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Concise review paper

The 'Cameroon Hot Line' (CHL): A unique example of active alkaline intraplate structure in both oceanic and continental lithospheres

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Abstract

The Cameroon Hot Line (CHL) is an active N30°E tectono-magmatic alignment, extending from Pagalu Island to Lake Chad. Its oceanic sector is comprised of six major volcanoes, and the continental sector of seven major volcanoes, numerous monogenic cones and more than sixty plutonic anorogenic ring complexes. The lavas and plutonic rocks have the typical mineralogy of the alkaline series. Nephelinites and alkaline lamprophyres are also present. The basalts from the oceanic and continental sectors have similar trace elements and Sr and Nd isotope compositions, attesting that the source is sublithospheric and that the continental crust plays no significant role in the magma genesis. Uncommon intermediate lavas originate through mixing between basaltic and felsic magmas. The evolution from basaltic to phonolitic magmas is explained through crystal fractionation. Compositions of most continental trachytes and of rhyolites require a crustal component. Metasomatism of carbonatitic affinity affected the lithospheric mantle during the magma ascent. DM and FOZO mantle components were involved in the genesis of the CHL parental magmas. ***To cite this article: B. Déruelle et al., C. R. Geoscience 339 (2007).***

Résumé

La « ligne chaude du Cameroun » (LChC) : l'unique exemple sur Terre d'une entité magmato-tectonique alcaline intraplaque active en domaines océanique et continental. La ligne chaude du Cameroun (LChC) est un alignement tectono-magmatique actif orienté N30°E, de l'île de Pagalu au lac Tchad. Le secteur océanique est composé de six volcans, et le secteur continental de sept volcans, de nombreux cônes monogéniques et de plus de 60 complexes annulaires plutoniques anorogéniques. Les laves et les roches plutoniques sont alcalines, avec leur minéralogie typique. Des néphélinites et des lamprophyres alcalins sont aussi présents. Les basaltes des secteurs océanique et continental ont des compositions géochimiques et isotopiques (Sr–Nd) semblables, attestant des sources magmatiques infralithosphériques, la croûte continentale n'ayant joué aucun rôle. Les laves

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intermédiaires sont rares et résultent de mélanges entre magmas basaltiques et felsiques. Les phonolites dérivent des magmas basaltiques par cristallisation fractionnée. En secteur continental, certains trachytes et les rhyolites ont été contaminés par la croûte continentale. Le manteau lithosphérique, traversé par les magmas, a été affecté d'un métasomatisme d'affinité carbonatitique. Les réservoirs mantelliques DM et FOZO sont impliqués dans la genèse des magmas parentaux de la LChC. ***Pour citer cet article : B. Déruelle et al., C. R. Geoscience 339 (2007).***

Keywords: Cameroon Hot Line; Alkaline; Sublithospheric; FOZO

Mots clés : Ligne chaude du Cameroun ; Alcalin ; Sublithosphérique ; FOZO

1. Introduction

The 'Cameroon Hot Line' (CHL) is the unique example on Earth of an active intraplate alkaline tectono-magmatic alignment simultaneously developed into both oceanic and continental domains. Oriented N30°E, it crosses the Gulf of Guinea and Cameroon on more than 2000 km, from Pagalu Island to Lake Chad (Fig. 1). The CHL is segmented by numerous N70°E shear zones (fracture zones) of Pan-African age (Fig. 2). These shear zones (for example, the Adamawa, also called Central Africa Shear Zone, and the Sanaga faults) and their extensions into the South-American continent (Patos, Pernambuco) before the opening of the South Atlantic Ocean traverse both the continental crust and the upper mantle down to a depth of 190 km [16,17]. They induced the development of oceanic fracture zones transverse to the mid-ocean ridge during the opening of the Atlantic Ocean in the Cretaceous. The morphology of the African coast, from the Gulf of Guinea to the Cape Palmas (Fig. 2) is directly related to these zones.

Among the numerous hypotheses that have been proposed to explain the structure and the formation of the CHL (for a comprehensive review and a discussion, see [12]), the most widely accepted structural explanation is that the CHL would be a succession of 'en-échelon' mega-tension gashes resulting from reworking during Aptian–Albian times of the N70°E shear zones at the beginning of the opening of the Central Atlantic Ocean [39]. The reworking of shear zones could be linked to the occurrence of hot lines in the asthenospheric mantle [5].

Numerous hypotheses have also been put forward to explain the characteristics of the magmatism along the CHL and to locate its source.

It has been proposed that the CHL originated from a sublithospheric 'hot zone' periodically fed and melted by a deep mantle plume head [33]. But the absence of a simple and regular age distribution (Fig. 3), which is expected in the case of a plume (hotspot trail), and the occurrence of a deep hot zone (400 km) overlaid by a cold shallow one [2] do not correspond to what is observed at Hawaii, paradigm of plume, and leads to discard this hypothesis [38].

More recently, the CHL has been considered as a hot line resulting from lithospheric cracks (N30°E) tapping a sublithospheric mantle [38]. The hotline hypothesis has been supported by deep-imaging seismic and gravity studies along the oceanic sector of the CHL [37]. Speculations for hotlines in the Atlantic part of the African plate have also been proposed to explain the occurrences of other oceanic rises (Walvis, Cape Verde–Canary...) as well as on the continental sector, but with the limitation that the presence of cratons does not permit crustal upwelling [37].

2. Geology

2.1. The volcanoes

The oceanic sector of the CHL (Fig. 1) is composed of six major volcanoes, one on each of Pagalu, São Tomé and Principe Islands and three (Santa Isabel, Biao and San Carlos) on Bioko Island. The continental sector is composed of Mt Etinde, Mt Cameroon, Mts Rumpi, Mt Manengouba, Mts Bambouto, Mt Mbam, and Mt Oku, which are built upon horsts that alternate with grabens (Kumba, Tombel, Mbo, Ndop, Tikar plain) where monogenic cones predominate. Whether the volcanism of the Cretaceous Benue rift west of Garoua and of the Kapsiki plateau is related or not to the CHL is still debated. The 69-Ma-old rhyolite flows and domes southwest of Lake Chad [71] would possibly be the northernmost occurrence of the CHL. Historical volcanic activity has been reported [12,14,65,68, and references herein] at Pico Santa Isabel (Bioko) in 1898, 1903, and 1923, and at Mt Cameroon, where six eruptions are known between 1868 and 2000. Massive outgassing of CO_2 occurred at Lakes Monoun (1984) and Nyos (1986), killing nearly 2000 persons and a large part of the cattle. The volcanism of Adamawa (distributed according to the N70°E trend) and of the Biu plateau (distributed according to the north–south

