The North–South Paleozoic to Quaternary trend of alkaline magmatism from Niger–Nigeria to Cameroon: Complex interaction between hotspots and Precambrian faults

Vincent Ngako a, Emmanuel Njonfang b,*, Festus Tongwa Aka c,1, Pascal Affaton d, Joseph Metuk Nnange a

a Institut de Recherches Géologiques et Minières (IRGM), B.P. 4110, Yaoundé, Cameroon
b Laboratoire de Géologie, Ecole Normale Supérieure, Université de Yaoundé I, B.P. 47 Yaoundé, Cameroon
c Institute of Mining and Geological Research (IRGM) Ekona, P.O. Box 370 Buca, Cameroon
d CEREGE, Europole de l’Arbois, B.P. 80, 13545 Aix-en-Provence Cedex 04, France

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Abstract

The alkaline magmatism from Niger–Nigeria to Cameroon forms large scale magmatic provinces across the African plate. It displays a N–S trend from Air in Niger to Jos Plateau in Nigeria changing southeastwards towards Cameroon. We have compiled recent petrological, geochemical and structural data on these magmatic provinces. The data show that although there is a general age decrease from one province to another (407 ± 8 Ma in Aïr to ≤66 Ma in Cameroon), there is no age migration in any given province, except in the Nigeria province (Younger Granites) where a rough NE–SW age decrease is observed. The relationship between these different magmatic provinces that share similar geochemical data, added to the SW–NE parallel trends of Nigeria, Benue Trough and Cameroon Line, is difficult to explain in terms of a simple northward motion of the African plate over a single hotspot. In the light of recent tectonic models, we suggest complex interaction between, on the one hand, at least two mantle plumes acting in succession (including the St. Helena mantle plume) and, on the other hand, lithospheric fractures that induce oblique alignments of new magmatic complexes.

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Keywords: Pan-African orogeny; West-Central Africa; Alkaline magmatism; Mantle plume; Hotspot; Lithospheric fractures

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* Corresponding author. Tel.: +237 231 65 23.
E-mail addresses: enjonfan@uydce.uninet.cm (E. Njonfang), akatongw@misasa.okayama-u.ac.jp (F.T. Aka).
1 Present address: Institute for Study of the Earth’s Interior, Okayama University at Misasa, Tottori-ken 689-0193, Japan.

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1. Introduction

After the Pan-African orogenesis in Western Africa (Fig. 1) around 600 Ma, geologic evolution is characterized by the emplacement of Mesozoic ring complexes in Central Nigeria, the formation of the Benue Trough (BT) during the Cretaceous, and the emplacement of ring complexes in Cameroon during the early Cenozoic, followed by volcanic activity since the Eocene. Although the tectonic origin of the BT has been linked to the opening of the South Atlantic Ocean (Benkhelil, 1989; Popoff, 1988; Brunet et al., 1988), the relationship between its evolution and Phanerozoic
(Paleozoic to Quaternary) magmatic activity in Western Africa is still unclear. Among the major unanswered questions related to this magmatic evolution are: the generalized abnormal thickness of the continental crust (less than 35 km in Western Africa, Fig. 2); the evolution of the BT into an abandoned rift; the difference in emplacement ages of ring complexes in Niger, Nigeria and Cameroon; and finally, the restriction of present volcanic activity to Mount Cameroon (last eruption in 2000). The broad southward age migration, added to the remarkable similarity in shape/size (Fitton, 1980, 1983) and geochemical features (Coulon et al., 1996) of the BT and the Cameroon Line (CL) suggests a possible relationship between these magmatic provinces and the same mantle plume. However, recent geochronological data in the Air province (Moreau et al., 1994) and in the CL (Marzoli et al., 2000) do not show age migration within a given magmatic province as formerly proposed and widely discussed by Déruelle et al. (1991, and references therein). Aka et al. (2004) even show that Plio-Quaternary volcanism (≤6 Ma) has been synchronous on the whole CL. The absence of space–time variation within a given magmatic province renders the relationship between one province and the other unclear. For instance, the early magmatic evolution in the BT is difficult to relate with the Cretaceous to Present activity on the CL. It is noteworthy that since the review of various hypotheses of the tectono-magmatic origin of the CL by Déruelle et al. (1991), the following views are still discussed: (1) a (failed) continental rifting (Guiraud et al., 1992; Guiraud and Maurin, 1992; Wilson and Guiraud, 1992) probably produced directly by a thermal anomaly in the asthenosphere; (2) rejuvenation of Precambrian faults (Moreau et al., 1994); (3) hot line or thermally anomalous linear zone in the Earth’s mantle (Meyers et al., 1998).

We have compile more recently available petrologic, geochemical and structural data on the different magmatic provinces. Here we interpret and discuss the data in the light of recent tectonic models that explain the origin of some linear intraplate magmatic chains and propose alternative explanations to classical hotspot models. We suggest

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Fig. 2. Map of crustal thickness (in km) in Central Africa based on gravity data (after Poudjom Djomani et al., 1995).
that the origin of magmatic provinces and local reverse age migration within a few of them, result from fundamental differences of crustal development of hotspot related magma in a continental and an oceanic domains.

2. The main magmatic provinces and magmatic activity

In this paper, we define a magmatic province as a broad geographic area (linear or not), characterized by intrusive and/or volcanic bodies, the ages of which approximately correspond to the same geological period, namely Ordovician–Devonian (480–400 Ma), Carboniferous (330–260 Ma), Triassic–Jurassic (215–140 Ma) and Tertiary (73–30 Ma), although overlapping ages are reported between some neighboring provinces.

