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Magmatism and rifting in Western and Central Africa, from Late Jurassic to Recent times

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ABSTRACT

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Mesozoic–Cenozoic magmatic activity in West and Central Africa is reviewed, with particular emphasis on the relationship between Mesozoic magmatism, major phases of continental rifting and the opening of the Equatorial Atlantic. It is suggested that during the initial stages of rifting, the activity of a mantle plume, the St. Helena hotspot, may have been important in weakening the lithosphere across the region. Evidence for magmatism concurrent with the onset of rifting in some basins supports such an active rifting model.

Magma compositions range from alkali to tholeiitic basalts and their differentiates. Transitional to tholeiitic basalts are comparatively rare and are generated by greater degrees of partial melting, at probably shallower mantle depths, than associated alkali basalts. In some instances their occurrence may be correlated with higher amounts of lithospheric extension. However, in other instances they appear early in the rift sequence when overall amounts of extension were small. These tholeiitic basalts often have geochemical characteristics dominated by an ancient sub-continental lithosphere isotopic signature, which may have been introduced by crustal contamination.

Cenozoic magmatism of alkaline affinity is widespread in West and Central Africa. In many instances, sites of activity appear to be structurally controlled by pre-existing basement fractures/lineaments of Mesozoic–Precambrian age. Most of the volcanic fields lie outside the boundaries of the Cretaceous rifts and many are associated with broad basement uplifts. However, there has also been a rejuvenation of tectono-magmatic activity within several of the Cretaceous rift basins during the Neogene. The parental magmas are considered to be generated mainly by partial melting of a zone at the base of the sub-continental lithosphere, which was variably metasomatised by the activity of mantle plumes beneath the African plate during the Mesozoic.

Introduction

Progressive fragmentation of the Gondwana super-continent during the Mesozoic resulted in the development of major sedimentary basins along the present day continental margins of Africa and South America and several distinct phases of rifting and magmatism within the African plate (Binks and Fairhead, 1992, this volume). During the Jurassic and Cretaceous, an Atlantic rift system propagated southwards in the northern hemisphere and northwards in the southern hemisphere towards a land bridge created by a Pan African orogenic belt in the equatorial region (Klitgord and Schouten, 1986; Uchupi, 1989). Ultimately rifting broke through this equatorial land bridge to form one continuous ocean basin.

Rifting along the line of the proto-South Atlantic was initiated in the Late Jurassic to Early Cretaceous, as South America began to drift away from Africa (seafloor spreading initiated at approximately 126 Ma; Nurnberg and Muller, 1991), and propagated steadily northwards. Voluminous

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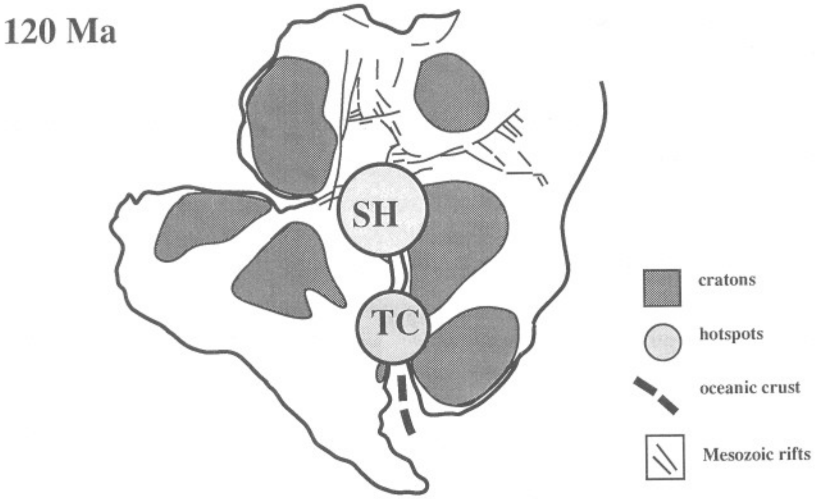

Fig. 1. Location of the St. Helena (*SH*) and Tristan da Cunha (*TC*) mantle hotspots at approximately 120 Ma.