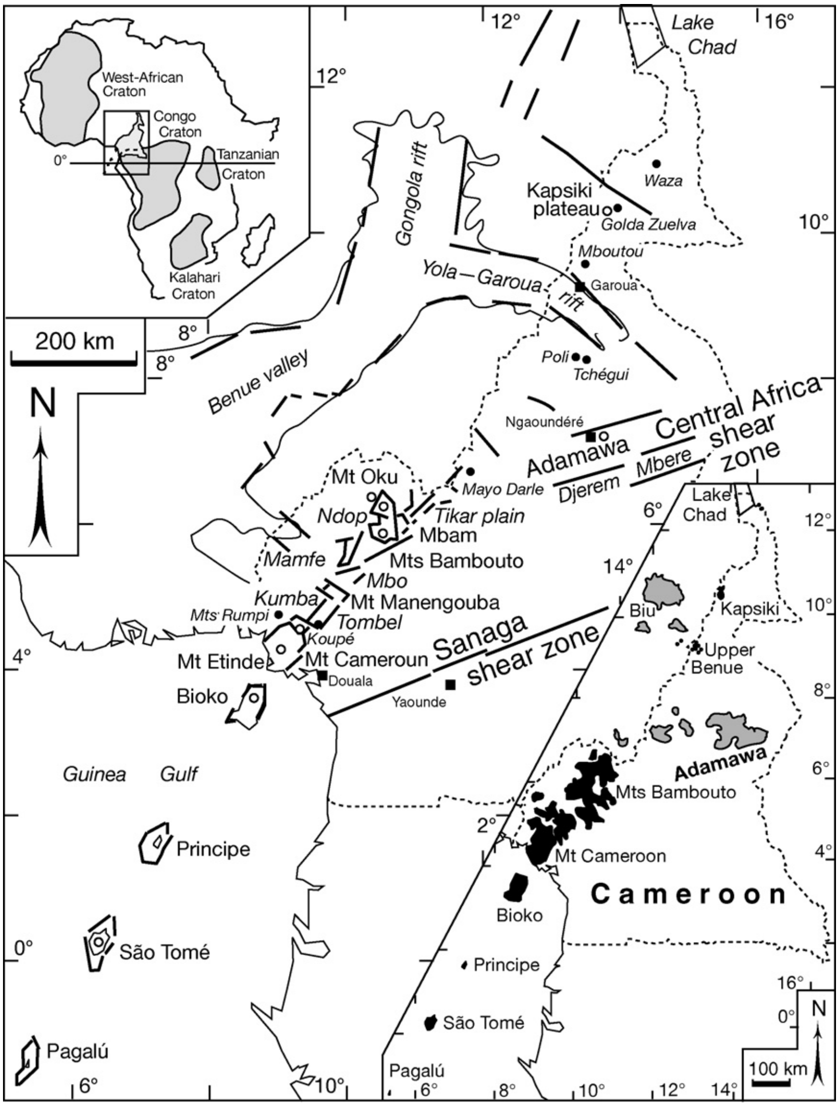

Fig. 1. The Cameroon hot line (CHL) is a N30°E-trending alignment that extends from Pagalu Island (Gulf of Guinea) to Lake Chad: it consists of oceanic and continental volcanoes and of anorogenic plutonic complexes (black circles, small *italics*). From a structural point of view, the continental sector is a succession of horsts and grabens (graben names in large *italics*). Mantle-derived xenolith occurrences are indicated by empty circles. Lower inset: Cainozoic volcanic rocks of the Cameroon Line (black) and of the other provinces (Adamawa and Biu plateau, grey). Upper inset: African cratons after [30].

Fig. 1. La ligne chaude du Cameroun s'étend de l'île de Pagalu au lac Tchad, entre les cratons Ouest-Africain et du Congo (cartouche supérieur, d'après [30]). En domaine continental, c'est une succession de horsts et de grabens (en grand *italique*), où sont installés les volcans. Les principaux plutons cénozoïques anorogéniques sont indiqués (petits ronds noirs, petit *italique*). Les gisements de nodules de roches ultramafiques sont indiqués par des petits ronds blancs. L'Adamaoua et le plateau de Biu sont deux autres entités volcaniques distinctes de la ligne chaude du Cameroun (en grisé, cartouche inférieur).

Gongola rift fracturation) does not belong to the CHL, as it is presently defined.

2.2. The anorogenic ring-complexes

Because of erosion, more than 60 anorogenic ring-complexes crop out along the continental segment of the Cameroon Line. They are more abundant in the southern part of the continental sector. Their ages are comprised between 6 and 70 Ma [38]. All the complexes have a typical alkaline character [12]. Trachytes and rhyolites are commonly associated to plutonic ring complexes and the Kokoumi massif is the only one that includes significant volumes of lamprophyres [46].

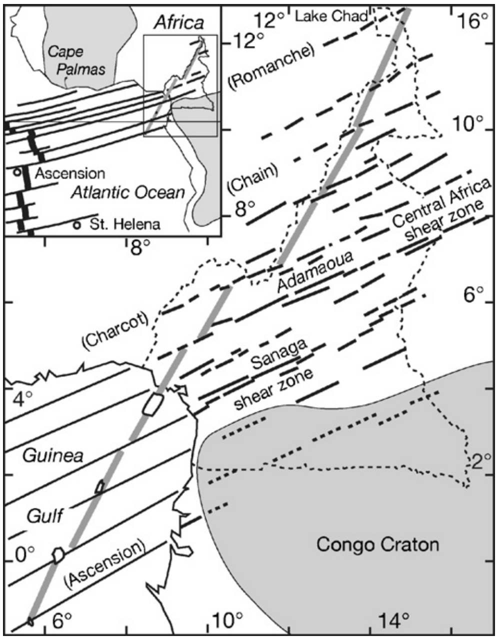

Fig. 2. The Cameroon Hot Line trends N30°E (thick grey lines). Its continental sector is segmented by Pan-African shear zones in Africa propagating as fracture zones into the Atlantic Ocean (data after [12,18,19,37,39,53,58]). Its northern extension towards Lake Chad is tentative only. Dotted lines in the Congo craton correspond to Proterozoic dykes of doleritic composition.

Fig. 2. La ligne chaude du Cameroun, orientée N30°E, est recoupée par des décrochements continentaux (orientés N70°E), qui se prolongent en zones de fractures en domaine océanique (voir cartouche, données d'après [12,18,19,37,39,53,58]). L'extension de la LChC vers le nord (lac Tchad) est supposée. Les lignes pointillées dans le craton du Congo correspondent à des fractures soulignées par des dykes d'âge Protérozoïque.

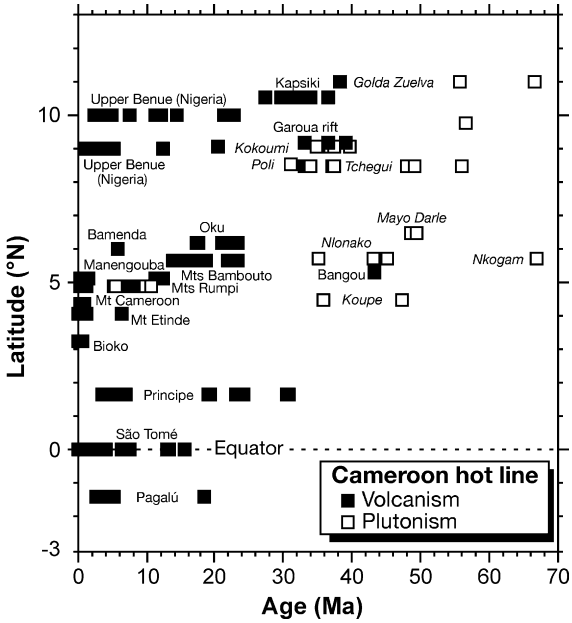

Fig. 3. Age distribution of volcanic and plutonic rocks from the Cameroon hot line (data from [13] and references herein, and [7,20,32,35,38,43,46–49,56]).

Fig. 3. Distribution des âges des roches volcaniques et plutoniques de la ligne chaude du Cameroun. Source des données : [7,20,32,35,38,43, 46–49,56].

3. Petrography

3.1. Nomenclature, geographical distribution of the lavas

All the rocks of the CHL (except the nephelinite series of Mt Etinde) are typically alkaline. The lithological sequence of differentiated alkaline series is complete and includes basaltic lavas (alkali basalts – and picrites –, hawaiites), intermediate lavas (mugearites and benmoreites), and felsic lavas (phonolites, trachytes, and alkali rhyolites) (Fig. 4). The lavas have been classified (see Fig. 7) according to their D.I. [70] and to their mineralogy (occurrence of hauyne, nosean or sodalite in the mode of phonolites, absence of feldspathoids in the mode of trachytes, and occurrence of glass and occasional quartz phenocrysts in rhyolites). Nevertheless, a gap separates the basaltic lavas from the felsic ones in both oceanic and continental sectors.

