4·40	3·00	3·00	3·71	3·25	3·45	3·53
FeO	8·36	8·80	8·38	5·34	7·36	9·14	2·92	6·38	8·96	7·79	6·29	6·71
MnO	0·15	0·17	0·17	0·12	0·23	0·20	0·17	0·16	0·18	0·16	0·15	0·14
MgO	5·37	5·25	7·50	6·32	5·96	3·52	2·26	8·42	5·12	5·72	5·56	5·36
CaO	7·32	9·84	8·51	8·25	8·75	6·99	5·45	8·61	6·44	8·21	8·68	8·06
Na_2O	4·18	3·58	3·16	2·79	2·98	3·20	9·40	3·04	4·75	3·00	3·53	3·26
K_2O	0·98	1·11	1·10	0·77	0·30	1·02	2·99	1·01	1·79	0·35	0·45	0·48
P_2O_5	0·66	0·54	0·58	0·35	0·18	0·63	0·47	0·50	1·01	0·13	0·20	0·20
H_2O^+	1·29	0·85	0·95	1·26	2·15	1·69	2·41	2·68	1·25	0·87	0·89	1·32
H_2O^-	0·03	0·17	0·07	0·54	0·75	0·52	0·16	0·18	0·11	0·62	0·12	0·57
Total	98·87	100·79	98·68	99·08	99·19	100·85	99·99	100·00	99·03	98·90	99·38	99·78
Qz				6·5	2·8	6·7				4·8	5	6·2
Or	5·9	6·5	6·6	4·6	1·8	6·1	18·1	6·1	10·8	2·1	2·7	2·8
Ab	34·7	27·3	27·3	24·2	26·1	27·4	18·1	26·4	27·7	26	30·3	28·1
An	23·1	27·6	26·2	25·6	26·6	22·7	4·3	28·7	21·2	27·6	22·5	25·2
Ne	0·7	1·6					34·3		7·2			
Di	8·3	14·8	10·9	11·5	14·2	7·2	16·9	9·7	4·4	11	16·3	11·7
Hyp			0·3	20·5	21·6	18·2		6·2		21·7	16·6	18·9
Ol	16·4	11·8	18·3				2·2	14·2	17·8			
Mt	3·3	2·9	3	2·4	2·9	3·4	1·5	2·4	3·2	2·8	2·5	2·6
Ilm	5·2	5·7	5·2	2·9	2·8	6·1	2·8	4·3	4·6	3	2·9	3·2
Ap	1·6	1·2	1·4	0·8	0·4	1·5	1·1	1·2	2·4	0·3	0·4	0·4
mg-no.	48·2	50·2	58	60·2	53·7	36·4	45·7	66·3	47	53·2	55·7	53·6
Cr	78	99	221	240	201	15	37	199	10	285	179	206
Ni	95	56	151	164	116	14	18	130	15	53	50	91
Co	52	30	47	38	30	26	17	34	38	34	24	30
Sc	10·6	20·3	22·3	18·0	21·9	22·2	5·9	22·7		22·1	19·6	19·0
V	139	229	214	138	183	211	104	252	165	200	167	140
Zn	168	113	133	86	114	165	97	74	179	125	105	125
Cu	39	40	57	64	100	34	18	24	20	36	8	38
Rb	19·0	19·5	24·9	19·2	5·9	26·8	44·7	22·2	26·6	8·9	10·5	14·2
Sr	717	633	695	409	293	528	832	1005	689	235	307	344
Ba	249	255	853	262	240	658	567	404	344	120	183	200
Zr	269	238	243	119	134	354	292	152	463	78	85	85
Nb	51	46	49	32	13	50	74	42	68	7	11	11
Ta	2·8	2·6	2·7	1·7	0·78	2·9	4·3	2·3	4·04	0·36	0·54	0·57
Y	20	20	20	16	21	41	23	16	37	20	17	21
La	29·31	29·44	32·11	19·02	12·89	38·37	40·69	22·41	41·49	7·15	10·21	8·88

(continued on next page)

Table 1: continued

	Northern Benue						Southern Benue					
	G1 basalts				G2 basalts		Alkaline			Tholeiitic		
Samples:	53 B1	143 B1	106 P6	104 P1	153 B1	152 B1	46 B1	111 B1	804 P1	86 B1	150 B4	113 B
Ce	67·55	64·49	70·61	37·31	27·85	86·29	81·70	46·97	102·15	15·66	22·18	19·10
Pr	8·78	7·84	8·72	4·46	3·50	10·94	9·11	5·90	13·44	2·20	2·90	2·58
Nd	38·57	32·64	36·84	18·47	15·17	47·45	33·90	25·29	59·73	10·74	13·37	12·64
Sm	8·65	6·95	7·68	4·19	3·84	10·67	6·13	5·55	13·10	3·45	3·76	3·85
Eu	3·12	2·40	2·06	1·53	1·41	3·49	2·09	2·04	4·28	1·38	1·48	1·49
Gd	8·30	6·59	7·41	4·34	4·69	10·80	5·62	5·72	12·13	4·53	4·43	4·81
Tb	1·18	1·03	1·06	0·65	0·78	1·71	0·88	0·87	1·78	0·76	0·73	0·78
Dy	5·58	5·61	5·54	3·50	4·66	9·70	4·64	4·83	9·18	4·44	4·23	4·65
Ho	0·89	1·05	1·02	0·64	0·91	1·83	0·88	0·95	1·60	0·86	0·79	0·88
Er	1·94	2·61	2·40	1·50	2·30	4·62	2·37	2·50	3·98	2·33	1·99	2·24
Tm	0·23	0·36	0·31	0·20	0·31	0·63	0·34	0·34	0·52	0·31	0·26	0·29
Yb	1·31	2·25	1·95	1·20	1·96	4·06	2·23	2·18	3·21	1·96	1·64	1·86
Lu	0·170	0·332	0·286	0·175	0·293	0·627	0·333	0·333	0·470	0·285	0·237	0·276
Hf	6·1	5·3	5·0	2·8	3·4	8·5	5·8	3·5	9·4	2·2	2·4	2·5
Pb	2·0	2·2	2·5	1·5	2·8	13·6	5·3	1·7	2·6	1·7	1·6	1·8
Th	2·7	2·9	3·1	2·7	1·7	3·1	5·1	2·1	3·6	0·9	1·2	1·3
U	0·88	0·98	0·98	0·75	0·33	0·97	1·60	0·71	1·28	0·21	0·28	0·32

Northern Benue. Alkaline transitional G1 basalts: Burashika (53 B1), Gwol (143 B1), Bima Hills (106 P6) and Guburunde (104 P1) areas. Tholeiitic transitional G2 basalts: Dumne (153 B1) and Guburunde (152 B1) areas.
Southern Benue. 46 B1: tephrite (Katyo); 111 B1: basalt (Wanakum Hills); 804 P1: basalt (Uturu); 86 B1: dolerite (Afikpo); 105 B4: dolerite (Oturkpo); 113 B: dolerite (Makurdi).

ially in the highly incompatible ones. The differentiated tholeiitic sample from Southern Benue (152 B1) falls in the alkaline field. Some incompatible trace element ratios distinguish the tholeiitic and alkaline groups. The alkaline rocks have lower La/Nb and Zr/Nb, and higher Ce/Pb, Th/Pb, U/Pb, Ta/Yb and Th/Yb ratios (Table 2). Within each magmatic group, no difference can be observed, in terms of trace-element ratios, between the rocks of the Northern and Southern Benue.