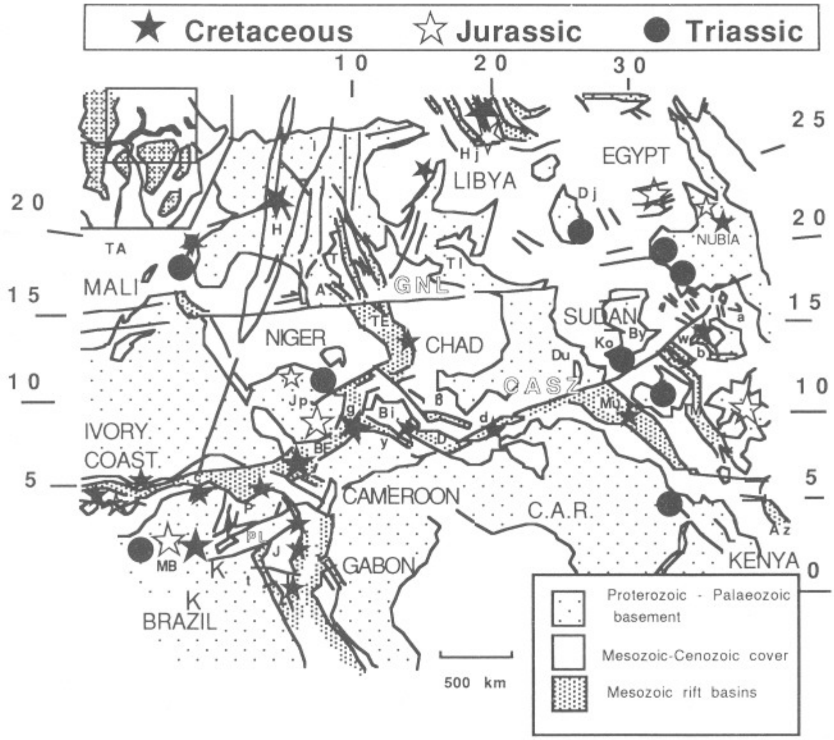

Fig. 2. Location of the major sites of Mesozoic magmatic activity in West and Central Africa.
The schematic structure of the area is based on maps of Guiraud and Maurin (1992, this volume), Binks and Fairhead (1992, this volume), Bosworth (1992) and A. Ibrahim and C.J. Ebinger (pers. commun., 1992). For detailed references see text. *U* = uranium mineralisation; *GNL* = Guinea–Nubian lineament; *CASZ* = Central African Shear Zone; *PL* = Pernambuco lineament; *K* = kimberlite activity.
Mesozoic rift basins. *BE* = Benue; *g* = Gongola; *y* = Yola; *D* = Doba; *d* = Doseo; *B* = Bongor; *c* = Ceara; *P* = Potiguar; *t* = Tucano; *J* = Jatoba; *MB* = Maranhao; *a* = Atbara; *b* = Blue Nile; *Mu* = Muglad; *M* = Melut; *Az* = Anza; *w* = White Nile; *TE* = Termit; *T* = Tenere.
Other localities. *TI* = Tibesti; *A* = Air; *H* = Hoggar; *Hj* = Haroudj; *Dj* = Djebel Uweinat; *Jp* = Jos Plateau; *TA* = Taoudenni; *Du* = Darfur; *By* = Bayuda Desert; *I* = Illizi; *Bi* = Biu Plateau; *Ko* = Kordofan.

tholeiitic flood basalt volcanism in Brazil and Southern Africa, between 120–130 Ma (Parana province, Brazil; Etendeka province, Namibia), has been related to the activity of a deep mantle plume (Tristan da Cunha hotspot) beneath the newly developing plate boundary (Richards et al., 1989; White and McKenzie, 1989; O'Connor and Duncan, 1990; Fig. 1). This suggests that, at least for the opening of the South Atlantic, there is an intimate relationship between hotspot activity and continental rifting.