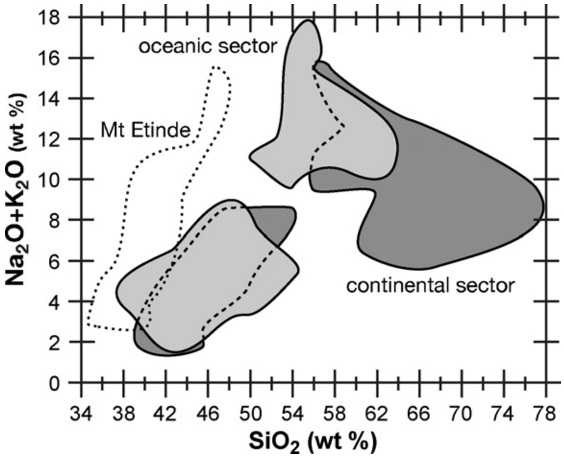

Fig. 4. Total alkalis–silica (TAS) diagram for the lavas of the Cameroon hot line. Nephelinites from Mt Etinde are indicated separately. Data from [12] and references herein and from [9,11,14,22,28,35,36,42–44, 55,62,63,65,71] and unpublished data.

Fig. 4. Distribution des laves des secteurs océanique et continental de la ligne chaude du Cameroun dans le diagramme SiO_2–($Na_2O + K_2O$). Le domaine des néphélinites du Mt Étindé a été présenté séparément. Source des données : [12] et références citées [9,11,14,22,28,35,36, 42–44,55,62,63,65,71], et données non publiées.

Trachytes are more abundant in the continental sector and rhyolites are absent from the oceanic one. Phonolites are more alkaline and less silica-rich in the oceanic sector. Although difficult to quantify, the volume ratio between felsic and basaltic lavas increases from the ocean–continent boundary region (Mt Cameroon and Bioko volcanoes are only composed of basalts) to the northern and southern extremities of the line.

3.2. *Alkaline lavas s.s.*

The basaltic lavas have seriate to porphyritic textures. Basalts contain phenocrysts of olivine and augite in a microlitic matrix of plagioclase, augite, and Ti-magnetite. Hawaiites contain abundant plagioclase phenocrysts. Mugearites contain rare phenocrysts of plagioclase, augite, Fe–Ti oxides, and of amphibole destabilized into clinopyroxene and oxides, and xenocrysts of sanidine, quartz, apatite, and biotite. Benmoreites contain feldspar and biotite phenocrysts and plagioclase and/or quartz xenocrysts. The felsic lavas have a microlitic porphyritic texture. Phonolites contain phenocrysts of sanidine, aegirine-augite, brown hornblende (kaersutite, hastingsite), Ti-rich aenigmatite, Fe–Ti oxides, nepheline and hauyne (or nosean or sodalite) in a matrix of microlites of sanidine, aegyrine–augite, and Fe–Ti oxides. Microphenocrysts of titanite and apatite may also occur. Trachytes contain mostly phenocrysts and microlites of K-felspar (sanidine, anorthoclase). Aegyrine-augite, Ti-rich aenigmatite, brown hornblende (hastingsite, pargasite), richterite, arfvedsonite, biotite, Fe–Ti oxides, occasional titanite, apatite, and zircon, and exceptional fayalite, may also occur in phenocrysts and/or microlites. Rhyolites have hyaloporphyritic to hyalopilitic textures; some of them are ignimbrites, pumices, or obsidians. They contain phenocrysts of sanidine–anorthoclase and occasional quartz, arfvedsonite, richterite, magnetite, ilmenite, aegyrine–augite, biotite, and zircon in a matrix of microlites of K-felspar and glass. In some samples, ghosts of fayalite phenocrysts [57] are commonly replaced by quartz and alkali feldspar.

3.3. *'Transitional' lavas*

Basaltic lavas (with D.I. > 32) close to hawaiites have been described at Mts Mbam [40], Bangou [20], and Bana [31], and qualified of transitional, or transitional towards tholeiites. These lavas are older than Miocene, strongly weathered (occurrence of epidote, carbonates, chlorite). They commonly erupted along fissures and are located in zones where high-temperature N70°E fracturation predominates [52,53]. Olivine phenocrysts are rare (Fo55–65) or absent, while plagioclase phenocrysts are abundant (mode $> 20\%$): hence the name 'plagioclase basalts' [31]. Pigeonite never occurs. These lavas do not present the mineralogical characteristics typical of tholeiitic lavas erupted in extension domains. Nevertheless, in Cameroon, dykes and sills of basaltic lavas (ages between 43 and 87 Ma) with typical continental tholeiitic character [45] occur in Cretaceous east–west semi-grabens of Mayo Oulo–Léré and Babouri–Figuil. These lavas do not belong to the CHL.

3.4. *Nephelinitic lavas*

The lavas from Mt Etinde [56] are peralkaline. They are melanephelinites, nephelinites *sensu stricto* and varied nephelinites (that contain one or more of the following minerals: nosean, melilite, perovskite, garnet, aenigmatite, leucite, and felspar) and hauynophyres.

3.5. *Lamprophyres*

Some alkaline lamprophyres (camptonites and monchiquites) occur at Mt Cameroon [50] and in the northern part of the continental sector of the CHL, in the Benue valley, at the Kokoumi ring-complex [46] and at Tchircotché [47,49]. They are contemporaneous with the nearby alkali basalts. Mt Cameroon camptonites contain olivine, clinopyroxene (diopside core), plagioclase, and Ti-magnetite phenocrysts in a matrix of plagioclase, amphibole, clinopyroxene, and magnetite microlites. Monchiquites from Tchircotché have a hyaloporphyritic texture with phenocrysts of olivine, clinopyroxene (diopside), amphibole (kaersutite) and/or microphenocrysts of biotite in an analcitic matrix of Fe–Ti oxides and apatite microlites, where feldspars may occur. These lamprophyres contain abundant (mode up to 8%) carbonate–analcite–glass ocelli.

3.6. *Plutonic rocks*

Ring-complexes are essentially made of sometimes layered (=cumulates) gabbroic rocks (with olivine and/or clinopyroxene) associated with syenites (with riebeckite), nepheline syenites, alkali granites and peralkaline granites (with riebeckite) [12 and references herein, 27,29,32,46,51,60]. Not all these rocks are systematically present in all ring complexes.

3.7. *Ultramafic xenoliths*

Numerous occurrences of ultramafic xenoliths have been found in basaltic lavas all along the CHL (Fig. 1):

six sites at São Tomé [6], two at Santa Isabel (Bioko) [13], and one in each of the other sites: Mt Cameroon [15], Barombi–Mbo (Kumba) [67], Lake Enep (Oku) [34,61], Nyos (Wum) [41,68] and Liri (South of the Kapsiki plateau) [66]. The rocks are mostly spinel lherzolites; some pyroxenites occur at São Tomé and at Mt Cameroon. Spinel [23] and garnet [69] lherzolites are also present in Adamawa.

4. Geochemistry and isotope geochemistry

Except the nephelinites of Mt Etinde, the silica–alkalis diagram (Fig. 4) points out the Daly gap between basaltic and felsic alkaline lavas. Mugearites and benmoreites are very scarce (15 and 13 samples respectively, among more than 400 samples for the whole CHL). In the oceanic sector, phonolites are poor in silica and trachytes are very scarce. Rhyolites only occur in the continental sector.

The basalts from the oceanic and continental sectors have similar trace element compositions (Fig. 5). These basalts are quite similar to St Helena basalts, although the latter are slightly richer in uranium. Although basalts from Adamawa do have patterns similar to those of CHL basalts, they have, by contrast, higher trace element contents (particularly from Rb to Nb).

Some lavas are considered as transitional or tholeiitic transitional according to their high Y/Nb ratios (>0.9) and to the gentle slope of their REE patterns $(La/Yb)_N < 12$) when compared to alkali basalts (Y/Nb < 1 and $(La/Yb)_N > 12$). The studied lavas of Mt Bana are not true basalts, but instead hawaiites with high SiO_2 (47.4–51.6%) and Al_2O_3 (>20%) contents and very low Ni contents (<20 ppm). Moreover, they are strongly weathered (sum of major element oxides often <98 wt%, sometimes <96 wt% [31]). Lavas from Mts Bangou [20] and Mbam [40] have the same characteristics. At Mt Bangou, the Ti–Zr–Y concentrations are typically in the range of alkaline lavas. The transitional character cannot be attributed to these lavas.