ISOTOPIC DATA

The Sr, Nd and Pb isotopic data are listed in Table 3 and illustrated in Figs 4–7. The alkaline rocks are characterized by lower $^{87}Sr/^{86}Sr_i$ ratios (0·7029–0·7037) and slightly higher $^{143}Nd/^{144}Nd_i$ ratios (0·5126–0·5129) compared with the tholeiitic ones ($^{87}Sr/^{86}Sr_i = 0{\cdot}7042$–$0{\cdot}7065$; $^{143}Nd/^{144}Nd_i = 0{\cdot}5125$–$0{\cdot}5127$). A similar feature exists in Hawaii, where tholeiitic basalts have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios than alkaline lavas (Chen & Frey, 1983; Frey & Roden, 1987). In Fig. 4, it should be noted that the alkaline rocks of the Northern Benue Trough (G1 basalts; 147–106 Ma) and from the Southern Benue Trough have broadly the same Sr–Nd isotopic ratios. By contrast, there is a clear temporal evolution within the tholeiitic group: the G2 tholeiitic transitional basalts from Northern Benue (139–131 Ma) have higher $^{87}Sr/^{86}Sr_i$ ratios (and slightly lower $^{143}Nd/^{144}Nd_i$ ratios) than the tholeiitic rocks from the Southern Benue Trough (60–49 Ma). Alkaline and tholeiitic samples also clearly differ according to their $^{206}Pb/^{204}Pb_i$ ratios (Figs 5 and 6; Table 3). In the alkaline rocks, this ratio exceeds 18·5 and a large compositional range exists, with values reaching 20·42. In the tholeiitic group, the variation is more restricted ($^{206}Pb/^{204}Pb_i = 17{\cdot}59$–$18{\cdot}48$). Within each magma group a temporal evolution is observed: in the alkaline rocks, $^{206}Pb/^{204}Pb_i$ ratios increase from the Northern Benue (147–106 Ma rocks) to the Southern Benue (88–68 Ma). An opposite tendency is apparent in the tholeiitic group between the

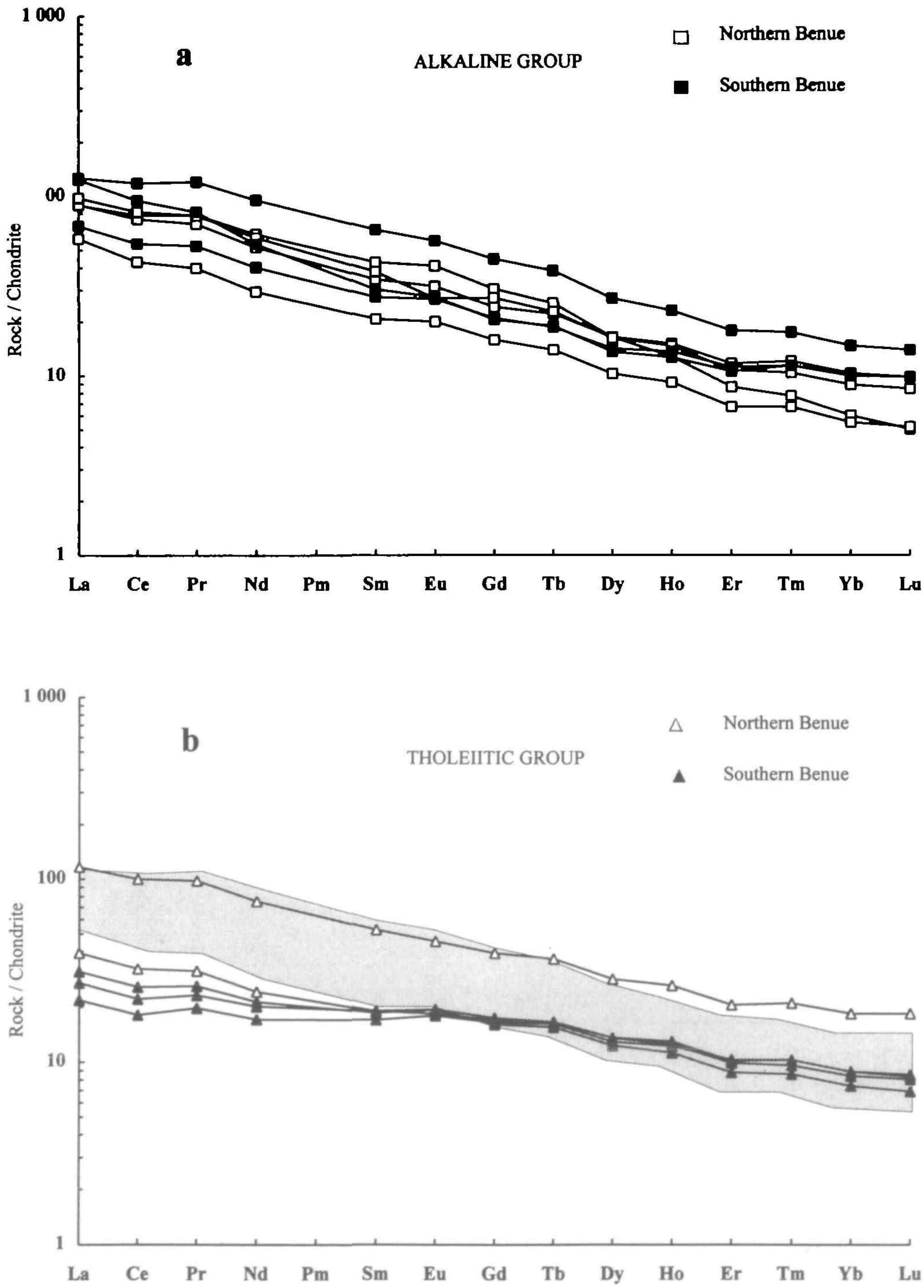

Fig. 2. Chondrite-normalized REE abundances; normalization values from Nakamura (1979). In (b), the hatched domain is the field of alkaline rocks of (a).