Rifting in the Equatorial region began in the Late Jurassic, culminating in seafloor spreading in the Early Albian at the southern end (ca. 112 Ma) and Late Albian (ca. 107 Ma) at the northern end (Uchupi, 1989). This stage of continental breakup is associated with a major phase of intra-continental rifting in parts of West and Central Africa (Guiraud and Maurin, 1992, this volume; Genik, 1992, this volume; Figs. 2 and 3), which has been related to stress build-up in the equatorial region due to the differential opening of the South and Central Atlantic oceans (Fairhead and Binks, 1991). O'Connor and Duncan (1990) have suggested that between 130–100 Ma the St. Helena hotspot was located beneath the site of the Equatorial Atlantic rift (Fig. 1) and thus, as for the South Atlantic, the activity of a deep mantle plume may have influenced the process of continental rifting. The final separation between the African and South American continents occurred at approximately 100–105 Ma (Mascle et al., 1986; Nurnberg and Muller, 1991) but subsidence within some of the rift basins continued until the Santonian, when there was a major phase of regional deformation (Benkhelil et al., 1988), possibly related to N–S compression between the African and European plates (Guiraud et al., 1987). Following this Santonian event, at ca. 85 ± 5 Ma (Genik, 1992, this volume),

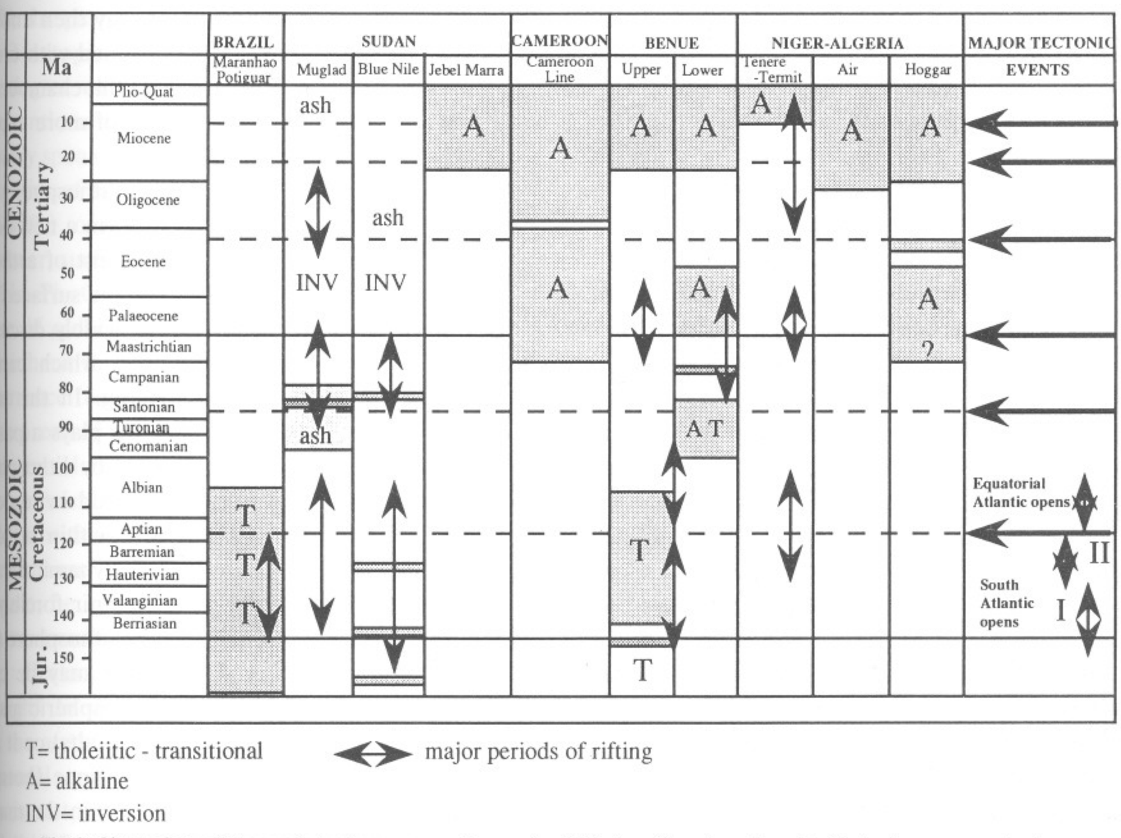

Fig. 3. Chronology of the main tectono-magmatic events within the rift system. For detailed references see text.

localised rifting continued into the Lower Eocene (Guiraud et al., 1992, this volume) with little associated magmatic activity.