The nephelinites (Mt Etinde) are characterized by their high Sr, Ba, Zr contents (higher than 10000, 3500, and 1100 ppm, respectively), by high LREE/HREE ratios $(22 < (La/Yb)_N < 48)$, and by high volatile contents (>0.6% CO_2; >8% H_2O and >2.0% SO_3).

Lamprophyres of the CHL have systematically lower MgO (<8%), Cr (<60 ppm) and Ni (<75 ppm) contents than the basalts, but their contents in incompatible elements are by far higher than those of basalts. Their normalized patterns $(22 < La/Yb)_N < 32)$ are steeper than those of basalts $(14 < La/Yb)_N < 28)$.

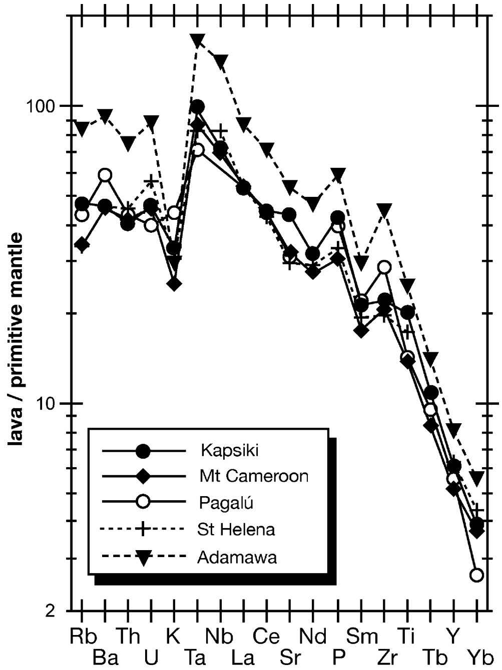

Fig. 5. Primitive mantle-normalized multi-element diagram for basalts of the Cameroon Hot Line (data from [9,25,44]). Primitive mantle after [26]. Basalts from Mt Cameroon and from the extremities of the continental (Kapsiki) and oceanic (Pagalu) sectors of the CHL are considered to be representative of the whole line. Basalts from St Helena [8] and Adamawa [54,59] are also indicated for comparison.

Fig. 5. Diagramme normalisé (manteau primitif d'après [26]) de basaltes de la ligne chaude du Cameroun. Ont été sélectionnés comme échantillons représentatifs, les basaltes du mont Cameroun, et ceux provenant des extrémités des secteurs continental (Kapsiki [48]) et océanique (Pagalú [25]) de la LChC [9]. Sont indiqués, pour comparaison, des basaltes représentatifs de Sainte-Hélène [8] et de l'Adamaoua [54,59]. Données d'après [1].

Basaltic lavas from both continental and oceanic sectors have identical Sr and Nd isotope compositions [9,24,25,33–36,43,44,62]. Their $(^{87}Sr/^{86}Sr)_i$ and ε_{Nd_i} vary between 0.70299 and 0.70343, and +1.7 and +7.0, respectively. Megacrysts (mostly of clinopyroxene) have similar isotope compositions [34]. Similarly, Hf isotope compositions are identical for both sectors of the CHL (ε_{Hf_i} mean ≈ +1.95 [3]). When compared to the atmosphere $^3He/^4He$ ratio (R_a), the helium isotope compositions of the CHL lavas show contrasting results: they are either considered as homogeneous around $6.3 \times R_a$ all along the CHL [4], or they increase from 4 to $6 \times R_a$ at the continent–ocean boundary to $\sim 8 \times R_a$ towards the northern and southern extremities of the CHL, reaching there values close to those of HIMU-type basalts [1]. Lead isotope compositions present significant regional variations [24,25,33]. Basalts from Pagalu, the southernmost island, are the least radiogenic ($^{206}Pb/^{204}Pb$:

19.01; $^{208}Pb/^{204}Pb$: 38.83), whereas basalts from volcanoes located near the continent–ocean boundary (Bioko, Mt Etinde, and Mt Cameroon) are strongly more radiogenic ($^{206}Pb/^{204}Pb$: 20.52; $^{208}Pb/^{204}Pb$: 40.34). By contrast, $^{207}Pb/^{204}Pb$ ratios do not vary significantly all along the CHL. Osmium isotope ratios ($^{187}Os/^{188}Os$) are lower in the oceanic sector (0.128–0.188) than in the continental one (0.145–0.557) [21]. Measurements of ^{238}U–^{230}Th–^{226}Ra disequilibria for lavas from historical eruptions of Mt Cameroon are well distinct for each eruption from 1909 to 2000, and do not show any evolution with time [72].

Phonolites have Sr–Nd–Pb isotope signatures similar to those of basaltic lavas. The same applies for trachytes from the oceanic sector. The whole lava series (from basalts to trachytes) of Principe [25] does not show any significant isotope variation. In the continental sector, some trachytes and rhyolites have initial Sr ratios higher (up to 0.715, Fig. 7) and ε_{Ndi} lower (from +3.22 to +0.32) than basalts.

Lamprophyres have Sr and Nd isotope compositions [47,48,50] close to those of basalts, even if $(^{87}Sr/^{86}Sr)_i$ values are slightly higher (0.70329–0.70387) and ε_{Ndi} slightly lower (+2.45 to +2.65) than those of basalts.

5. Discussion

5.1. Hot spot, hot line?

Following the hypothesis of the presence of a fossil hot spot at the continent–ocean boundary [24], it has been suggested that the magmatic activity along the CHL could be related to an active plume with a HIMU ($\mu = {}^{238}U/^{204}Pb$) signature initiated in the deep mantle and that this plume would be currently expanding at the asthenosphere–lithosphere boundary, entraining ambient materials represented by a mixture between depleted (DM) and enriched (EMI) mantle components [33]. As there is no hot-spot trail (regular age progression along the line), the classical stationary hot-spot model can be discarded.

An alternative model to explain volcanic alignments is that of the 'hot line'. First proposed for the volcano-tectonic alignment that extends from Easter Island to San Felix and San Ambrosio islands in the eastern Pacific Ocean [5], the hot-line hypothesis has been proposed for the CHL volcano-tectonic alignment [13], and sustained with seismic and gravimetric data in the oceanic domain [37]. The development of a hot line is accompanied by a crustal uplift in the oceanic and continental sectors. Other hot lines have been proposed for the Atlantic Ocean (Walvis, Cap-Vert, Canaries...) and the Africa continent [37]. They would represent the surface expression of asthenospheric convective rolls that could produce lithospheric uplift, decompression melting, and accumulation of melts. Upwelling could also cause the reactivation of pre-existing (Pan-African) lithospheric fractures. The emplacement of numerous volcanoes (from 40 Ma ago to Present) and of numerous plutonic ring-complexes (from 70 to 30 Ma ago) along the CHL appears to be strongly controlled by these lithospheric fractures.

5.2. Nature of the mantle source, magma genesis, and magma differentiation

5.2.1. Sublithospheric source

The geochemical and isotopic similarities between the CHL oceanic and continental basalts attest that the continental crust did not play any role in the magma genesis and that the source is not of lithospheric origin. Indeed, the oceanic sector of the CHL is built upon a young oceanic lithosphere of Upper Cretaceous age, while the continental lithosphere is much older and of Pan-African age (>500 Ma). The Sr–Nd–Hf isotope compositions imply that the lithospheric contribution is negligible. Osmium isotope ratios [21] and data from U–Th–Ra disequilibria [72] also suggest an asthenospheric origin for the basaltic magmas of the CHL.

Nephelinites from Mt Etinde have a deeper source than basaltic magmas. They erupted at the very limit between the ocean and the continent, where fracturation (fractures at the continent-ocean boundary and regional N30°E and N70°E zones) is more intense and deeper.

Lead isotope variations require relatively recent U/Pb and Th/U fractionations (~125 Ma) in the upper mantle [24].