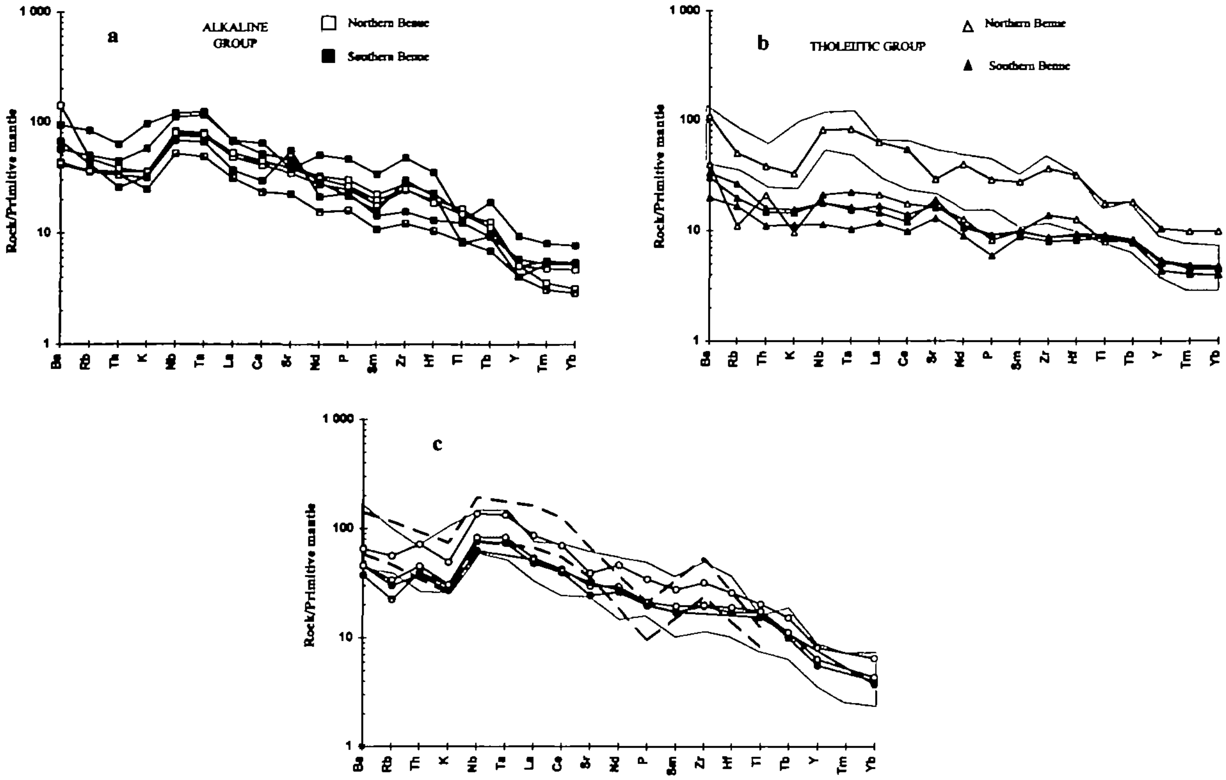

Fig. 3. Incompatible trace-element patterns for basaltic rocks of the Benue Trough normalized to primitive mantle; normalization values from Hofmann (1988), except P (from Sun & McDonough, 1989). In (b), the hatched domain corresponds to alkaline rocks of (a). (c) Comparison between the alkaline rocks of the Benue (hatched domain), basalts from the Cameroon Line (field shown by the dashed lines) and basalts from St Helena (circles). Data for the Cameroon Line are from Halliday *et al.* (1995). St Helena basalts are from White & Hofmann (1982) and from Chaffey *et al.* (1989).

Table 2: Variation intervals and average values (in brackets) of some incompatible trace element ratios for alkaline and tholeiitic rocks of the Benue Trough, compared with ocean island basalts and N-MORB reservoirs

	Benue				OIB		OIB	N-MORB
	Alkaline group		Tholeiitic group		EM1	EM2	HIMU St Helena	
La/Nb	0·53–0·66	[0·59]	0·77–1·02	[0·90]	0·86–1·19	0·89–1·09	0·69	1·07
Zr/Nb	3·62–5·27	[4·79]	7·08–11·14	[8·80]	4·2–11·4	4·5–7·3	4·5	30
Th/Nb	0·05–0·08	[0·06]	0·06–0·13	[0·11]	0·10–0·12	0·11–0·16	0·08	0·07
Ce/Pb	15·40–33·78	[28·28]	6·34–13·86	[10·0]	20		34	25
Th/Pb	0·96–1·80	[1·33]	0·23–0·75	[0·57]				
U/Pb	0·33–0·72	[0·53]	0·11–0·24	[0·17]				
Ta/Yb	1·06–2·14	[1·48]	0·18–0·71	[0·39]				
Th/Yb	0·96–2·29	[1·65]	0·46–0·87	[0·70]				

Data sources: Weaver *et al.* (1987); Weaver (1991); Chauvel *et al.* (1992); Vidal (1992). For the Benue Trough, values are from Table 1.

Table 3: Isotope data for basaltic rocks of the Benue Trough

	Northern Benue						Southern Benue					
	G1 basalts				G2 basalts		Alkaline			Tholeiitic		
Samples:	53 B1	143 B1	106 P6	104 P1	153 B1	152 B1	46 B1	111 B1	804 P1	86 B1	150 B4	113 B
Ages (Ma)	147	123	106	139	131	139	68	83	88	55	60	49
$^{87}Rb/^{86}Sr$	0·10282	0·08549	0·09772	0·13584	0·09231	0·1191	0·19555	0·06235	0·09536	0·24535	0·10822	0·15098
$^{87}Sr/^{86}Sr$	0·70309±13	0·70339±12	0·70380±11	0·70336±20	0·70662±11	0·70644±17	0·70316±14	0·70368±13	0·70326±15	0·70545±10	0·70437±12	0·70573±13
$^{87}Sr/^{86}Sr_i$	0·70288	0·70324	0·70366	0·70308	0·70648	0·70619	0·70299	0·70361	0·70314	0·70526	0·70428	0·70563
ε_{Sr}	−23·4	−16·8	−13	−20·5	27·1	23·6	−23·2	−14·1	−20·6	8·9	−5	14
$^{147}Sm/^{144}Nd$	0·1339	0·13152	0·12982	0·13957	0·16242	0·15974	0·10957	0·1366	0·13733	0·20205	0·17402	0·19012
$^{143}Nd/^{144}Nd$	0·51295±10	0·51282±10	0·51274±12	0·51286±10	0·51264±14	0·51268±11	0·51287±12	0·51299±15	0·51291±13	0·51260±13	0·51273±13	0·51270±13
$^{143}Nd/^{144}Nd_i$	0·51282	0·51271	0·51265	0·51272	0·51251	0·51252	0·51283	0·51291	0·51283	0·51253	0·51266	0·51264
ε_{Nd}	7·2	4·5	2·9	5·3	0·7	1·4	5·2	7·4	5·9	−0·8	2	1·2
$^{206}Pb/^{204}Pb$	20·161	19·855	19·802	19·240	18·469	18·580	20·633	20·232	19·841	17·759	17·696	18·305
$^{206}Pb/^{204}Pb_i$	19·497	19·314	19·376	18·540	18·316	18·482	20·420	19·878	19·394	17·693	17·593	18·219
$^{207}Pb/^{204}Pb$	15·661	15·663	15·686	15·660	15·659	15·629	15·699	15·664	15·634	15·504	15·493	15·570
$^{207}Pb/^{204}Pb_i$	15·630	15·638	15·666	15·628	15·651	15·625	15·689	15·647	15·614	15·501	15·488	15·566
$^{208}Pb/^{204}Pb$	39·675	39·448	39·694	39·248	39·006	38·514	40·028	39·22	39·102	38·235	38·82	38·704
$^{208}Pb/^{204}Pb_i$	39·009	38·882	39·259	38·523	38·747	38·411	39·806	38·877	38·704	38·142	38·676	38·590