Within West and Central Africa there are numerous occurrences of Tertiary–Quaternary magmatic activity. The majority of the volcanic fields lie outside the boundaries of the Mesozoic rifts (Fig. 4) but there has also been a rejuvenation of tectono-magmatic activity within several of the Cretaceous basins during the Neogene (particularly the Benue Trough of Nigeria; Fig. 3). Several of the volcanic fields are situated upon broad basement uplifts (e.g. Hoggar, Air, Tibesti and Jebel Marra) which may reflect diapiric upwellings of asthenospheric upper mantle beneath the African plate, initiated at fairly shallow depths (< 500–600 km). Field relationships in many areas (e.g. Hoggar, Jos Plateau and Benue Trough) suggest that pre-existing basement fractures/lineaments may have exerted a fundamental control on the location of volcanism. The causes of the Tertiary–Quaternary magmatism within West and Central Africa are not fully understood. However, reactivation of pre-existing fault zones must clearly be a response to localised tensional stresses within the African plate. Pavoni (1991) has suggested that, on a larger scale, Equatorial Africa may be underlain by a zone of deep mantle upwelling focussed at 10°E, 0°N which may explain the widely scattered occurrences of igneous activity.

This paper presents a review of the age relationships and geochemical characteristics of the major occurrences of Mesozoic–Cenozoic magmatic rocks within West and Central Africa and relates these to the tectono-magmatic evolution of the African plate. The locations of the most important sites of igneous activity, referred to in subsequent sections, are shown on Figs. 2 and 4. The chronology of tectono-magmatic events within several of the major Cretaceous basins and selected areas of Cenozoic volcanism is summarised in Fig. 3. Of particular importance in petrogenetic interpretations of the magmatism is the role of the St. Helena hotspot in the initial stages of plate separation in the Equatorial Atlantic and in the metasomatism of the base of the continental lithosphere. This metasomatised boundary layer appears to have been a major source component in the petrogenesis of some of the Cenozoic magmas (Halliday et al., 1990). In general, attention is focussed on the geochemical characteristics of the most mafic igneous rocks occurring in a particular area, as these yield the most information about mantle sources and magma generation processes (Wilson, 1989).

Magmatic activity associated with intra-continental rifts

A wide compositional spectrum of magmatic activity may be associated with rifting of the continental lithosphere. The geochemical characteristics of the primary, mantle derived, mafic magmas, ranging from silica undersaturated alkaline magmas (nephelinites, basanites and alkali basalts), through transitional basalts to subalkaline continental tholeiites, reflect varying degrees of partial melting of both asthenospheric and lithospheric mantle sources (Wilson, 1989). Any of these parental magma types may then undergo crystal fractionation, often combined with crustal contamination, in high-level magma chamber systems to produce a diverse range of more evolved magma types.

Extension of the continental lithosphere and subsequent plate separation to form a new ocean basin necessarily involves the ascent of asthenospheric mantle material towards the surface. Two end-member models have been widely discussed in the literature (Wilson, 1989) which can be termed *active* and *passive* rifting. In the latter case the upwelling asthenosphere plays a passive role in filling the gap produced by lithospheric extension (e.g. Buck, 1986), induced in response to deviatoric tensional stresses within a plate. Active rifting differs in that a dynamically upwelling asthenospheric mantle diapir forcibly intrudes and deforms the overlying lithosphere (e.g. Fleitout et al., 1986). This diapir may be composed of normal depleted asthenospheric mantle (the source of mid-ocean ridge basalts) or it may be a chemically distinct mantle plume (hotspot) derived from a boundary layer within the mantle (e.g. 670 km seismic discontinuity or the core/