2.1. The Niger–Nigeria Paleozoic to Mesozoic super province

The Niger–Nigeria super province (Fig. 3B) comprises from north to south, the Air anorogenic magmatic province (N. Niger), the Damagaram-Mounio province (S. Niger) and the Jos Plateau or “Younger Granite” province of Nigeria (Moreau, 1982; Bowden and Kinnaird, 1984; Cahen et al., 1984). Demaiffe and Moreau (1996) showed that the Air province is structurally and chronologically independent of the Damagaram-Mounio and the Younger Granite of Nigeria provinces.

A general review of the different types of Paleozoic ring complexes in the Air is given by Moreau et al. (1991, 1994), Demaiffe et al. (1991) and Demaiffe and Moreau (1996). The authors recognized 28 complexes among which the largest cone sheet in the world (the Meugueur-Meugueur, 65 km in diameter, Moreau et al., 1986) and one of the smallest intrusion (Tagueû, 0.8 km in diameter, Demaiffe et al., 1991). Most of the intrusions have a circular shape, but some are elliptical or semi-circular. They have been divided into three main types (Fig. 3C), based on the nature and abundance of rock-types (Moreau et al., 1991; Demaiffe et al., 1991). (1) the Taghouaji type is composed mainly of alkaline and peralkaline syenite and granite, with or without associated metaluminous granites (18 complexes); (2) the Goundaï type is composed mainly of acid volcanic rocks (rhyolitic tuffs and ignimbrites) with quartz syenite ring dykes (three complexes); (3) the Ofoud type (seven complexes) is characterized by a large proportion of basic rocks varying from troctolites and leucogabbros to true anorthosites, intruded by mildly to peralkaline syenites and granites (Brown et al., 1989; Demaiffe et al., 1991).

In the Younger Granites of Nigeria, over 50 intrusions forming a series of high-level anorogenic complexes have been recognized (Badejoko, 1986; Orajaka, 1986). These circular or elliptical intrusions have an average diameter of 10–25 km. Each of the ring-complexes began as a chain of volcanoes (Bowden and Kinnaird, 1984). Volcanic rocks

Fig. 3. (A) The Air province in West Africa. (B) Geographic localisation of the Air (N. Niger), Damagaram-Mounio (S. Niger) and Younger Granites (Nigeria) alkaline provinces. 1: Pan-African basement; 2: Phanerozoic Ring-complexes. (C) Geological sketch map of Air (After Demaiffe and Moreau, 1996).
commonly occur, especially in the northernmost complexes (Rahaman et al., 1984). Basic intrusive rocks represent less than 1% of the total area of the province (against 40–80% in the Air) and include monzonites and monzogabbros (basaltic lavas are more common). Anorthosites occur only as xenoliths in a doleritic dyke near Jos (Wright, 1975). There are several distinctive granite types (Kinnaird, 1985): (i) peralkaline granites and related syenites (with alkali or calcic amphibole); (ii) peraluminous biotite alkali feldspar granites and biotite syenogranites; (iii) metaluminous fayalite and hornblende-bearing granites and porphyries with amphibole or biotite.

### 2.2. The Benue Trough

The magmatic province of the BT constitutes a spatial link between the alkaline to peralkaline province of Nigeria to the North and the CL to the South. Detailed account of its petrology and geochemistry can be found in Baudin (1991) and the main characteristics in Maluski et al. (1995) and Coulon et al. (1996). Two principal magmatic domains are recognized, northern and southern Benue. In the northern domain, magmatism is characterized by transitional alkaline basalts and transitional tholeiitic basalts; acidic magmatism (rhyolites and granophyres) of

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**Fig. 4.** A compilation of Cameroon and Nigeria geological maps showing the location of ring-complexes of Nigeria and Cameroon and volcanic massifs of the Cameroon Line. K: Koupé; NL: Nlonako; NK: Nkogam; Nt: Ntumbaw; Ko: Kokouni; MD: Mayo Darlé. Age range of magmatic activity in the Benue Trough after Maluski et al. (1995). Note the rough NE–SW decrease of ages in the Younger Granites of Nigeria (numbers are in million years, after Rahaman et al., 1984) and the location of some syntectonic Pan-African granitoids along the Cameroon Line: Stars (Toteu et al., 2001); NG: Ngondo complex (Tagne Kamga et al., 1999); BA: Bandja complex (Ngüesi Tchankam et al., 1997); FO: Fomopéa complex (Kwékam, 1993). CCSZ: Central Cameroon Shear Zone; TF: Tcholliré Fault; Arrows: sense of displacement. Nigerian faults and shear zones after Rahaman et al. (1984) and Ferré et al. (1998). C.A.R.: Central African Republic.
peralkaline nature is also present. In the southern Benue, several magmatic districts exhibit alkaline or tholeiitic affinities. Alkaline rocks include: basalts, dolerites, rhyolites, trachytes, phonolites, phonotephrites, tephriphonolites, camptonites and nepheline syenites. Only doleritic sills display a clear mineralogical tholeiitic affinity and correspond chemically to quartz tholeiites.

2.3. The Cameroon Line

The CL, made up of an oceanic (Annobon, Sao Tome, Princep and Bioko) and a continental (Mounts Etinde, Cameroon, Manengouba, Bambouto, Oku, Ngaoundere, Bui and Mandara mountains) sectors, is active since the Cenozoic. Its activity includes emplacement of plutonic complexes (more than 60) in the continental sector and volcanic eruptions (Fig. 4). Volcanic rocks are usually aligned and in places associated with the plutonic complexes. The plutonic complexes are small in size (mostly 5–10 km in diameter) and except for four complexes in North and South-west Cameroon, they are mainly constituted of granites or syenites, to which subordinate intermediate and basic rocks are sometimes associated (Kambou et al., 1989; Njonfang et al., 1992; Njonfang and Moreau, 2000). The Mboutou, Kokoumi and Nigo complexes, in North Cameroon comprise basic rocks (Jacquemin et al., 1981; Parsons et al., 1986; Ngounouno et al., 2001; Kamdem et al., 2002). The Ntumbaw complex in NW Cameroon (Ghogomu et al., 1989) contains predominantly intermediate rocks. Syenites are mostly saturated and granites oversaturated; both displaying mineralogical and geochemical characteristics of alkaline to peralkaline rocks. The Kokoumi complex is entirely undersaturated with a gabbro–nepheline monzosyenite–nepheline syenite series (Ngounouno et al., 2001). It is also particular in that the plutonic series is cut by lamprophyric dykes (Ngounouno et al., 2001).