i: Sr, Nd and Pb isotopes ratios corrected to age of emplacement. Sr, Nd and Pb isotopic compositions have been determined at Clermont Ferrand. The analytical procedure has been described by Deniel *et al.* (1994). Over the period of measurements, replicate analyses of standards gave, for National Bureau of Standards (NBS) 987, $^{87}Sr/^{86}Sr = 0·71024 \pm 4$ (2σ) and, for La Jolla, $^{143}Nd/^{144}Nd = 0·51184 \pm 3$ (2σ). As estimated from replicate analyses of the NBS 981 standard, maximum errors on $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are 0·12%, 0·16% and 0·20%, respectively. ^{40}Ar–^{39}Ar ages are from Maluski *et al.* (1995).

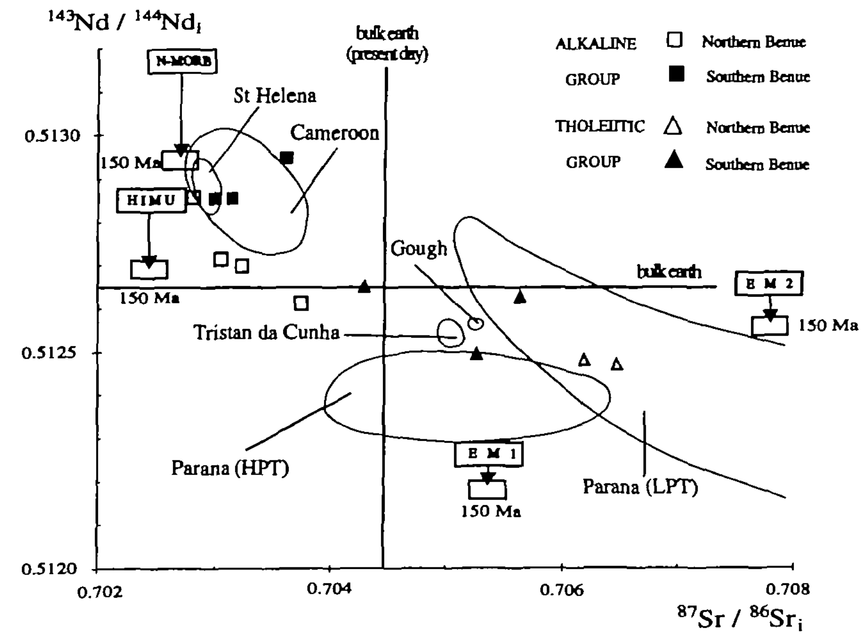

Fig. 4. $^{143}Nd/^{144}Nd_i$ vs $^{87}Sr/^{86}Sr_i$ ratios for basaltic rocks of the Benue Trough. EM1, EM2, HIMU and N-MORB compositions from Hart (1988). For each mantle reservoir, the field shown by the arrow corresponds to the composition of the reservoir at 150 Ma; the evolution of the $^{143}Nd/^{144}Nd$ ratio of the mantle reservoirs through time is the most sensitive to radiogenic growth over the period of time considered. This evolution has been estimated assuming μ ratios of 22 for the HIMU reservoir (Chauvel *et al.*, 1992), 8 for the other reservoirs and a $^{147}Sm/^{144}Nd$ of 0·222 for the depleted mantle (Ben Othman *et al.*, 1984). Fields for St Helena, Gough, Tristan da Cunha are from Staudigel *et al.* (1984); Parana from Hawkesworth *et al.* (1986) and Petrini *et al.* (1987); (HPT, high P_2O_5–TiO_2; LPT, low P_2O_5–TiO_2); Cameroon Line from Halliday *et al.* (1988) and Lee *et al.* (1994).

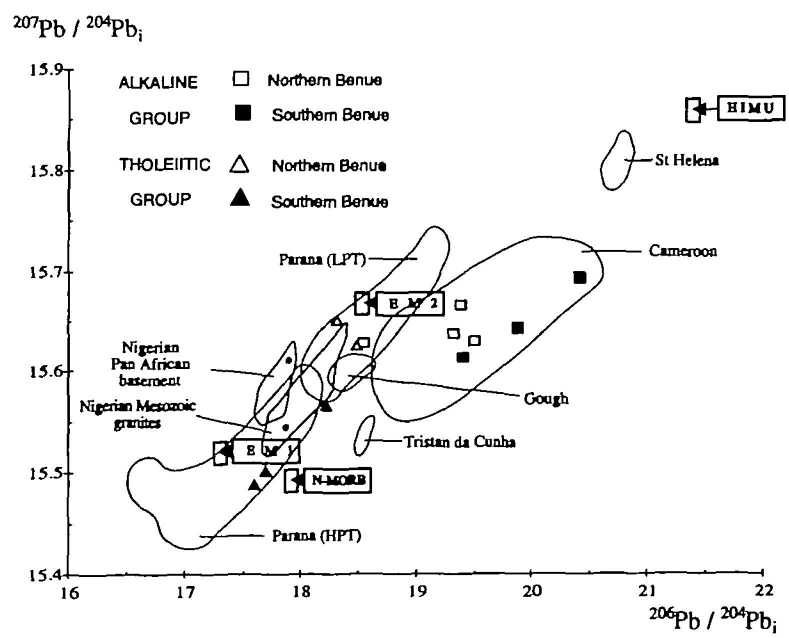

Fig. 5. $^{207}Pb/^{204}Pb_i$ vs $^{206}Pb/^{204}Pb_i$ ratios. Same data sources as in Fig. 4. Arrows show the evolution through time of the mantle reservoirs for the $^{206}Pb/^{204}Pb$ ratio which is sensitive to radiogenic growth. A μ ratio of 22 has been assumed for the HIMU reservoir and of 8 for the other reservoirs (Chauvel *et al.*, 1992). The fields for the Nigerian Pan African basement and for the Nigerian granites are from Halliday *et al.* (1988). Filled circles are granulite facies xenoliths C74C and C74F from Halliday *et al.* (1988).