mantle boundary). Passive rifting models predict that the onset of magmatic activity should occur after the initiation of rifting and that the magmas should show a general decrease in alkalinity with time, marking the progressive passive upwelling of asthenospheric mantle beneath the rift zone. In contrast in the case of active rifting domal uplift and magmatism should precede the onset of rifting and the erupted magmas may have geochemical characteristics indicative of partial melting of geochemically distinct plume components. In practice, however, the recognition of the relative timing of rifting and associated magmatic activity is often complicated by the diachronous development of individual sub-basins within a particular rift and by the cover of younger volcanic and sedimentary rocks that tend to obscure the early rift sequences. Additionally reactivation of pre-existing basement faults may further complicate interpretations.

In general, only the geochemical characteristics of the most primitive mafic magmas can yield information about mantle source regions (Wilson, 1989). In particular trace element and Sr–Nd–Pb–O isotopic data may constrain both the depth and degree of partial melting and the nature of the mantle source (lithosphere v. asthenosphere). Broadly speaking transitional-tholeiitic basalts are indicative of fairly high degrees of partial melting (20–30%) of sub-lithospheric mantle sources. However, such continental tholeiites often exhibit Sr–Nd–Pb–O isotopic characteristics similar to those of old continental lithosphere, which they may inherit through crustal contamination. Their occurrence can sometimes be correlated with those areas of a rift system which appear to have experienced the greatest amounts of lithospheric extension and crustal thinning. However, in many rifts transitional to tholeiitic basalts can be of diverse ages, both pre- and syn-rift. They can predate, be synchronous with or post-date alkaline magmatic activity within the same region (e.g. Cretaceous magmatism of the Benue Trough). In such cases it is the structural setting not the amount of extension which exerts a fundamental control on magma compositions and this is not always predictable. However, when tholeiitic flood basalt activity initiates the magmatic evolution of a particular rift system an active rather than a passive rifting mechanism is indicated (Kampunzu and Mohr, 1991). The geochemical characteristics of rift-related alkali basalts are indicative of relatively low degrees of partial melting (ca. 2–10%) of incompatible element enriched mantle sources which may reside within mantle plumes or within the continental lithosphere.

Mesozoic–Cenozoic rifting in West and Central Africa

An extensive Late Jurassic–Early Tertiary rift system exists in West and Central Africa extending for over 4000 km from Nigeria, northwards into Niger and Libya and eastwards through southern Chad into Sudan and Kenya (Fig. 2). The development of this rift system has been related to the differential opening of the Central and South Atlantic oceans, starting some 150 Ma ago when wrench fault zones extended from South America into the Gulf of Guinea and Africa, dissipating their strike-slip movement into extensional basins in Niger, Sudan and Kenya (Fairhead, 1986, 1988; Benkhelil, 1988; Popoff, 1988; Fairhead and Binks, 1991; Nürnberg and Müller, 1991). Reeves et al. (1986) and Guiraud and Maurin (1991) have suggested that the initiation of the Sudanese and Kenya rifts might also have been related, at least in part, to the separation of Madagascar and India from Africa. However, Bosworth (1992) considers that Late Jurassic rifting in Sudan may be too young for this to be the case, as the breakup of the East African margin had already occurred by 157 Ma (Rabinowitz et al., 1983), and that it may represent the establishment of E–W extensional intraplate stresses during the initial rifting of the proto-south Atlantic ocean.