Volcanic rocks are more varied mostly undersaturated in the oceanic part and undersaturated to oversaturated in the continental part. At the continent–ocean boundary (COB), Bioko and Mount Cameroon are mainly basaltic. Etinde located to the intermediate southwestern flank of Mt. Cameroon is made up entirely of undersaturated lavas (Nkoumbou et al., 1995). The other continental massifs are usually bimodal. Mafic lavas comprise basanites, alkali basalts, hawaiites and mugearites and the silicic lavas comprise benmoreites, trachytes, phonolites and/or rhyolites (Deruelle et al., 1991; Nono et al., 1994; Marzoli et al., 2000; Ngounouno et al., 2000; Kagou Dongmo et al., 2001; Nkouathio et al., 2002). Data from the oceanic sector of the CL (Deruelle et al., 1991, and references therein; Lee et al., 1994) indicate basanite to hy-normative basalt, tristanite and trachyte in Annobon; basalt to trachyte and phonolite with no compositional gap in Sao Tome; nepheline, basanite, tristanite, trachyphonolite, phonolite and alkali basalt in Princep and basanite to hy-basalt in Bioko. In Princep, the oldest rocks (31 Ma) are basal hyaloclastite breccias that contain fragments of fresh tholeiite. Aka et al. (2004) noted a geographic control on the distribution of $^{3}$He/$^{4}$He ratios along the CL, with high-μ OIB-like values on the continent/ocean boundary zone (Bioko, Mount Cameroon and Etinde) increasing to mantle (MORB-like) values in its oceanic (towards Annobon) and continental (towards Ngaoundere) terminals. Even though a review of the CL volcanism by Deruelle et al. (1991) suggests that it is entirely alkaline in nature, some transitional affinities have recently been described in the Mbam, Bangou, Bambouto and Oku volcanic centers in the West and Northwest Cameroon (Moundi et al., 1996; Marzoli et al., 2000; Fosso et al., 2005).

Some mafic lavas of the CL are rich in ultramafic xenoliths (Lee et al., 1996; Aka et al., 2004). These occur in both the continental sector as in Oku and Nyos (Nana et al., 2001; Temdjim et al., 2004) and in the oceanic sector as in Sao Tome (Caldeira and Munha, 2002).

3. Spatio-temporal evolution of magmatic activity

On the basis of ages decreasing from the Air ring complexes, North of Niger (480–400 Ma) to the Younger Granites of Nigeria in the South (215–140 Ma) through the Damagaram, South of Niger (330–260 Ma) (Bowden et al., 1976; Karche and Vachette, 1978), the Niger-Nigeria large magmatic province has been defined as a unique feature in the world of practically continuous within plate anorogenic volcanism and plutonism with progressive southern shift of centers of magmatic activity (Bowden and Karche, 1984). At the scale of the Air province alone, the ages would decrease from 487 Ma in the North to 407 Ma in the South (Bowden and Karche, 1984). But, new radiometric data (Rb/Sr method) on the same sample powders by Moreau et al. (1994) do not confirm this space-time migration model. Instead, the new results show that the emplacement of the Air ring complexes took place within a very short time at 407 ± 8 Ma, close to the Silurian–Devonian boundary or the lowest Early Devonian. In Nigeria, the ages in the Younger Granites, from Dutse (213 Ma) in the North to Afu (141 Ma) in the South, show that major local migrations of magmatic activity were concentrated along at least two ENE–WSW linear zones (Rahaman et al., 1984) (Fig. 4).

A detailed chronology of emplacement of volcanic rocks of the BT has been established using $^{40}$Ar/$^{39}$Ar radiometric method and the following magmatic evolution is revealed (Maluski et al., 1995). (1) During the Late Jurassic to Albian period (147–106 Ma), magmatism probably occurred in the whole BT. It is particularly expressed in the northern Benue where it is represented by alkaline transitional basalts and associated peralkaline rhyolites (bimodal volcanism) and by tholeiitic transitional basalts. (2) Between 97 and 81 Ma, magmatism was concentrated in the southern Benue, was exclusively alkaline and predominantly intrusive. (3) During the period 68–49, the first magmatic products, also restricted to the southern Benue, were
alkaline and the last ones tholeiitic. As in the Air province (e.g., Moreau et al., 1994), no clear time–space age migration of magmatism in the BT is apparent.

Previous radiometric data (Rb/Sr and K/Ar methods) for the anorogenic plutonic complexes of the CL (see review by Kamdem et al., 2002) indicate that their emplacement occurred from the Paleocene (ca 67 Ma) to the Oligocene (ca 30 Ma). The oldest age was obtained on the Golda Zuelva granite in the north and the youngest on a Mt. Bana granite in the west (Lasserre, 1978). However the Nkogam and Mboutou complexes in the West and North gave 66 and 60 Ma, respectively (Lasserre, 1978; Caen-Vachette et al., 1987) pointing to the lack of time–space migration of plutonism. This conclusion is corroborated by the ages recently obtained for the Kokoumi complex, SW of Mboutou (39 Ma) and for the Hossere Nigo, west of Adamawa recently obtained for the Kokoumi complex, SW of Mbou.