5.2.2. FOZO, HIMU?

Geochemical characteristics and Pb isotopic compositions of basalts have been initially interpreted [24,33] as suggesting a HIMU-type mantle source similar to that of St Helena, the influence of the HIMU component decreasing on 400 km, northwards and southwards, from the continent–ocean boundary [24]. It is noteworthy that St Helena is located on the southwards extension of the CHL (Fig. 2, inset). Nevertheless, in Pb–Pb, Pb–Sr and Sr–Nd isotope diagrams (Fig. 6), all the data for the basalts (and nephelinites) of the CHL define broad domains encompassing the recently redefined [64] FOZO (FOcal ZOne). The CHL domains are generally outside the typical HIMU field. Therefore, CHL basaltic magmas do not result from the mixing between the Atlantic MORB component (DM) and HIMU. The

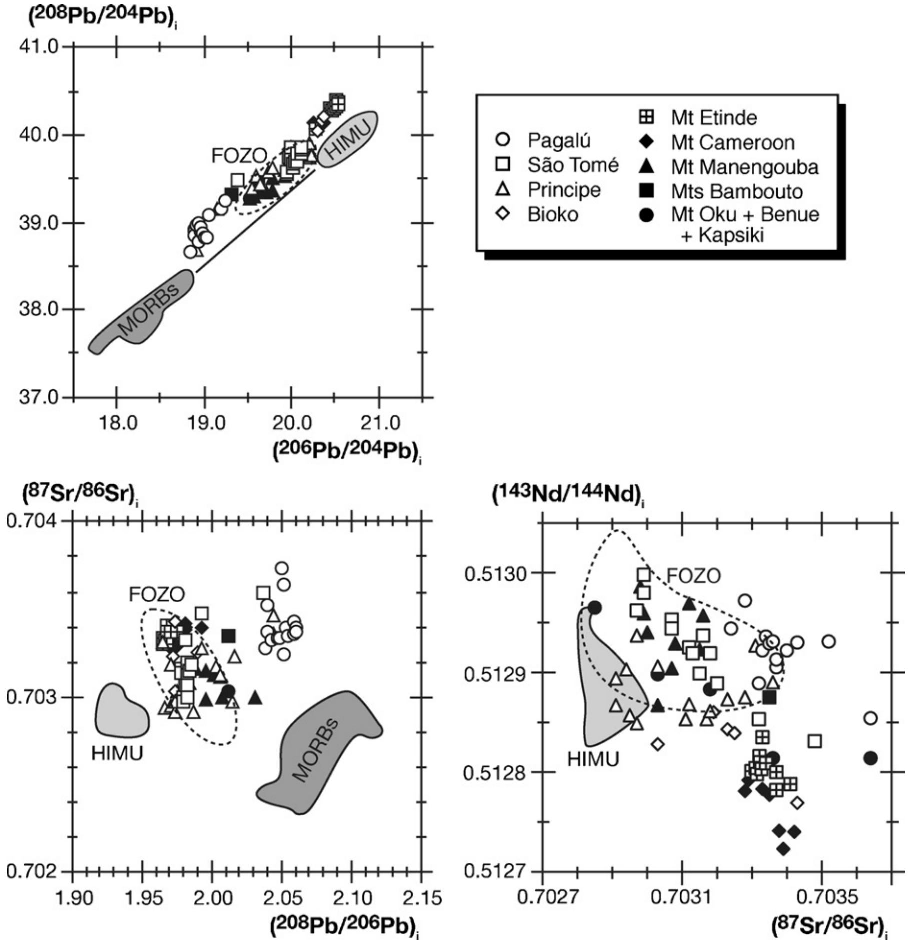

Fig. 6. $(^{87}Sr/^{86}Sr)_i$–$(^{143}Nd/^{144}Nd)_i$, $(^{208}Pb/^{206}Pb)_i$–$(^{87}Sr/^{86}Sr)_i$ and $(^{206}Pb/^{204}Pb)_i$–$(^{208}Pb/^{204}Pb)_i$ diagrams for basalts of the Cameroon hot line (data after [24,25,33–36,44,46,47,49,62] and unpublished). FOZO (Focal Zone) and HIMU fields after [64]. Data from St Helena [8] and N-MORBs from the Central Atlantic Ocean [64 and ref. herein] are also presented for comparison. The basalts of the Cameroon hot line plot above the line between St Helena basalts and Atlantic N-MORBs.

Fig. 6. Diagrammes $(^{87}Sr/^{86}Sr)_i$–$(^{143}Nd/^{144}Nd)_i$, $(^{208}Pb/^{206}Pb)_i$–$(^{87}Sr/^{86}Sr)_i$ et $(^{206}Pb/^{204}Pb)_i$–$(^{208}Pb/^{204}Pb)_i$ pour les laves de la « ligne du Cameroun » (données d'après [24,25,33–36,44,46,47,49,62] et données non publiées). Les champs de Sainte-Hélène [8] et des réservoirs mantelliques FOZO (FOcal ZOne), HIMU et des N-MORBs (basaltes de l'Atlantique central) sont indiqués (données d'après [64] et références citées).

isotopic dataset suggests that both DM and FOZO were involved in the genesis of CHL alkaline series, as shown for the majority of alkali basalts from oceanic islands. Moreover, a component with a radiogenic Pb signature distinct from HIMU is also needed. The differentiated lavas of the CHL derived from the evolution of these basaltic magmas by crystal fractionation of olivine, clinopyroxene, Fe–Ti oxides, plagioclase, and apatite (e.g., [35,44,48]).

5.2.3. Metasomatic effects

Evidence of metasomatism in the mantle source of the CHL parental magmas has been deduced from mantle xenoliths, on the one hand, and from lamprophyres and nephelinites, on the other hand.

Metasomatized peridotites are likely to be representative of enriched subcontinental lithosphere, the commonly accepted metasomatic agent being partial melts that form a network of thin veins lacing mantle peridotite beneath zones of recent volcanism and that induce the crystallization of K-rich amphibole [15,34].

The occurrence of amphibole (pargasite) in upper-mantle xenoliths (spinel lherzolites, websterites, wehrlites, pyroxenites) at Mt Cameroon [15], Mt Bambouto [36], Mt Oku [34], and Nyos [68] suggests that the lithospheric mantle beneath the CHL has been metasomatized. The presence of fluid inclusions and interstitial carbonates in amphibole-free mantle xenoliths from São Tomé [6] is another evidence of metasomatic fluid activity. Moreover, the low Al_2O_3 (<4 wt%) and high CaO (21–24 wt%) contents of clinopyroxenes, their REE enrichment and also the relatively high f_{O2} (above the FMQ buffer) in dunites [6] in São Tomé xenoliths [6] are also suggestive of a metasomatic influence by carbonatitic fluids. LREE enrichment in clinopyroxenes and amphiboles from mantle xenoliths [67,68] points to a cryptic metasomatic event by fluids enriched in those elements.

The lamprophyres of the CHL (monchiquites from Kokoumi [46] and Tchircotché [49] and camptonites from Mt Cameroon [50]) have high incompatible element contents and contain hydrated (kaersutite, biotite) and/or carbonate minerals, suggesting that they originate from a volatile-rich infra-lithospheric metasomatized peridotite mantle. The various Mt Etinde nephelinites contain pockets of carbonates or interstitial carbonates, indicating that the mantle source from which the nephelinitic magmas derive has probably been metasomatized by liquids of carbonatitic affinities [56]. It is interesting to note that lamprophyres and nephelinites are clearly related to domains of lithosphere extension such as continental rift (Benue) and Atlantic Ocean opening zone (Mt Etinde, Mt Cameroon).

The isotopic characteristics of the various xenoliths from the continental sector of the CHL suggest that they could represent fragments of sub-continental lithosphere that formed during the Pan-African orogeny and were subsequently enriched during metasomatism at the time of early break-up of Gondwana [34,68].