The intra-continental rifts generally follow the comparatively warmer and weaker lithosphere of the Pan African mobile belts (Fig. 1), avoiding the cratonic regions. On a local scale the complexity of the rift geometry may be controlled by the mechanical anisotropy of the continental lithosphere (Fairhead and Green, 1989; Bosworth, 1992), particularly the location of large scale shear zones. Strike-slip movement along these zones appears to be dissipated or transformed into extensional basins oriented at high angles (90–120°) to the shear direction (Daly et al., 1989; Binks and Fairhead, 1992, this volume). A major trans-lithospheric mega-shear, termed the Central African Shear Zone (CASZ), Ngaoundere or Foumban lineament (Browne and Fairhead, 1983), extends ENE from the Gulf of Guinea, through southern Chad and the Central African Republic into western Sudan. This is a dextral shear, formed during the Pan African orogeny (Jorgensen and Bosworth, 1989), delineated by broad mylonite zones. Martin et al. (1981) have shown that it aligns with the Pernambuco dextral transcurrent fault system in Brazil. Reactivation of the lineament during the Cretaceous appears to have controlled the development of many of the structural features of the Central African rift system. In Sudan a system of NW–SE striking extensional basins terminate against this fault zone (Bosworth, 1992; Fig. 2). In west-central Africa, the Benue Trough and Gongola rift form a series of basins, parallel to NE trending late Pan-African mylonite zones, that extend from the Niger delta into the Lake Chad region. Here they link into a series of NNW trending basins (Termit, Tenere, Tefidet) extending from Chad through eastern Niger into southernmost Algeria (Daly et al., 1989).

Fairhead and Green (1989) have demonstrated that the rift system of West and Central Africa is associated with a broad positive Bouguer anomaly, up to 450 km wide, interpreted as a zone of crustal thinning due to lithospheric extension. On the basis of both geological and geophysical data it has been suggested that the rifts are classic examples of passive extensional basins (McKenzie, 1978; Binks and Fairhead, 1992, this volume). This is supported by the general low level of magmatic activity throughout much of the rift system. However, available geochemical data for the magmatic rocks, discussed in the following sections, show that the overall picture might not be quite so simple. In particular the St. Helena hotspot may have played an important role in weakening the lithosphere across the region during the Early Cretaceous.

Major tectonic events within the rift system

Guiraud and Maurin (1992, this volume) recognise in West and Central Africa two main phases of rifting separated by a major Aptian (ca. 117 Ma) unconformity (Fig. 3).

(1) *Neocomian–Early Aptian* (ca. 144–117 Ma): rifting 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 Benue Trough of Nigeria (Fig. 3).

(2) *Middle–Late Aptian–Albian* (ca. 117–98 Ma): evidenced in the intra-continental basins of West and Central Africa. The large NNW–SSE to NW–SE oriented troughs of Niger and Sudan opened or deepened at this time. At the same time pull apart basins developed in an oblique extensional regime from Benue to southern Chad, related to strike-slip movement along the Central African Shear Zone (Bosworth, 1992). The end of this rifting event is marked by a major unconformity along the Gulf of Guinea and northeastern Brazil margins at the end of the Albian (ca. 100 Ma), which is a clear marker of the opening of the Equatorial Atlantic (Mascle et al., 1988; Fig. 3).

Following these Early Cretaceous rifting episodes most of the basins continued to evolve, often as a consequence of thermal sag. Rifting essentially ended in the Santonian (ca. 85 Ma) when regional compression occurred (Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume). This caused deformation of the rift sequence in the Benue, Yola, Bornu, S Termit, Doba, Doseo, Muglad and Anza basins. However, following this compressional event, some basins experienced a further episode of rifting in the Late Cretaceous and/or Palaeogene (Guiraud et al., 1992, this volume; Guiraud and Maurin, 1992, this volume; Genik, 1992, this volume; Bosworth, 1992). These include the West African Benue

Trough and Niger rifts and the Central African Muglad and Anza rifts.

Mesozoic magmatism

Benue Trough

The Benue Trough forms the major part of a NE–SW trending sedimentary basin, 50–150 km wide, which extends for over 1000 km from the Niger delta to Lake Chad (Fig. 2). Its northern end is Y-shaped, formed by the E–W trending Yola rift and the north trending Gongola rift. Benkhelil (1989) presents an excellent review of its origin and evolution. Burke and Dewey (1974) described the Benue as the failed arm of a Cretaceous RRR triple junction, situated on the site of the present day Niger delta, with the two other rift arms having subsequently developed into the northern South Atlantic ocean and the Equatorial megashear zone. This model remains attractive, particularly in view of O'Connor and Duncan's (1990) location of the St. Helena hotspot beneath this area at approximately 130 Ma.