New radiometric data (K/Ar and 40Ar/39Ar methods) on volcanic rocks from the CL (Lee et al., 1994; Marzoli et al., 1999, 2000; Ngounouono et al., 2000; Aka et al., 2004; Montigny et al., 2004; Fosso et al., 2005) show that volcanic activity ranges from Upper Eocene (45 Ma) to the Present and not from Oligocene (30 Ma) as established for the distribution of volcano-capped swells along the line (Burke, 2001). The striking point is the SW younging volcanism in the oceanic sector from Principe (31 Ma) to Pagalu (5 Ma) islands (Lee et al., 1994). The oldest age so far obtained (45 Ma) on CL volcanic rocks is on Mt. Bangou, located southeast of Mt. Bambouto. Therefore, as for anorogenic complexes, it is difficult to consider volcanic activity along the CL in terms of a steady time–space migration, symptomatic of a hotspot reference frame as the Hawaiian Islands.

From the above synthesis, it is seen that alkaline magmatism in West-Central Africa shows a time–space migration by ages decreasing from the Silurian–Devonian boundary (407 ± 8 Ma) in the Air province (North of Niger) through the Younger Granites of Nigeria (213–141 Ma), the BT (147–49 Ma) to the Paleocene-Present activity on the CL. This Activity is affected by a major translithospheric mega-shear that was formed during the Pan-African orogeny (Guiraud and Maurin, 1992). In Cameroon, the basement is affected by a major transtilospheric mega-shear that extends ENE from the Gulf of Guinea, through southern Chad and the Central African Republic into western Sudan. This Central African Shear Zone referred to as the Ngaoundéré or Foumban lineament (Browne and Fairhead, 1983; Cornachia and Dars, 1983) or the Central Cameroon Shear Zone (Ngako et al., 1991), is a dextral shear that was formed during the Pan-African orogeny (Jorgensen and Bosworth, 1989) and is delineated by broad mylonite zones (Cornachia and Dars, 1983). The Patos and Pernambuco-Adamawa branches and their N–S relays control the geometry of the BT (Maurin et al., 1986; Guiraud and Maurin, 1992) and the CL, respectively (Fig. 1). Detailed structural studies of some syntectonic Pan-African granitoids in Cameroon (Kwékam, 1993; Nguessi Tchankam et al., 1997; Tagne Kamga et al., 1999; Tagne

4. Relationships between tectonics and magmatism

4.1. The Pan-African structural inheritance

Three main structural units characterize the Pan-African basement in western and central Africa (Fig. 1): shear zones, fold zones and thrust zones. Shear zones are the most prominent and represent lithospheric faults (Ngako et al., 1991; Moreau et al., 1994; Poudjom Djomani et al., 1997). The structure of the Air basement, that was built during the Pan-African orogeny (Black et al., 1991; Liégeois et al., 1994), results from the assembly of three major terranes (Assodé, Barghot and Aouzegeueur) separated by N–S trending shear-zones or mega-thrusts (Fig. 3C). These shear zones and thrusts control: (1) the variation in thickness and/or deformation of the sedimentary cover; (2) the location of basement topographic highs and; (3) the location of the magmatic activity (Moreau et al., 1994). The most important of those shear zones, the Raghane mega-shear zone (Fig. 3C) can be observed over a 400 km distance in Air and runs for more than 1000 km, as it corresponds to the southern extension of the 8°30' E lineament of the Hoggar (Demaiffe and Moreau, 1996; Abdelsalam et al., 2002). In general, N–S mega-thrust faults were followed by NW–SE trending sinistral wrench faults and by complementary ENE–WSW and NE–SW trending dextral faults (Ball, 1980). In Nigeria, the major faults are NE–SW to NNE–SSW and ENE–WSW trending dextral wrench faults (Rahaman et al., 1984, and references therein; Ferré et al., 1998). Distribution of Triassic–Jurassic anorogenic ring complexes in the Jos Plateau defines a sigmoidal megagash geometry with a ENE–WSW mean direction that is probably linked to shear movement along pre-existing ENE–WSW trending wrench faults in the Pan-African basement (Rahaman et al., 1984; Black et al., 1985). This suggests that the Air and Younger Granites provinces were not emplaced under the same stress regime (Demaiffe and Moreau, 1996). The BT is a NE–SW trending extensional sedimentary basin (Benkhelif et al., 1988; Benkhelif, 1989) considered to be the failed arm of a Cretaceous triple junction, the two other rift arms of which subsequently developed into the South Atlantic Ocean and the Equatorial mega-shear zone (Burke and Dewey, 1974). Opening of the trough has also been attributed to reactivation during Cretaceous–Early Tertiary times of late Pan-African NE trending dextral shear zones (Guiraud and Maurin, 1992). In Cameroon, the basement is affected by a major transtilospheric mega-shear that extends ENE from the Gulf of Guinea, through southern Chad and the Central African Republic into western Sudan. This Central African Shear Zone referred to as the Ngaoundéré or Foumban lineament (Browne and Fairhead, 1983; Cornachia and Dars, 1983) or the Central Cameroon Shear Zone (Ngako et al., 1991), is a dextral shear that was formed during the Pan-African orogeny (Jorgensen and Bosworth, 1989) and is delineated by broad mylonite zones (Cornachia and Dars, 1983). The Patos and Pernambuco-Adamawa branches and their N–S relays control the geometry of the BT (Maurin et al., 1986; Guiraud and Maurin, 1992) and the CL, respectively (Fig. 1). Detailed structural studies of some syntectonic Pan-African granitoids in Cameroon (Kwékam, 1993; Nguessi Tchankam et al., 1997; Tagne Kamga et al., 1999; Tagne
Kamga, 2003) show that they are broadly elongated and aligned NE-SW, consistent with their successive emplacement coeval with acting and oblique sinistral shear zones formed during an earlier deformation phase (Ngako, 1999). For example, in the Ngondo complex (1000 km²), the geometry of the internal foliation trajectories and the joint orientation suggest that it was controlled by a N30° sinistral shear zone (Tagne Kamga et al., 1999), a conclusion early drawn for the Bandja complex (Ngàkò, 1999). In the Biu Plateau, the distribution of volcanic necks appears to be controlled by a N–S alignment of Tertiary faults. The emplacement of Paleocene and Eocene alkali granite intrusions in Cameroon appears to be similarly fault controlled (Moreau et al., 1987). Indeed, it is partly superimposed on a pre-existing fracture zone (Déruelle et al., 1991), the Central African Shear Zone (Corncichia and Dars, 1983) (Fig. 4). Else, it has been suggested that volcanoes in the offshore part of the CL are located at places where the CL crosses fracture zones (see Meyers et al., 1998, and references therein) while inland volcanoes are located along structures related to Riedel-style shear zones (Déruelle et al., 1991). Fold zones are characterized by Pan-African domes or diapirs of granitoid (calc-alkaline) rocks (Grant, 1978; Ngako, 1999). They determine broad areas bounded by the Nigerian and Cameroonian shear zones and are dominantly characterized by the occurrence of Paleozoic to Cenozoic ring complexes. Thrust zones (Ball et al., 1984; Jégouzo, 1984; Nédélec et al., 1986, 1993; Nzenti et al., 1988; Pénaye et al., 1993) charac-