5.2.4. *Silica-rich evolved lavas: crustal contamination?*

Whilst the basaltic magmas have not been contaminated during their ascent through the continental crust, their differentiation is accompanied by a significant crustal contamination, as demonstrated by their Sr–Nd isotope compositions (e.g., Mts Bambouto [35], Benue valley [48] Kapsiki plateau [44]). The magmatic evolution from basalt to phonolite can be modelled by crystal fractionation without crustal contamination [44,48]. On the contrary, the evolution to trachyte and rhyolite requires a crustal component, as indicated by their high $(^{87}Sr/^{86}Sr)_i$ and low ε_{Nd_i} values. A contamination (up to 10 wt% [48]) by a continental crust ($^{87}Sr/^{86}Sr \approx 0.750$) allows to explain the high $^{87}Sr/^{86}Sr$ values of some trachytes and rhyolites (Fig. 7).

At Tchabal Nganha (Adamawa), $(^{87}Sr/^{86}Sr)_i$ values regularly increase with increasing Rb and SiO_2 contents

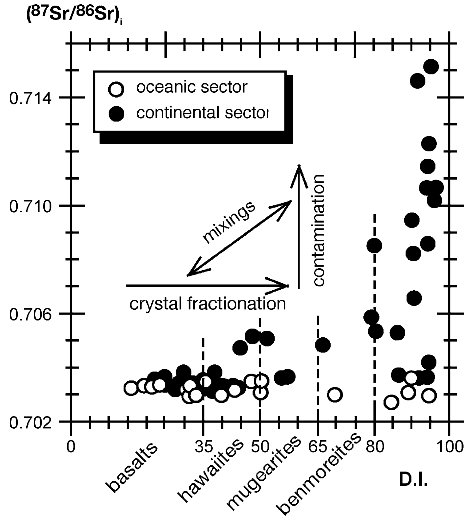

Fig. 7. Sr-isotope initial ratio variations *vs* Differentiation index (D.I.) [70] for the differentiated lavas of the Cameroon hot line. Phonolites, trachytes and rhyolites have D.I. > 80. The arrows indicate the results of contamination by a continental crust, of mixings between basaltic and evolved magmas, and of fractional crystallization (same data sources as for Fig. 6).

Fig. 7. Variations de la composition isotopique initiale du Sr en fonction de l'indice de différenciation I.D. [70] pour les suites différenciées de la ligne du Cameroun. Les phonolites, trachytes et rhyolites ont des I.D. > 80. Les flèches indiquent les effets : de la contamination par la croûte continentale, des mélanges magmatiques entre magmas évolués et magmas basaltiques, et de la cristallisation fractionnée. Source des données : voir Fig. 6.

[59], suggesting assimilation coupled with crystal fractionation process (AFC) [10].

5.2.5. *Magma mixings*

Intermediate lavas (mugearites and benmoreites) have mineralogical characteristics (simultaneous presence of two populations of feldspar phenocrysts, occurrence of xenocrysts) typical of both basaltic and evolved magmas, suggesting that they can originate through mixing between these two magma types (Fig. 7). Nevertheless, considering the very limited number of mugearites and benmoreites observed in the CHL when compared to ubiquitous basalts and hawaiites, on the one hand, and to phonolites, trachytes and rhyolites, on the other hand, this process (which tends to reduce the Daly gap) must have been very limited.

6. Conclusions

The Cameroon Hot Line (CHL) is a N30°E magmato-tectonic megastructure of Central Africa, and the paradigm of active hot lines on Earth, a concept originally defined for the Easter chain in the Pacific Ocean. It stretches on both the oceanic and continental domains on more than 2000 km, from the Gulf of Guinea, Central Atlantic Ocean, to Lake Chad. This line is marked by numerous volcanoes and plutonic ring-complexes of Cainozoic to Recent age. As there is no regular age progression along the line, the classical plume model can be discarded. Nevertheless, the volcanic and plutonic rocks display the typical petrological and geochemical signature of alkaline intraplate magmatism, the Mt Etinde nephelinites being peralkaline.

Geophysical studies in the oceanic sector suggest that the volcanic alignment could be related to a deep-mantle hot line. Lithospheric uplift induced decompression melting and the upwelling of melted material provoked the reactivation of pre-existing (Pan-African) N70°E lithospheric fracture zones that previously affected the African and South-American continents at the beginning of the opening of the central Atlantic Ocean.

The parental basaltic magmas have similar Sr and Nd isotopic composition in both oceanic and continental sectors of the line, which implies a common sublithospheric mantle source. These magmas have been enriched during their ascent through the lithospheric mantle that has been metasomatized by volatile-rich (carbonatitic) fluids. In isotopic diagrams, CHL lavas define broad domains encompassing FOZO, but not HIMU. Besides DM, a radiogenic Pb component, distinct from HIMU, is needed to explain the observed range of isotopic composition. Differentiation of basaltic magmas to trachytes and rhyolites in the continental domain was accompanied by significant crustal contamination, whereas evolution to phonolites has not been affected.

Nowadays, the volcanic activity is dominated by eruptions of basaltic lavas (Bioko Island, Mt Cameroon) and gases (Lakes Monoun, Nyos) and concentrated in the central zone of the line, where both the N30°E and N70°E fracturations are by far more intense.

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References

[1] F.T. Aka, K. Nagao, M. Kusakabe, H. Sumino, G. Tanyileke, B. Ateba, J. Hell, Symmetrical helium isotope distribution on the Cameroon Volcanic Line, West Africa, Chem. Geol. 203 (2004) 205–223.

[2] D.L. Anderson, Y.-S. Zhang, T. Tanimoto, Plume heads, continental lithosphere, flood basalts and tomography, in: B.C. Storey (Ed.), Magmatism and the causes of continental break-up, Geol. Soc. Lond. Spec. Publ. 68 (1992) 99–124.

[3] C.J. Ballentine, D.-C. Lee, A.N. Halliday, Hafnium isotopic studies of the Cameroon line and new HIMU paradoxes, Chem. Geol. 139 (1997) 111–124.

[4] D.N. Barfod, C.J. Ballentine, A.N. Halliday, J.G. Fitton, Noble gases in the Cameroon Line and the He, Ne, and Ar isotopic composition of high-μ (HIMU) mantle, J. Geophys. Res. 104 (1999) 29509–29527.

[5] E. Bonatti, C.G.A. Harrison, Hot lines in the Earth's mantle, Nature 263 (1976) 402–404.

[6] R. Caldeira, J.M. Munhá, Petrology of ultramafic nodules from São Tomé Island, Cameroon Volcanic Line (oceanic sector), J. Afr. Earth Sci. 34 (2002) 231–246.

[7] J.-M. Cantagrel, C. Jamond, M. Lasserre, Le magmatisme alcalin de la ligne du Cameroun au Tertiaire inférieur, données géochronologiques K/Ar, C. R. somm. Soc. geol. France 6 (1978) 300–303.

[8] D.J. Chaffey, R.A. Cliff, B.M. Wilson, Characterization of the St Helena magma source, in: A.D. Saunders, M.J. Norry (Eds.), Magmatism in the Ocean Basins, Geol. Soc. Lond. Spec. Publ. 43 (1989) 257–276.

[9] C. Chauvel, A.N. Dia, M. Bulourde, F. Chabaux, S. Durand, P. Ildefonse, M. Gérard, B. Déruelle, I. Ngounouno, Do decades of tropical rainfall affect the chemical compositions of basaltic lava flows in Mt Cameroon? J. Volcanol. Geotherm. Res. 141 (2005) 195–223.

[10] D.J. DePaolo, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization, Earth Planet. Sci. Lett. 53 (1981) 189–202.

[11] B. Déruelle, C. Moreau, E. Nkonguin Nsifa, Sur la récente éruption du mont Cameroun (16 octobre–12 novembre 1982), C. R. Acad. Sci. Paris, Ser. II 296 (1983) 807–812.

[12] B. Déruelle, C. Moreau, C. Nkoumbou, R. Kambou, J. Lissom, E. Njongfang, R.T. Ghogomu, A. Nono, The Cameroon Line: a review, in : A.B. Kampunzu, R.T. Lubala (Eds.), Magmatism in Extensional Structural Settings. The Phanerozoic African Plate, Springer-Verlag, Berlin, Germany, 1991 , pp. 274–327.

[13] B. Déruelle, I. Ngounouno, J.-M. Bardintzeff, Wehrlites et pyroxénites en nodules dans les basaltes du Mt Cameroun: évidence d'un métasomatisme mantellique, J. Soc. Geosci. Afr. 1 (2001) 90–91.