The orientation of the trough is controlled by northeast trending dextral shear zones of late Pan-African age (Guiraud and Maurin, 1992, this volume; Maurin et al., 1986). These were reactivated during the opening of the Benue by sinistral shear. Transtensional tectonics appear to have dominated the evolution of the trough from the Aptian to the present. However, major compressional episodes of short duration occurred in the Santonian (ca. 80 Ma) and at the end of the Cretaceous (ca. 65 Ma) (Benkhelil, 1989; Fig. 3).

Volcanic activity in the Benue was particularly important during the Cretaceous–Early Tertiary and took place during several phases, contemporaneous with the opening and infilling of the trough. Baudin (1991) recognises three main magmatic phases on the basis of $^{39}Ar/^{40}Ar$ dating: Early Cretaceous (141–106 Ma), Albian–Santonian (95–83 Ma) and Palaeocene–Eocene (65–47 Ma). The first phase is related to the main extensional tectonic regime which affected the trough. Magmatic activity stopped in the northeastern part of the trough (Upper Benue) in the late Albian (106 Ma) but continued until the Eocene (47 Ma) in the southwestern part (Lower Benue; Fig. 3). The oldest recorded rocks are Late Jurassic transitional basalts and occasional rhyolitic flows which were emplaced at 147 ± 7 Ma in the Bima Hills (Burashika complex) of the Gongola rift (Popoff et al., 1982). These are contemporaneous with the end of a period of emplacement of anorogenic granitic ring complexes in the Jos Plateau (186–141 Ma; Van Breemen et al., 1975). Flows of transitional basalts have been dated at 127 ± 6 Ma in the upper part of the Benue (Baudin, 1986). Umeji and Caen-Vachette (1983) recorded an Aptian (113 ± 3 Ma) age for rhyolites at Yandev (Middle Benue). Albian ages (100–105 Ma) were obtained for transitional tholeiitic basalts of the Gwol region (Upper Benue) by Popoff et al. (1982). This episode has also been identified in the Lower Benue (Guiraud et al., 1987). A few magmatic bodies were emplaced shortly after the Santonian compressional phase in the Lower Benue (ca. 74 Ma; Benkhelil, 1989). However, this is very minor activity associated with a tensional regime which prevailed in the Lower Benue at this time.

The magmatism of the Upper Benue is predominantly basaltic, although rhyolites occur locally. The basalts are transitional from alkaline to tholeiitic types. Magmatic activity is located on the edges of basement horsts, associated with major ENE–WSW, NW–SE, N–S and E–W trending faults (Benkhelil, 1989; Popoff, 1988a,b). In contrast the Lower Benue is characterised by a diverse range of igneous rocks (basalts, dolerites, lamprophyres, trachytes, syenites, phonolites, granophyres) in the form of lava flows, pyroclastics, dykes, sills, necks and domes. Unlike the Upper Benue, intrusive forms are predominant. The structural context of the magmatism is difficult to constrain because of poor outcrop and the effects of the Santonian deformation event (Baudin, 1991).