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**Fig. 5.** (a) Basins and swells of the African plate (after Burke, 2001) showing among others, in the rectangle the Cameroon Line of 10 volcano-capped swells and the three swells at the landward end of the Cameroon Line (the Jos, Biu and Ngoundéré swells). (b) Detail of the rectangle showing ages’ distribution (in million years) of volcano-capped swells. H: Hoggar; A: Air; T: Tibesti; D: Darfur; J: Jos Plateau; Bi: Biu Plateau; AD: Adamawa Plateau; O: Mount Oku; Ba: Mount Bambouto; M: Mount Manengouba; C: Mount Cameroon; Bi: Bioko island; P: Principe island; ST: São Tomé island, A: Annobon island, s: seamount. Age data sources are: Grant et al. (1972), Fitton and Dunlop (1985), Halliday et al. (1988), Lee et al. (1994), Frank et al. (1999), Marzoli et al. (1999), Kagou Dongmo et al. (2001) and Aka et al. (2004).
terize the main structures of the Pan-African belt and overlay the archaean and eburnean boundary. These zones reveal no post-Pan-African magmatic activity, neither intrusive, nor effusive.

4.2. Swell-and-basin structures and magmatic provinces

Topographically, the general structures in western and central Africa suggest a long-lived continental extension activity, ongoing at least since Ordovician from one magmatic province to the other. These structures are represented either by large African lithospheric domes or swells such as the Hoggar, Air, Adamawa, Tibesti, Darfur (Poudjom Djomani et al., 1997; Burke, 2001) and the Great Lakes of East Africa (Ebinger et al., 1989), or by grabens, such as the BT (Benkhelil et al., 1988) (Fig. 5).

Domes correspond to high plateaus and mark the early stages of rift evolution. In Air, Jallouli (1989) estimated the thickness of the elastic lithosphere to be 20-30 km which is thin for a continental environment, but comparable to what is commonly observed in rift zones (Poudjom Djomani, 1993). Hartley et al. (1996) estimated a particularly thin elastic thickness for the lithosphere in the general region of the CL and Poudjom Djomani et al. (1997), in a more local study, with similar data sets but using somewhat different analytical procedures, found both crustal thickness and elastic thickness of lithosphere to be unusually thin in the continental part of the CL. For example, their map of crustal thickness (their Fig. 6) has a minimum value of 18 km at ca. lat. 7°N, long. 11.5°E recently referred to by Burke (2001) as the location of a mantle plume (the ‘711 plume’). The location of these swells coincides with magmatic provinces of different ages as in Air and in the CL. In Cameroon, the four islands of Bioko, Principe, São Tomé and Annobon and the four central volcanoes of Mount Cameroon, Manengouba, Bambouto and Oku occupy swells of the CL (Fig. 5). Also included are two large seamounts, one between Bioko and Principe and the other between Principe and São Tomé (Burke, 2001). They define a 1000-km long SW–NE straight line and display a “swell and basin” geometry which recalls the horst and graben structure of the whole CL (Déruelle et al., 1991).

In West and Central Africa, Guiraud and Maurin (1992) recognize two main phases of rifting separated by