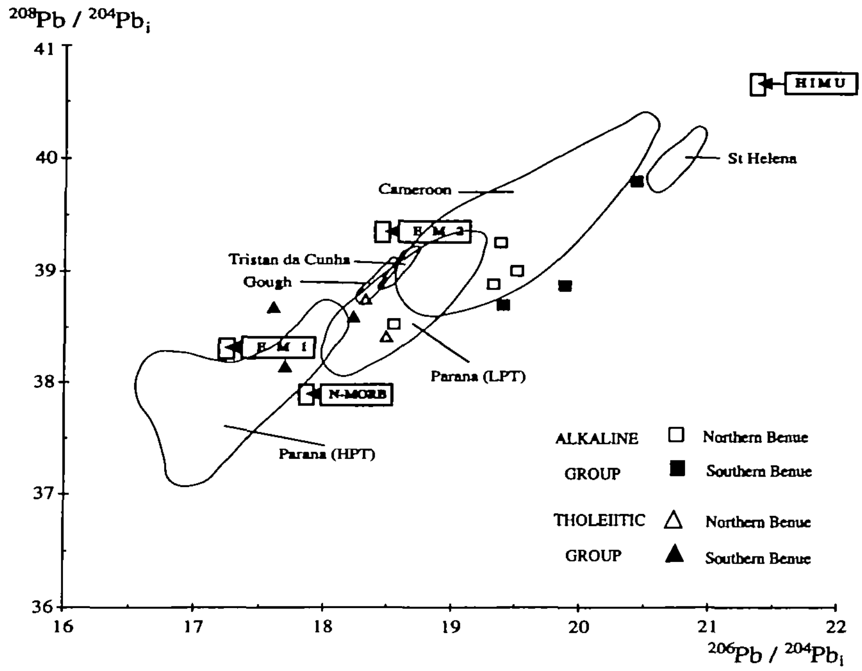

Fig. 6. $^{208}Pb/^{204}Pb_i$ vs $^{206}Pb/^{204}Pb_i$ ratios. Same data sources as in Fig. 4; additional data from Zindler & Hart (1986) and Le Roex *et al.* (1990).

Northern (G2 basalts: 139–131 Ma) and the Southern Benue (60–49 Ma). In Fig. 5 it can be observed that: (1) samples from the Southern Benue Trough have the lowest $^{206}Pb/^{204}Pb_i$ and $^{207}Pb/^{204}Pb_i$ ratios; (2) the northern G2 tholeiitic transitional basalts have $^{207}Pb/^{204}Pb_i$ ratios similar to those of the alkaline group; (3) there is no clear evolution of $^{207}Pb/^{204}Pb_i$ ratios within the alkaline group.

The distinct isotopic signatures and temporal change of the two groups are well expressed in the $^{87}Sr/^{86}Sr_i$ vs $^{206}Pb/^{204}Pb_i$ diagram (Fig. 7). In the

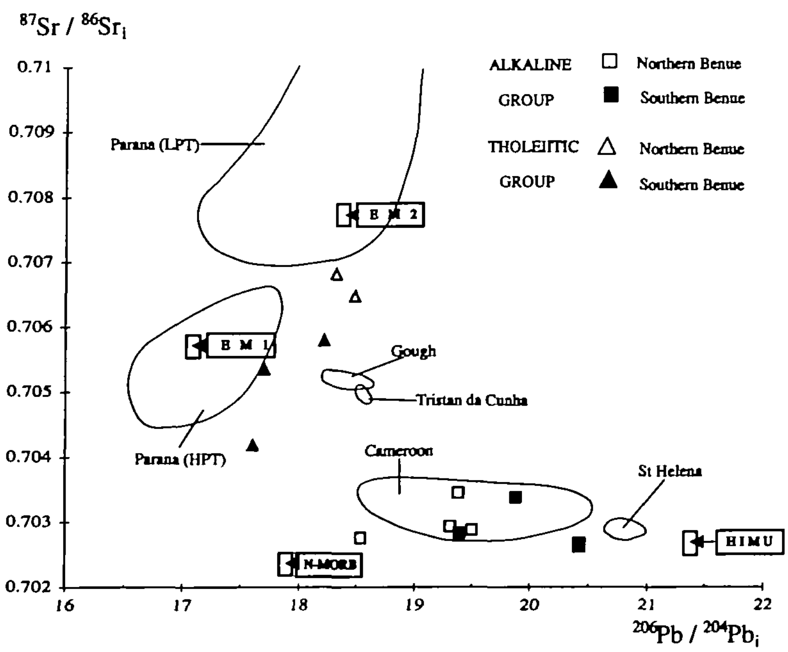

Fig. 7. $^{87}Sr/^{86}Sr_i$ vs $^{206}Pb/^{204}Pb_i$ ratios. Same data sources as in Figs 4 and 6.

alkaline group, an increase in the $^{206}Pb/^{204}Pb_i$ ratios is observed from north to south, the $^{87}Sr/^{86}Sr_i$ ratios remaining broadly constant. In contrast, in the tholeiitic group, both $^{87}Sr/^{86}Sr_i$ and $^{206}Pb/^{204}Pb_i$ decrease through time from north to south. Finally, it must be pointed out that the compositional similarity between the alkaline basaltic rocks of the Benue Trough and the basalts of the Cameroon Line, already outlined for trace-elements, is confirmed by isotopic compositions (Figs 4–7); this similarity is also observed for Sr and Nd isotopes with the St Helena basalts (Fig. 4).

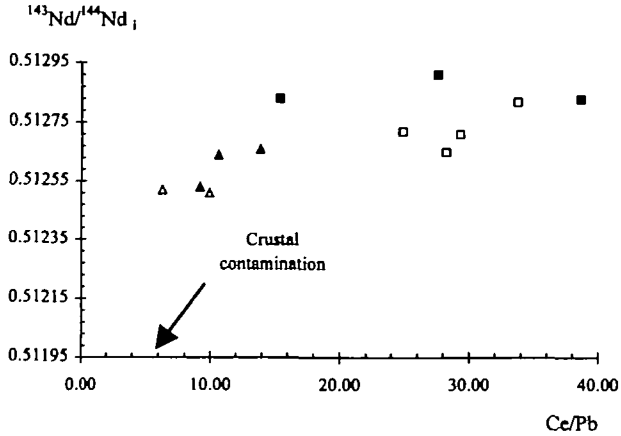

Fig. 9. Ce/Pb vs $^{143}Nd/^{144}Nd_i$ ratios. Same symbols as in Fig. 8.