[14] B. Déruelle, J.-M. Bardintzeff, J.-L. Cheminée, I. Ngounouno, J. Lissom, C. Nkoumbou, J. Etame, J.V. Hell, G. Tanyileke, J. N'ni, A. Bekoa, N. Ntomu, A. Nono, P. Wandji, J. Fosso, D.G. Nkouathio, Éruptions simultanées de basalte alcalin et de hawaiite au mont Cameroun (28 mars–17 avril 1999), C. R. Acad. Sci. Paris, Ser. IIa 331 (2000) 525–531.

[15] B. Déruelle, I. Ngounouno, C. Nkoumbou, Mt Cameroon, Mt Etinde, and Bioko Island volcanoes of the 'Cameroon hot Line'. Evolution of Ocean Island Volcanoes, Penrose Conf. Ser., Galapagos Islands, 4–12 June 1998, abstract volume, p. 28.
[16] C. Dorbath, L. Dorbath, J.D. Fairhead, G.W. Stuart, A teleseismic delay time study across the Central African Shear Zone in the Adamawa region of Cameroon, West Africa, Geophys. J. R. Astron. Soc. 86 (1986) 751–766.
[17] L. Dorbath, C. Dorbath, G. Stuart, D. Fairhead, Structure de la croûte sous le plateau de l'Adamaoua (Cameroun), C. R. Acad. Sci. Paris, Ser. II 298 (12) (1984) 539–542.
[18] R.A. Edwards, R.B. Whitmarsh, R.S. Scrutton, Synthesis of the crustal structure of the transform continental margin off Ghana, northern Gulf of Guinea, Geo-Mar. Lett. 17 (1997) 12–20.
[19] J.-P. Fail, L. Montadert, J.-R. Delteil, P. Valéry, P. Patriat, R. Schlich, Prolongation des zones de fractures de l'océan Atlantique dans le golfe de Guinée, Earth Planet. Sci. Lett. 7 (1970) 413–419.
[20] J. Fosso, J.-J. Ménard, J.-M. Bardintzeff, P. Wandji, F.M. Tchoua, H. Bellon, Les laves du mont Bangou : une première manifestation volcanique éocène, à affinité transitionnelle, de la ligne du Cameroun, C. R. Geoscience 337 (2005) 315–325.
[21] A. Gannoun, K.W. Burton, D. Barfod, A. Halliday, Osmium-isotope variations in Cameroon Line basalts: HIMU mantle versus crustal contamination, AGUFM.V21D.07G, 2001 (abstract).
[22] B. Gèze, Sur les massifs volcaniques du Cameroun occidental, C. R. Acad. Sci. Paris 212 (1941) 498–500.
[23] M. Girod, J.-M. Dautria, E. Ball, D. Soba, Estimation de la profondeur du Moho sous le massif volcanique de l'Adamaoua (Cameroun) à partir de l'étude d'enclaves de lherzolite, C. R. Acad. Sci. Paris, Ser. II 298 (1984) 699–704.
[24] A.N. Halliday, J.P. Davidson, P. Holden, C. DeWolf, D.-C. Lee, J.G. Fitton, Trace element fractionation in plumes and the origin of HIMU mantle beneath the Cameroon line, Nature 347 (1990) 523–528.
[25] A.N. Halliday, A.P. Dickin, A.E. Fallick, J.G. Fitton, Mantle dynamics: a Nd, Sr, Pb and O isotopic study of the Cameroon line volcanic chain, J. Petrol. 29 (1988) 181–211.
[26] A.W. Hofmann, Chemical differentiation of the Earth: the relationship between mantle, continental crust, oceanic crust, Earth Planet. Sci. Lett. 90 (1988) 297–314.
[27] H. Jacquemin, J. Gouhier, W. Brown, I. Parsons, Les associations minérales du complexe anorogénique de Mboutou (Nord Cameroun), C. R. Acad. Sci. Paris 292 (1981) 203–206.
[28] E. Jérémine, Sur les laves des massifs volcaniques du Cameroun occidental, C. R. Acad. Sci. Paris 212 (1941) 495–498.
[29] R. Kambou, J.-P. Nzenti, D. Soba, Apport à la connaissance des complexes anorogéniques d'âge Tertiaire de la ligne du Cameroun : le massif pluto-volcanique de Tchégui (Nord Cameroun), C. R. Acad. Sci. Paris, Ser. II 308 (1989) 1257–1260.
[30] A.B. Kampunzu, M. Popoff, Distribution of the main Phanerozoic African rifts and associated magmatism: introductory notes, in : A.B. Kampunzu, R.T. Lubala (Eds.), Magmatism in Extensional Structural Settings, The Phanerozoic African Plate, Springer-Verlag, Berlin, 1991, pp. 2–10.
[31] G. Kuepouo, J.-P. Tchouankoue, T. Nagao, H. Sato, Transitional tholeiitic basalts in the Tertiary Bana volcano-plutonic complex, Cameroon Line, J. Afr. Earth Sci. 45 (2006) 318–332.
[32] M. Lasserre, Mise au point sur les granitoïdes dits « ultimes » du Cameroun : gisement, pétrographie et géochronologie, Bull. BRGM, 2^{e} ser., sect. IV 2 (1978) 143–159.
[33] D.-C. Lee, A.N. Halliday, J.G. Fitton, G. Poli, Isotopic variations with distance and time in the volcanic islands of the Cameroon line: evidence for a mantle plume origin, Earth Planet. Sci. Lett. 123 (1994) 119–138.
[34] D.-C. Lee, A.N. Halliday, G.R. Davies, E.J. Essene, J.G. Fitton, R. Temdjim, Melt enrichment of shallow depleted mantle: a detailed petrological, trace element and isotopic study of mantle-derived xenoliths and megacrysts from the Cameroon line, J. Petrol. 37 (1996) 415–441.
[35] A. Marzoli, P.R. Renne, E.M. Piccirillo, C. Francesca, G. Bellieni, A.J. Melfi, J.B. Nyobe, J. N'ni, Silicic magmas from the continental Cameroon Volcanic Line (Oku, Bambouto and Ngaoundere): ^{40}Ar–^{39}Ar dates, petrology, Sr–Nd–O isotopes and their petrogenetic significance, Contrib. Mineral. Petrol. 135 (1999) 133–150.
[36] A. Marzoli, E.M. Piccirillo, P.R. Renne, G. Bellieni, M. Iacumin, J.B. Nyobe, A.T. Tongwa, The Cameroon Volcanic Line revisited: petrogenesis of continental basaltic magmas from lithospheric and asthenospheric mantle sources, J. Petrol. 41 (2000) 87–109.
[37] J.B. Meyers, B.R. Rosendahl, C.G.A. Harrison, Z.-D. Ding, Deep-imaging seismic and gravity results from the offshore Cameroon Volcanic Line, and speculation of African hotlines, Tectonophysics 284 (1998) 31–63.
[38] R. Montigny, I. Ngounouno, B. Déruelle, Âges K–Ar des roches magmatiques du fossé de Garoua (Cameroun) : leur place dans le cadre de la « ligne du Cameroun », C. R. Geoscience 336 (2004) 1463–1471.
[39] C. Moreau, J.-M. Regnoult, B. Déruelle, B. Robineau, A new tectonic model for the Cameroon Line, Central Africa, Tectonophysics 139–141 (1987) 317–334.
[40] A. Moundi, J.-J. Ménard, E. Reusser, F.M. Tchoua, V.J. Dietrich, Découverte de basaltes transitionnels dans le secteur continental de la ligne du Cameroun (massif du Mbam, Ouest-Cameroun), C.R. Acad. Sci. Paris, Ser. IIa 332 (1996) 831–837.
[41] R. Nana, Pétrologie des péridotites en enclaves dans les basaltes alcalins récents de Nyos : apport à la connaissance du manteau supérieur de la ligne du Cameroun, thèse université Yaoundé-1 2001 (170 p.).
[42] I. Ngounouno, B. Déruelle, Données nouvelles sur le volcanisme cénozoïque du plateau Kapsiki (Nord du Cameroun), C. R. Acad. Sci. Paris, Ser. IIa 324 (1997) 285–292.
[43] I. Ngounouno, B. Déruelle, D. Demaiffe, R. Montigny, Données nouvelles sur le volcanisme cénozoïque du fossé de Garoua (Nord du Cameroun), C. R. Acad. Sci. Paris, Ser. IIa 325 (1997) 87–94.
[44] I. Ngounouno, B. Déruelle, D. Demaiffe, Petrology of the bimodal Cenozoic volcanism of the Kapsiki plateau (northernmost Cameroun, central Africa), J. Volcanol. Geotherm. Res. 102 (2000) 21–44.
[45] I. Ngounouno, B. Déruelle, R. Guiraud, J.-P. Vicat, Magmatismes tholéiitique et alcalin des demi-grabens crétacés de Mayo Oulo-Léré et de Babouri-Figuil (Nord du Cameroun–Sud du Tchad) en domaine d'extension continentale, C. R. Acad. Sci. Paris, Ser. IIa 333 (2001) 201–207.
[46] I. Ngounouno, C. Moreau, B. Déruelle, D. Demaiffe, R. Montigny, Pétrologie du complexe alcalin sous-saturé de Kokoumi (Cameroun), Bull. Soc. geol. France 172 (2001) 675–686.
[47] I. Ngounouno, B. Déruelle, D. Demaiffe, R. Montigny, Les monchiquites de Tchircotché, vallée de la haute Bénoué (Nord du Cameroun), C. R. Geoscience 335 (2003) 289–296.
[48] I. Ngounouno, B. Déruelle, D. Demaiffe, Petrology of the Cenozoic volcanism in the Upper Benue valley, northern