![Fig. 6. Map showing some hotspots and hotspot tracks in Africa. Thick dotted line: Hotspot tracks since 100 Ma B.P. to their presently active locations (Duncan, 1981). Thin dotted line: ‘Cameroon’ hotspot tracks since 200 Ma B.P. from Hoggar to Mount Cameroon (Van Houten, 1983); Continuous thin line: Hotspot track from Sierra Leone to St. Helena (Morgan, 1983); 1: Mesozoic super plume axis (Wilson, 1997); 2: Ethiopian plume axis (Ebinger and Sleep, 1998). The ‘711’ plume is after Burke (2001). Numbers in parentheses represent ages in Ma. See text for more details.](image-url)
a major Aptian (ca. 117 Ma) unconformity. (1) The Neocomian-Early Aptian (ca. 144–117 Ma) phase that began in the basins of East and Northeast Brazil, Gulf of Guinea, South Chad, Sudan, Kenya, North and East Niger, North Egypt and Libya. Late Jurassic magmatic activity appears to precede this rifting phase in Northeast Brazil, South Sudan and the BT of Nigeria. (2) The Middle-Late Aptian-Albian (ca. 117–98 Ma) phase marked among others by the development of pull apart basins in an oblique extensional regime from Benue to southern Chad, related to strike-slip movement along the Central African Shear Zone (Bosworth, 1992). Magmatic activity in the BT was particularly important during the Cretaceous-Early Tertiary and took place during several phases, contemporaneous with the opening and infilling of the trough (Wilson and Guiraud, 1992). The first phase (Early Cretaceous: 141–106 Ma; Baudin, 1991) is related to the main extensional tectonic regime which affected the trough. During the Tertiary, basaltic magmas were emplaced throughout the entire trough with the greatest concentration in the NE (Wilson and Guiraud, 1992). This Post-Cretaceous extension and volcanism in the Upper Benue corresponds to a period of general stress release after the Santonian or Cretaceous compressional events (Benkhelil, 1989). In general, magmatic activity is predominantly basaltic (basalts are transitional from alkaline to tholeiitic types) in the Upper Benue, although rhyolites occur locally. In the Garoua basin, which represents the eastern continuation of the Yola branch of the Upper Benue, the strata are cut by lineaments which may have acted as strike-slip or normal faults. Tertiary-Quaternary magmatism associated with these lineaments occurs as dolerite sills, Paleocene (65–60 Ma) alkaline complexes and Neogene trachy-phonolite necks and dykes (Guiraud et al., 1987). An entirely younger undersaturated anorogenic complex (Kokoumi) belonging to the basin and including a gabbro-nepheline syenite series (39 Ma) and lamprophyre dykes (20.5 Ma) has been recently studied (Ngounouno et al., 2001).

5. Discussion and conclusions

From the synthesis above, it appears that (1) there is a time-space link among the magmatic alkaline provinces in West-Central Africa, from 407 ± 8 Ma in Air (North Niger) and 330–260 Ma in Damagaram-Mounio (South Niger) to 66-present in Cameroon through 213–141 Ma in Jos Plateau (northern Nigeria) and 147–49 Ma in the BT (southern Nigeria). The migration follows a North–South trajectory in the Air-Damagaram-Jos provinces, and a NW–SE trajectory in the BT-CL provinces; (2) only the Air province displays a N–S trend of magmatic complexes, the Jos Plateau, BT and CL complexes show three parallel lines rather trending NE–SW; (3) Each trend is parallel to a shear or fracture zone: N–S Raghane shear zone for the Air, NE trending wrench fault for Jos Plateau, NE-trending dextral shear zone for the BT, NE-trending sinistral fault oblique to the Central African Shear Zone or fracture zones directed N70°E for the CL (Fig. 4); (4) Only the ages of the Younger Granites of Nigeria become steadily younger from Dutse (213 Ma) in the NE to Afu (141 Ma) in the SW over a distance of 420 km; (5) There is a great overlap between the third magmatic period in the BT (68–49 Ma) and the ages of anorogenic complexes (66–30 Ma) of the CL, while the beginning of the first magmatic period (147 Ma) coincide, within analytical error range, with the end of the emplacement of granite complexes of Nigeria (141 Ma). All these geometrical, structural, geochemical and geochronologic data would suggest a complex interaction of mantle plumes with a northward moving continental lithosphere intensely deformed during Pan-African and including deep seated faults controlling the Phanerozoic extension and creation of successive magmatic provinces or magmatic lines.

The origin of intra-plate magmatism on the African continent (and elsewhere in the world, e.g., Smith and Lewis, 1999) is still a topic of great contention. Some workers such as Halliday et al. (1990), Wilson and Guiraud (1992), Lee et al. (1994) and Ebinger and Sleep (1998) link it to the role of mantle plumes. Mantle plumes are objects largely independent of plates and large-scale mantle circulation. They carry heat and isotopes from their source (any internal boundary layer) to the surface (Loper and Stacey, 1983). Isolated plumes coming from a localized source of buoyancy (either thermal or compositional) have been shown to explain quantitatively a number of hotspot features such as the dynamic swells (Sleep, 1990; Olson, 1990). For low buoyancy ratio (i.e. weak density anomaly of chemical origin), large domes or “superswells” are generated whereas for higher buoyancy ratio, long-lived thermochemical plumes are produced (Davaille, 1999; Davaille et al., 2002). On the basis of (i) fluid mechanics arguments; (ii) the observations of the huge volumes that must be melted to produce flood basalts and (iii) the long durations of their conduits which must produce island chains, Courtillot et al. (2003) suggested a core-mantle boundary origin for primary plumes. Such plumes are thought to be more voluminous, are over 500 km in diameter, have ascended a much greater distance (Griffiths et al., 1989). But for Anderson (2000), all non-plate boundary volcanism can be explained by shallow plate-related stresses that fracture the lithosphere and cause volcanism along these cracks, promoted for instance by a secondary eye-driven convection in the upper mantle.