DISCUSSION

Crustal contamination

In attempting to identify the mantle sources involved in the genesis of the Mesozoic basaltic magmatism of the Benue Trough, crustal contamination must be evaluated as a preliminary possibility. To assess the role of crustal contamination, trace-element ratios can be used in conjunction with isotopic compositions. An example is shown in the Th/Nb vs $^{143}Nd/^{144}Nd_i$ diagram (Fig. 8), where it can be noted that: (1) the range of variation of the Th/Nb is small (0·05–0·13) for all the basaltic rocks considered in this study, compared with the wider range of the Nd isotopic compositions; (2) no correlation exists between Th/Nb and the $^{143}Nd/^{144}Nd_i$ ratios within each magmatic group, as would be expected in case of crustal contamination; (3) the overall chemical evolution of the two magmatic groups diverges from the crustal contamination trend. The lack of correlation between other trace-element ratios sensitive to crustal contamination, such as Ce/Pb, and isotopic compositions (Fig. 9) also argues against a significant contribution of continental crust. Other arguments point in the same direction: (1) the lack of negative anomalies in Nb and Ta in spiderdiagrams (Fig. 3) which might suggest a crustal input; (2) the $^{87}Sr/^{86}Sr_i$ vs SiO_2 diagram (Fig. 10, in which no correlation exists within the alkaline group, whereas, in the more radiogenic tholeiitic group, correlation is negative; (3) in Fig. 5, the temporal isotopic evolution within each magmatic group, from the north to the south of the Benue Trough precludes the intervention of crustal contamination, as no trend towards the composition of the local crust is observed, especially for the tholeiitic group. Therefore we conclude that crustal contamination, if it occurred, was not sig-

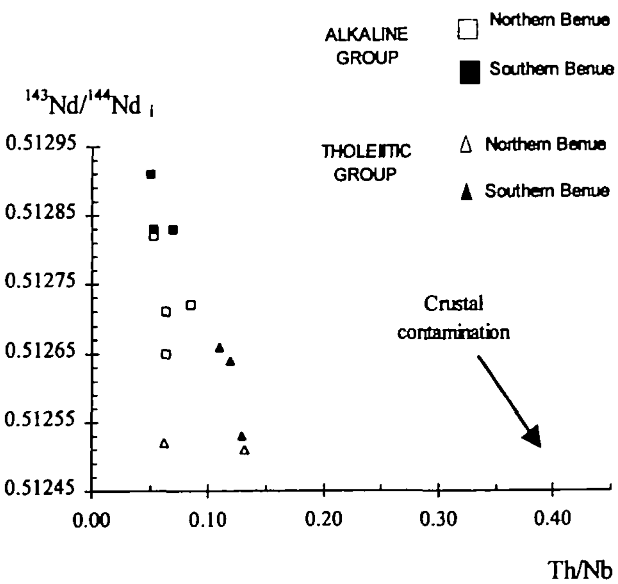

Fig. 8. Th/Nb vs $^{143}Nd/^{144}Nd_i$ ratios.

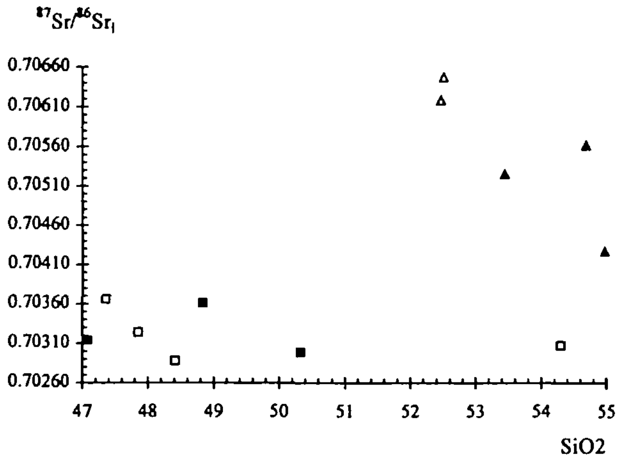

Fig. 10. SiO_2 (recalculated on an anhydrous basis) vs $^{87}Sr/^{86}Sr_i$ ratios. Same symbols as in Fig. 8.

nificant enough to obscure the geochemical signatures of the mantle sources during the genesis of the Mesozoic basaltic magmatism of the Benue Trough.

Mantle sources

Incompatible trace-element ratios combined with radiogenic isotopes are a powerful tool in the identification of mantle sources involved in the genesis of basaltic magmas. The distinct geochemical signatures of the alkaline and tholeiitic Mesozoic basaltic rocks of the Benue Trough suggest that they were derived from different mantle sources. Moreover, the variation observed for some geochemical characteristics, between the basaltic rocks of the Northern and Southern Benue Trough, within each magmatic group (alkaline and tholeiitic), suggests a temporal change of the contributing mantle sources. In Table 2, some discriminant incompatible trace element ratios of the basaltic rocks of the Benue Trough are compared with those characterizing the OIB and the N-MORB reservoirs. The alkaline group displays trace-element ratios similar to those of the St Helena basalts (Fig. 3c; Chaffey *et al.*, 1989) which constitute the sole known example defining the HIMU reservoir in the Atlantic Ocean. The tholeiitic group exhibits trace-element ratios indicative of an origin from an EM-type mantle source, except for the Ce/Pb ratio, which is lower than 20, a value considered typical for EM1–EM2 basalts (Chauvel *et al.*, 1992). However, it has been recently shown (Halliday *et al.*, 1995) that this ratio is highly variable in the OIBs from the Central Atlantic, with values as low as 15. Moreover, in the tholeiitic rocks of the Benue, the range of variation of the Ce/Pb ratio is extended to low values as it includes a fractionated sample (152 B1) characterized by the lowest Ce/Pb ratio (6·3).

The temporal change of the isotopic composition of the mantle reservoirs, down to 150 Ma, is reported in Figs 4–7. For that purpose, μ ratios of 20 for HIMU, and of 10 for EMs and MORB sources have been assumed. $^{147}Sm/^{144}Nd$ ratios of 0·222 and 0·15 have been taken respectively for the MORB and for the EM–HIMU sources. The general negative correlation observed for the Benue Trough samples in the $^{87}Sr/^{86}Sr_i$ vs $^{143}Nd/^{144}Nd_i$ diagram (Fig. 4) would require some form of mixing between two isotopically distinct mantle end-members: HIMU or N-MORB, and EM mantle components. In this diagram, the location of the alkaline basaltic rocks is close to the N-MORB and HIMU poles; these two mantle components have Sr and Nd compositions that are too close to clearly relate the source of the alkaline group to one or the other of these two end-members. The tholeiitic rocks tend towards an EM2 mantle source, particularly those of the Northern Benue.