Cameroun (central Africa), Contrib. Mineral. Petrol. 145 (2003) 87–106.

[49] I. Ngounouno, B. Déruelle, R. Montigny, D. Demaiffe, Petrology and geochemistry of monchiquites from Tchircotché (Garoua rift, north Cameroon, central Africa), Mineral. Petrol. 83 (2005) 167–190.

[50] I. Ngounouno, B. Déruelle, R. Montigny, D. Demaiffe, Les camptonites du mont Cameroun, Cameroun, Afrique, C. R. Geoscience 338 (2006) 537–544.

[51] E. Njonfang, C. Moreau, Implications pétrogénétiques de l'étude du complexe plutono-volcanique de Nda Ali (Sud-Ouest Cameroun), C. R. Acad. Sci. Paris, Ser. II 314 (1992) 1051–1056.

[52] E. Njonfang, C. Moreau, F. Tchoua, La bande mylonitique Foumban–Bankim, Ouest Cameroun. Une zone de cisaillement de haute température, C. R. Acad. Sci. Paris, Ser. IIa 327 (1998) 735–741.

[53] E. Njonfang, V. Ngako, M. Kwekam, P. Affaton, Les orthogneiss calco-alcalins de Foumban–Bankim : témoins d'une zone interne de marge active panafricaine en cisaillement, C. R. Geoscience 338 (2006) 606–616.

[54] O.F. Nkouandou, Pétrologie du volcanisme au nord et à l'est de Ngaoundéré, thesis, université Pierre-et-Marie-Curie (Paris-6), 2006.

[55] D.G. Nkouathio, J.-J. Ménard, P. Wandji, J.-M. Bardintzeff, The Tombel graben (West Cameroon): a recent monogenic volcanic field of the Cameroon Line, J. Afr. Earth Sci. 35 (2002) 285–300.

[56] C. Nkoumbou, B. Déruelle, D. Velde, Petrology of Mt Etinde nephelinite series, J. Petrol. 36 (1995) 373–395.

[57] J. N'ni, Magmatogenèse du versant sud-ouest des Monts Bambouto–Bamenda (ligne du Cameroun) : géologie, volcanologie et pétrographie, thèse d'État, université Yaoundé-1, 2004.

[58] J. N'ni, B. Bonin, R. Brousse, Migration de l'activité magmatique de la ligne du Cameroun : réactivation de segments de failles anciennes du socle panafricain, C. R. Acad. Sci. Paris, Ser. II 302 (1986) 453–456.

[59] A. Nono, B. Déruelle, D. Demaiffe, R. Kambou, Tchabal Nganha volcano in Adamawa (Cameroon): petrology of a continental alkaline lava series, J. Volcanol. Geotherm. Res. 60 (1994) 147–178.

[60] I. Parsons, W.L. Brown, H. Jacquemin, Mineral chemistry and crystallization conditions of the Mboutou layered gabbro–syenite–granite complex, North Cameroon, J. Petrol. 27 (1986) 1305–1329.

[61] F. Princivalle, G. Salviulo, A. Marzoli, E.M. Piccirillo, Clinopyroxene of spinel-peridotite mantle xenoliths from Lake Nji (Cameroon Volcanic Line, W Africa): crystal chemistry and petrological implications, Contrib. Mineral. Petrol. 139 (2000) 503–508.

[62] L. Roffet, Géochimie du volcanisme du Mont Cameroun et du Mont Etinde, DEA, université Joseph-Fourier, Grenoble, France, 2003.

[63] H. Sato, S. Aramaki, M. Kusakabe, J.-I. Hirabayashi, Y. Sano, Y. Nojiri, F. Tchoua, Geochemical difference of basalts between polygenetic and monogenetic volcanoes in the central part of the Cameroon volcanic line, Geochem. J. 24 (1990) 357–370.

[64] A. Stracke, A.W. Hofmann, R.S. Hart, FOZO, HIMU, and the rest of the mantle zoo, Geochem. Geophys. Geosyst. 6 (2005) Q05007, doi:10.1029/2004GC000824.

[65] C.E. Suh, R.S.J. Sparks, J.G. Fitton, S.N. Ayonghe, C. Annen, R. Nana, A. Luckman, The 1999 and 2000 eruptions of Mt Cameroon: eruption behaviour and petrochemistry of lava, Bull. Volcanol. 65 (2003) 267–281.

[66] J. Tamen, Contribution à l'étude géologique du plateau Kapsiki (Extrême-Nord, Cameroun) : volcanologie, pétrologie et géochimie, thèse de 3e cycle, université Yaoundé-1, 1998.

[67] M.I. Teitchou, M. Grégoire, C. Dantas, F.M. Tchoua, Le manteau supérieur à l'aplomb de la plaine de Kumba (ligne du Cameroun), d'après les enclaves de péridotites à spinelles dans les laves basaltiques, C. R. Geoscience 339 (2007) 101–109.

[68] R. Temdjim, P. Boivin, G. Chazot, C. Robin, É. Rouleau, L'hétérogénéité du manteau supérieur à l'aplomb du volcan de Nyos (Cameroun) révélée par les enclaves ultrabasiques, C. R. Geoscience 336 (2004) 1239–1244.

[69] R. Temdjim, Contribution à la connaissance du manteau supérieur du Cameroun au travers de l'étude des enclaves ultrabasiques et basiques remontées par les volcans de Youkou (Adamaou) et de Nyos (ligne du Cameroun), thèse d'État, université Yaoundé-1, 2005.

[70] C.P. Thornton, O.F. Tuttle, Chemistry of igneous rocks. I, Differentiation Index, Am. J. Sci. 258 (1960) 664–684.

[71] J.-P. Vicat, A. Pouclet, Y. Bellion, J.-C. Doumnang, Les rhyolites hyperalcalines (pantellérites) du lac Tchad. Composition et signification tectonomagmatique, C. R. Geoscience 334 (2002) 885–891.

[72] T. Yokoyama, F.T. Aka, M. Kusakabe, E. Nakamura, Plume-lithosphere interaction beneath Mt. Cameroon volcano, West Africa: constraints from ^{238}U–^{230}Th–^{226}Ra and Sr–Nd–Pb isotope systematics, Geochim. Cosmochim. Acta 71 (2007) 1835–1854.