5.1. A St. Helena type of hotspots for the Air-Damagaram-Jos Plateau–BT–CL magmatic trend

Most of the African hotspots have been active since the Cretaceous (Duncan, 1981). To explain the extensive Triassic-Early Jurassic magmatism along the West African and North American margins, Wilson (1997) suggested the location of a pre-Pangea continental break-up ‘super plume’ axis beneath West Africa (Fig. 6). Studies of uplift
history, topography and seismic tomography of the African plate and underlying mantle (Lithgow-Bertelloni and Silver, 1998) indicate that southern Africa is underlain by a large-scale buoyant, low seismic velocity structure extending from just above the core-mantle boundary to near the base of the African lithosphere and that the ascend of this material could be feeding many hotspots in Africa (Gurnis et al., 1999). The question arises as to which of the African hotspots was responsible for the magmatism for the CL suggested by Lee et al. (1994) to be at the hotspots sharing almost similar criteria. The plume source 3He/4He ratios are low compared to that of the primary geochronologic and structural relations between the Aïr–BT and break up of Equatorial Atlantic and (3) the geochronologic and structural relations between the Air–Damagaram-Jos-BT–CL magmatic provinces, it may be suggested that the genesis of these magmatic provinces lies in the interaction between the St. Helena hotspot and deep lithospheric fractures. Courtillot et al. (2003) suggest that surface hotspots (plume manifestations) on Earth may have three distinct origins corresponding to the three boundary layers between the core-mantle boundary and the surface of the Earth: (i) deepest part of the lower mantle referred to as “Morganian”; (ii) bottom of the transition zone at the top of the largest transient domes that correspond to the superswells; (iii) upper mantle features referred to as “Andersonian”; these may be linked to the asthenosphere and be a passive response to forms of lithospheric breakup. The authors term the first type Primary hotspots and the others, Secondary hotspots; but the Andersonian hotspot seems to us more likely, based on Halliday et al. (1990) who considered the HIMU Pb isotope signature of the CL to be inherited from relatively recent U/Pb fractionation at 125 Ma during impregnation of the uppermost mantle by the St. Helena hotspot when the Equatorial Atlantic opened.

5.2. At least two plumes beneath West and Central Africa

The overall N–S trend changing to NW–SE one recalls that of the renowned Hawaiian-Emperor seamount chain described by Stock and Molnar (1987). This inter-province time–space migration within a ca 410 Ma period and over a distance of ~1650 km would correspond to an average migration speed of the African plate of ca 0.4 cm/yr in a northward direction over a deep (relatively fixed) heat source. But, based on the fact that all plumes born (as traps) in the last 100 Ma (i.e. Ethiopia-Yemen/Afar) are still quite active, whereas those born between 100 and 140 Ma may be failing and those older than 150 Ma do not in general have an active trace (Duncan and Richards, 1991; Courtillot et al., 1999), it is very difficult to explain the whole trend, by a simple motion of plate above one stationary hotspot as in the Hauawaiian system. The 1650 km distance stretched by the magmatic provinces is more than three times the postulated diameter of the of the St. Helena plume tail (O’Connor and Le Roex, 1992; Wilson, 1992). Richards and Lithgow-Bertelloni (1996) demonstrated the difficulty of explaining abrupt plate motion changes in terms of mantle buoyancy forces that evolve continuously. This is in agreement with Demaille and Moreau (1996) who concluded from the alignment of the Air complexes and the Nigerian Younger Granites along the Raghane shear zone (N–S trending) and a ENE megashear respectively, that they were not emplaced under the same stress regime. It is also corroborated by the age data (Rahaman et al., 1984) which show a faster rate of migration within the Nigerian province (Shira to Afu) of 0.9 cm/yr than the migration between the southern Niger (Matsena) and the Nigerian (Shira) provinces which can be calculated at 0.3 cm/yr. Burke (2001) demonstrated that a single plume, dubbed the “711” plume, formed the Nigerian granites, generated a topographic dome at ca. 140 Ma on which the triple- rift system among which the BT developed and was also involved in forming the Cameroon granitic complexes: (i) Between 213 and 141 Ma, the 711 plume generated a 400 km-long line of intrusions as the continent moved over it. (ii) From 140 Ma to 66 Ma, the plume moved ca. 300 km with respect to the overlying continental lithosphere, having been caught up in the evolution of the Benue rift system (Maluski et al., 1995) rather than forming a line of intrusions. (iii) Since 66 Ma, the 711 plume has stayed in the same place, close to lat. 7°N and long 11.5°E, but has been associated with the development of the CL. This is geochemically supported by the similar major and trace element chemistry between the Biu Plateau known as the landward end of the CL and the Jos Plateau lavas and the fact that the Jos Plateau lavas also span a similar range in isotopic composition, overlapping the data of the CL as a whole (Rankenburb et al., 2004).