Diagrams involving Pb isotopic ratios better identify the role played by the HIMU reservoir, as the HIMU and N-MORB isotopic signatures are very different. In the $^{207}Pb/^{204}Pb_i$ vs $^{206}Pb/^{204}Pb_i$ (Fig. 5), and $^{208}Pb/^{204}Pb_i$ vs $^{206}Pb/^{204}Pb_i$ (Fig. 6) diagrams, two mixing arrays can be identified: (i) between EM1, EM2 and N-MORB for the tholeiitic rocks and (ii), for the alkaline group, starting from the extremity of the first mixing trend and pointing in the direction of a HIMU source. With the exception of one sample (104 P1; Table 3), all the alkaline rocks have high $^{206}Pb/^{204}Pb_i$ ratios (19–20·42), relative to the EM2 end-member. This feature strongly suggests the involvement of a plume in the genesis of the alkaline basaltic magmas of the Benue Trough. The $^{87}Sr/^{86}Sr_i$ vs $^{206}Pb/^{204}Pb_i$ diagram (Fig. 7) is also consistent with a three-component mantle mixing model. It shows that the tholeiitic rocks originate from an enriched mantle (EM1–EM2 mixing trend), whereas the alkaline ones lie on a mixing array between an N-MORB mantle and a HIMU (plume) source. In Figs 4–7, the isotopic compositional fields of basalts from the Cameroon Line, from the South Atlantic islands (i.e. St Helena, Tristan da Cunha–Gough) and from Parana, are also reported; it must be noted that: (1) the alkaline group of the Benue Trough plots in the same field as the Cameroon Line and points towards the St Helena end-member; (2) the tholeiitic group lies close to the Parana–Tristan da Cunha–Gough basalts, which display an EM isotopic signature (Wilson, 1992).

Therefore, on the basis of the geochemical data, we conclude that three types of source were involved in the genesis of the Mesozoic basaltic rocks of the Benue Trough:

(1) An enriched mantle, probably the subcontinental lithosphere, from which the tholeiitic rocks were derived. That lithospheric mantle is at least 2500–2000 Ma old, according to radiometric data obtained on granites and migmatites from the crustal basement of the Benue rift (Bessoles & Lasserre, 1977). This basement has been reactivated by the Pan-African orogeny (600 Ma); it has been suggested (Ashwal & Burke, 1989) that, in Africa, lithospheric mantle underlying Pan-African reactivated crust is more enriched than lithospheric mantle located below cratonic areas.

(2) A HIMU-type (plume) component which was involved in the genesis of the alkaline basaltic rocks

and, consequently, in the formation of the Benue rift. According to the postulated location of the St Helena hot spot in the Equatorial Atlantic at about 130 Ma (O'Connor & Duncan, 1990), and on the basis of the geochemical similarity between the alkaline basaltic rocks of the Benue and the basalts of the St Helena island [Table 2 and Chaffey *et al.* (1989)], we conclude that the St Helena hot spot was involved in the genesis of the alkaline basaltic magmas of the Benue Trough.

(3) A depleted asthenospheric upper mantle (N-MORB source), which was involved in the genesis of the alkaline basaltic magmas of the Benue Trough.

A temporal evolution of the mantle sources is apparent in the isotopic diagrams. The two points that emerge are the following:

(1) In the alkaline group, the basaltic rocks of the Southern Benue Trough (88–68 Ma old; Table 3) have higher $^{206}Pb/^{204}Pb_i$ ratios than the older (147–106 Ma) G1 alkaline transitional basalts of the Northern Benue Trough (Figs 5–7). This can be interpreted as reflecting a decreasing influence of the N-MORB source and an increasing contribution of the HIMU (plume) component through time in the genesis of the alkaline basaltic magmatism.

(2) Regarding the tholeiitic group, it should be noted that the mantle source which gave rise to the G2 tholeiitic transitional basalts of the Northern Benue (139–131 Ma) was more enriched than that from which the tholeiitic basaltic rocks of the Southern Benue (60–49 Ma) were derived. This is clearly evidenced in Fig. 4. In Figs 5 and 7, the G2 tholeiitic transitional basalts of the Northern Benue are closer to the EM2 pole than the younger tholeiitic rocks from the Southern Benue, which tend towards the EM1 end-member.

A tentative model accounting for the change of the mantle sources during the successive magmatic periods which occurred in the Benue rift can be proposed:

(1) During the period 146–106 Ma, magmatism was probably active throughout the rift. In the Northern Benue, alkaline transitional basalts (G1), associated with peralkaline rhyolites, erupted contemporaneously with tholeiitic transitional basalts (G2). This implies that two main mantle sources delivered basaltic magmas during that period: the enriched subcontinental lithosphere, from which the G2 basalts were derived, and the plume, which produced the G1 basalts. The involvement of an N-MORB-type source in the genesis of the G1 basalts (see Fig. 7) could be accounted for by contamination of the plume head with the surrounding depleted asthenospheric mantle, during the ascent of the plume to the base of the lithosphere, according to the Griffiths & Campbell (1990) model of plume structure. During this span of time, which corresponds to the first rifting episodes of the Benue (Guiraud & Maurin, 1991), lithospheric extension was moderate, so that the plume probably did not penetrate the lithosphere. Heat transfer from the plume and/or decompression melting related to extension could be responsible for the generation of the G2 (tholeiitic) basalts. The volumes of magmatic products emplaced during the 147–106 Ma period (as well as for the following magmatic periods) were small; this suggests that the St Helena plume was cool and weak (i.e. with a low buoyancy flux; Sleep, 1990; Wilson, 1992).

(2) After the emplacement, in the Northern Benue, of the 106 Ma G1 basalts, magmatism was concentrated in the southern part of the rift, probably as a consequence of the opening of the Equatorial Atlantic and the northeastward motion of the African plate.

(3) Magmatic rocks emplaced between 97 and 81 Ma were exclusively alkaline; they represent St Helena plume-derived melts. Subcontinental lithospheric mantle was not involved in magma genesis during this time.

(4) During the third magmatic period (68–49 Ma), magmatism was first alkaline and then tholeiitic. The alkaline rocks belonging to the second (97–81 Ma) and third (68–49 Ma) magmatic periods display a more pronounced HIMU signature (higher $^{206}Pb/^{204}Pb$ ratios for constant $^{87}Sr/^{86}Sr$; Fig. 7) than those of the first period. An original heterogeneity in the plume to explain the isotopic evolution within the alkaline group can probably be discounted, given the regularity of the time–composition variation observed in the Benue Trough. This evolution could be accounted for by an increasing contribution of the plume tail, in which assimilation of the surrounding mantle is minimal (Griffiths & Campbell, 1990). Thus, the alkaline basaltic rocks of the Southern Benue may have originated from the plume tail, explaining their higher $^{206}Pb/^{204}Pb$ ratios relative to the G1 alkaline basalts of the Northern Benue that we suspect to be derived from the plume head. Thus, beneath the Southern Benue, the influence of the plume tail appears prominent in the genesis of alkaline basaltic magmas from about 90 Ma.

The proposed stronger contribution of the plume tail in the genesis of the alkaline basalts of the Southern Benue could result from (1) the flattening and deflection of the plume head which was entrained at the base of the lithosphere, consequent to the drifting of the African plate towards NE; and/or (2) thinning of the continental lithosphere beneath the Southern Benue, in the direction of the passive margin of the Atlantic Ocean (Merki, 1972; Oreke & Fairhead, 1984; Ponsard & Saugy, 1989), allowing a more pronounced penetration of the plume tail to shallower depths, into the overlying lithosphere. This second hypothesis is supported by the higher HREE abundances (for given MgO) displayed by the alkaline basaltic rocks of the Southern Benue Trough, compared with the alkaline basalts from the north (Fig. 2). This suggests that the alkaline basaltic rocks from the south were generated at shallower depths, with less residual garnet in the source, probably in relation to a greater degree of upwelling of the St Helena plume owing to thinner lithosphere in the ocean–continent transition zone than beneath the continent.