5.3. Controls by lithospheric fractures

Paleomagnetic measurements (e.g. Burke, 1996) show a rotation of the African plate through ca. 45° counter-clockwise about a poorly defined internal pole in the general area of lat 7°N, long 11.5°E, between ca.140 and 30 Ma. Even if the N–S trend of the Niger complexes could be linked to the NE–SW trend of the CL complexes via this 45° counter-clockwise rotation, the parallelism between the BT and the Nigerian Younger Granites to the North and the CL to the South, seems consistent with a structural link between them, in addition to the role of the 711 plume.
According to Wilson and Guiraud (1992), the Tertiary in the northern part of the CL was characterized by an E–W extension (Guiraud et al., 1987), resulting from a general stress release following the Santonian compressional event. The extensional tectonic regime controlled the location of the Neogene to Quaternary volcanic rocks of the CL and those of the Jos Plateau, the northern Benue and of the Biu Plateau. Remote sensing and autocorrelation analyses in the CL (Moreau et al., 1987) and in the Air massif (Moreau et al., 1994) suggest a control by lithospheric structures for the emplacement of the ring complexes as well as a relationship between a transtensional regime and intraplate alkaline magmatism. According to their model, only a sinistral shear along the N70°E (Adamawa) direction is consistent with a tension gash having the CL trend. In this Riedel model (Fig. 7a), $T = N25^\circ E$, $R = N55^\circ E$, $R' = N175^\circ E$, $P = N85^\circ E$ with $\sigma_1$ oriented $N40^\circ E$ and $\sigma_3 = N130^\circ E$. In the model proposed for the Air massif (Fig. 7b), the N20°E direction represents the Riedel direction (R) of a N5°E dextral shear zone assimilated to the Raghane shear zone (Liégeois et al., 1994); the N50°E, N90°E and N170°E could correspond to the T (compressional axis), $R'$ sinistral and $P$ dextral directions, respectively. More recently, Burke (2001) distinguished an ancestral CL marked by the plutonic complexes emplaced between 66 and 30 Ma, during the 45° rotation of the African plate and a CL of volcano-capped swells which formed on top of the granitic complexes after the rotation ceased at ca. 30 Ma. He suggests that the granitic complexes recorded a zone of extension and may indicate the presence of a short wavelength shallow-mantle convection system and that the convection pattern set up at 30 Ma appears to have occupied the existing zone of extension and perhaps to have assimilated an existing convection pattern. According to him, that extensional stress developed as part of the local stress field at the right-angled bend (Emery and Uchupi, 1984) in the Cameroon continental margin. Indeed, the location and azimuth of the two lines overprint Pan-African paleo-sutures marked by the alignment of synkinematic granites onshore and by the fact that the opening of the South Atlantic followed the Pan-African suture of the Adamastor Ocean, West of the Mid-Atlantic Ridge (Smith and Lewis, 1999); therefore indicating the role of rejuvenation of Precambrian faults during Cretaceous time (Moreau et al., 1987) in the emplacement of the CL. For Lee et al. (1994), the CL originates from a sublithospheric enriched “hot zone” periodically fed and melted deep mantle plumes, and this zone of hotter mantle represents reactivated mantle previously enriched during the breakup of the South Atlantic in the Mesozoic. Of relevance here is the fact that isotopic systematics of some lavas from the oceanic sector of the CL imply the involvement of a continental crustal component (Rankenburg et al., 2005) and the “LOMU” component in Mid-Atlantic Ridge basalts described by Douglass et al. (1999) and Douglass and Schilling (2000) is isotopically similar to Pan-African continental crust. Assuming that the line as a whole shares a common source, Rankenburg et al. (2005) propose that the continental signature seen in the oceanic sector of the CVL is caused by shallow contamination, either by continent-derived sediments or by rafted crustal blocks that became trapped in the oceanic lithosphere during continental breakup in the Mesozoic. The focus of magmatism is therefore partly controlled by preferential flow paths through the lithosphere (Lee et al., 1994). As suggested by Smith (1993), the parallelism between the BT and the CL can better be explained in terms of controls of lithospheric structures; these are readily illustrated by intraplate volcanism in the Atlantic Ocean basin, which can be considered the simplest example of...

Fig. 7. Riedel models proposed to explain the main structures controlling the emplacement of the Cameroon (a) and Air (b) ring complexes, found on satellite imagery and the autocorrelation graphs (Moreau et al., 1987, 1994).
ripping as the ridge system still parallels the continental margins (Smith and Lewis, 1999).

5.4. An alternative for the SW–NE Nigeria, Benue Trough and CL parallel trendings

An alternative model, susceptible to take into account the whole geometry and structure of the intraplate magmatism in West and Central-Africa could be that of Hieronymus and Bercovici (2000). This model explains the distribution of non-hotspot island and seamount chains in terms of the vulnerability of the lithosphere to magma penetration due to lithospheric stresses and the effects of melting of the conduit walls. Their theory is based on the assumption that (1) transport of magma through the brittle part of the lithosphere occurs via fractures and (2) melt is distributed uniformly at the base of the lithosphere. It turns out that an initial perturbation is required in all cases to localize the volcanic activity. This initial perturbation may be provided by a change in the tectonic stress field due to a plate motion reorganization (which is amplified locally by an inhomogeneity in the lithosphere), the formation of a small sublithospheric melting anomaly or a change in convection. Hieronymus and Bercovici (2000) have finally shown that multiple lines of volcanoes can result from interaction of flexural, membrane and tectonic stresses. Indeed: (i) due to the tensile membrane stresses, several volcanoes typically form in the space between any two volcanoes of the initial chain; (ii) membrane stresses perpendicular to the axis of the volcanic line (or ridge) also interact with the flexural stresses to generate volcanism away from the axis. This off-axis volcanism eventually forms additional lines of volcanoes parallel to the first one.

Following the above model, the fact that geometric techniques (Wessel and Kroenke, 1997) do not clearly locate any fixed hotspot in the Air province indicate that the N–S trending complexes are likely to be self-propagating disturbances of magmatic loads and associated flexure with a more or less uniform sublithospheric melt distribution as illustrated in the Fig. 4 of Hieronymus and Bercovici (2000). The NE–SW trending Younger Granites of Nigeria initiated at time of plate motion change, marked by a change in the tectonic stress field as already mentioned by Demaiffe and Moreau (1996) and were emplaced following some local perturbation, the formation of a small sublithospheric melting anomaly. Here, melt migration may be aided by tectonic and flexural stresses, such that the complexes are limited in extent to the melting region of the plume. Membrane stresses perpendicular to the axis of the Younger Granite trend, interacted with the flexural stresses to generate the NE–SW BT and CL trends. Noteworthy is the volumetrically restricted Mesozoic to Cenozoic magmatism of the BT (Maluski et al., 1995) which is similar to the small size of the CL granitic complexes and their volcano-capped swells (Burke, 2001). Shen et al. (1995) demonstrated that the individual lines of volcanoes compete with each other for melt. It is thus possible that the region between the volcanic lines has largely been drained of magma, thus allowing only the formation of small magmatic bodies (Scheirer et al., 1996).

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