The last eruptive episodes of the third magmatic period were tholeiitic; they have been dated at 60, 55 and 48 Ma (Maluski *et al.*, 1995) (Table 3). During that interval, no influence of the plume can be observed. The mantle source of these youngest tholeiitic basalts appears to be an EM1 end-member (Fig. 7), i.e. a source much less enriched, in terms of Sr isotopes, than that which gave rise to the older G2 tholeiitic transitional basalts of the Northern Benue, which point towards EM2. This evolution can be tentatively correlated with geological setting: going towards the passive oceanic margin of the Gulf of Guinea, transition from continental to oceanic lithosphere occurs. This transition is located beneath the Southern Benue, as revealed by geophysical data which show the existence of oceanic crust beneath the Niger delta (Ponsard & Saugy, 1989; Benkhelil *et al.*, 1988). Thus, it could be assumed that the tholeiitic basalts from Southern Benue were derived from an oceanic-type lithosphere (younger than 130 Ma; Emery & Uchupi, 1984), less enriched than the old subcontinental lithosphere which includes continental crust, partly Precambrian in age, and from which the G2 tholeiitic transitional basalts of Northern Benue were generated.

Geodynamic implications

The initial stages of rifting between Africa and South America and the opening of the South Atlantic Ocean have been related to the activity of Lower Cretaceous super-plume activity (Wilson, 1992). Two major mantle plumes, St Helena and Tristan da Cunha appear to have exerted a fundamental control on the process of continental break-up. These two plumes display contrasting features. The Tristan da Cunha plume has generated the voluminous tholeiitic Parana and Etendeka flood basalts. In Brazil, the Parana volcanism occurred between 137 and 127 Ma (Renne *et al.*, 1992; Turner *et al.*, 1994), i.e. broadly contemporaneous with the first magmatic period (147–106 Ma) we have defined in the Northern Benue. According to the high rate of magmatic production, the Tristan da Cunha plume is thought to be a 'strong' plume, i.e. with high buoyancy flux and temperature (Sleep, 1990; Schilling, 1991). Moreover, the flood basalts of the Parana display an EM geochemical signature, like the Tristan da Cunha–Gough recent volcanics (Hawkesworth *et al.*, 1986; Le Roex *et al.*, 1990) and like the tholeiitic basaltic group of the Benue (Figs 4–7). By contrast, the St Helena basalts have predominantly HIMU characteristics (Chaffey *et al.*, 1989), and small volumes of magmatic products are associated with the St Helena hot spot; these are represented by the Benue Trough alkaline volcanics, emplaced between 147 and 68 Ma, and by the Cameroon Line, which is also linked to this plume (Halliday *et al.*, 1988). Thus, the St Helena plume appears to have been much weaker (small buoyancy flux) and cooler than Tristan da Cunha. As proposed by Wilson (1992), the St Helena plume may have cooled by entrainment of depleted upper-mantle material; this hypothesis is in agreement with our data suggesting that an N-MORB-type source was involved in the genesis of the alkaline basaltic magmatism of the Northern Benue.

From about 70 Ma, magmatism of the Cameroon Line replaced the Mesozoic to Early Cenozoic magmatism of the Benue Trough. The remarkable 'Y' shape and size similarities between the Benue Trough and the Cameroon Line (Fig. 1) led Fitton (1980) to conclude that they were related to a common hot-zone in the asthenosphere, over which the African plate moved and, therefore, that they form a migrating rift system. In the Cameroon Line, plutonism (alkaline anorogenic ring complexes) lasted from 70 to 35 Ma (Fitton, 1987); it was followed by alkaline volcanism (35 Ma to the present; Cantagrel *et al.*, 1978; Dunlop & Fitton, 1979; Dunlop, 1983). Lavas of the northwestern branch of the 'Y'-shaped Cameroon Line (alkaline basalts, trachytes and phonolites) were emplaced in the northern end of the Benue; this is the case for the Biu plateau basalts (Fig. 1) dated between 23 and 7 Ma and between 3 Ma and the present (Grant *et al.*, 1972; Guiraud *et al.*, 1987).

The Mesozoic to Early Cenozoic alkaline basaltic rocks of the Benue Trough and those of the Cameroon Line exhibit very similar geochemical features (Fig. 3c and Figs 4–7). Basalts from the

Cameroon Line lacking any obvious evidence of crustal contamination (for the continental segment) have $^{87}Sr/^{86}Sr_i$ ratios between 0·7029 and 0·7035 (Halliday *et al.*, 1988, 1990), i.e. the same range as found for the alkaline basaltic rocks of the Benue Trough. The $^{206}Pb/^{204}Pb_i$ ratios of the Cameroon Line basalts (between 18·6 and 20·5) are also identical to those determined for the alkaline basalts of the Benue. Other geochemical similarities exist between these two magmatic provinces, as follows:

(1) In the Cameroon Line, Pb is less radiogenic and Sr is more radiogenic in transitional to hypersthene-normative basalts as compared with silica-undersaturated compositions. The same feature has been observed between the alkaline and tholeiitic groups of the Benue (this study). For the Cameroon Line, this has been interpreted as a consequence of the interaction between a rising plume component and the lithosphere (Halliday *et al.*, 1988).

(2) In the Cameroon Line, a temporal evolution to more radiogenic lead isotopic compositions with decreasing age has been noticed (e.g. in Principe and São Tomé islands) (Halliday *et al.*, 1988; Lee *et al.*, 1994). A similar evolution characterizes the alkaline lavas of the Benue.

(3) In the Benue Trough, the highest $^{206}Pb/^{204}Pb$ ratios have been measured in the alkaline lavas cropping out in the southern part of the rift, in the vicinity of the continent–ocean transition (Katyo and Okigwi areas). In the Cameroon Line, the highest $^{206}Pb/^{204}Pb$ have also been determined in lavas erupted in the continent–ocean boundary zone (Halliday *et al.*, 1990). This may indicate the location of the St Helena fossil plume tail, beneath the Gulf of Guinea, which reactivated to provide a source for the magmatism of the Cameroon Line volcanics (Halliday *et al.*, 1990; Wilson, 1992; Wilson & Guiraud, 1992).

Therefore, according to these strong similarities, it seems logical to conclude that magma generation in the Benue Trough and in the Cameroon Line has been controlled by the St Helena plume. This interpretation is consistent with recent data on the NE–SW trending seamount volcanic chain joining St Helena to the Cameroon Line. Dredged samples have been recently dated by the ^{40}Ar–^{39}Ar method (O'Connor & Le Roex, 1992); this study has revealed that seamounts become progressively older towards the continent. Therefore, the St Helena seamount chain probably represents the track of the plume tail, as the result of African plate migration over the St Helena hot spot.

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