In general there is little published data concerning the geochemical characteristics of the Cretaceous–Tertiary igneous rocks of the Benue Trough. However, both alkalic and transitional tholeiitic rock types are known from both the Upper and Lower Benue (Benkhelil, 1989; Baudin, 1991; Fig. 3). During the mid-Albian transitional basalts were emplaced in the Upper Benue contemporaneous with alkaline volcanics in the Lower Benue (Popoff, 1988a). Baudin (1991) has demonstrated that alkali basalts from the Benue have distinctly different Nd–Sr isotopic characteristics from transitional tholeiitic types [alkali basalts: $0.7028 < (^{87}Sr/^{86}Sr)_i <$ 0.7037; $0.5126 < (^{143}Nd/^{144}Nd)_i < 0.5129$; tholeiitic basalts: $0.7042 < (^{87}Sr/^{86}Sr)_i < 0.7065$; $0.5125 < (^{143}Nd/^{144}Nd)_i < 0.5127$] which indicates their derivation from different mantle sources. It is possible that the tholeiitic magmas have incorporated components derived from partial melting of enriched domains within the sub-continental lithospheric mantle, whilst the alkaline magmas preferentially sample a sub-lithospheric source. However, it is also possible that the tholeiitic magmas have acquired their Nd–Sr isotopic characteristics through crustal contamination. Oxygen isotope data would be required to confirm this. The alkali basalts have geochemical characteristics similar to those of basalts from the oceanic island of St. Helena (Baudin, 1991).

Nigeria—Jos Plateau

Emplacement of Triassic–Jurassic anorogenic alkali granite ring complexes in the Jos Plateau of Nigeria preceded the opening of the Gulf of Guinea and the Benue Trough. The ring complexes are roughly orientated along a N–S axis and give Rb–Sr ages ranging from 213 Ma in the north to 141 Ma in the south (Rahaman et al., 1984; Vail, 1989). They comprise a wide variety of rock types including alkali granite, syenite and trachyte with minor gabbro, dolerite, rhyolite and ignimbrite. Their origin is controversial. Earlier hypotheses suggested that the magmatism was triggered by the northward migration of the African plate over a mantle plume (Bowden and Turner, 1974; Bowden et al., 1976; Karche and Vachette, 1976). However, more recently it has been suggested that they are linked to shear movements along pre-existing ENE–WSW trending wrench faults in the Pan African basement (Rahaman et al., 1984; Black et al., 1985). To the north of the Jos Plateau, there are similar alkali granite ring complexes in southern Niger and Aïr which are Palaeozoic in age (Vail, 1989).

Vannucci et al. (1989) give a K–Ar date of 157 ± 5 Ma for evolved mildly alkaline basaltic volcanic rocks from Sokoto State, NW Nigeria, which are clearly contemporaneous with the Younger Granite intrusions of the Jos Plateau. The lavas are located at the margin of the Cretaceous–Palaeocene Iullemeden basin. They have high initial $^{87}Sr/^{86}Sr$ ratios (0.70597–0.70633) suggesting that the parental magmas have experienced high level crustal contamination or that they are derived from an enriched mantle source.

In northeastern Nigeria, widespread uranium mineralisation occurs along major fracture zones within the Precambrian crystalline basement bounding the Cretaceous deposits of the Benue Trough (Maurin and Lancelot, 1990). Isotopic data indicate an age of 148 ± 12 Ma for the crystallisation of primary pitchblende, which crystallised in an en-echelon array of mega tension-gashes, formed due to regional dextral wrenching along a N140°E trend. On a regional scale this fracturing episode and the uranium mineralisation are contemporaneous with the earliest phase of volcanic activity in the Upper Benue Trough. It is also comparable with the age of the youngest alkali granites of the Jos Plateau (Rahaman et al., 1984). The Pb isotopic composition of galenas associated with the uranium mineralisation is similar to that of the Tertiary–Quaternary volcanic rocks of the Cameroon volcanic line and Hoggar. Whilst this might suggest that the mineralising fluids had a mantle origin, it is equally possible that the Tertiary–Quaternary magmas may have acquired their Pb isotopic characteristics through crustal contamination.

Central and north Cameroon rifts

In the north of Cameroon and along the Chad border there are many small basins of Neocomian–early Aptian age (ca. 130–118 Ma) which have a general E–W trend (Maurin and Guiraud, 1990). These are older than the large Albo-Aptian basins in the adjacent Benue Trough, Eastern Niger and southwestern Chad (Guiraud and

Maurin, 1992, this volume). The basins contain interstratified alkali basalt flows, associated with dolerite dykes and sills. The dykes are numerous, often up to 50 km long, and strike N70° to E–W parallel to the basin boundary faults. These dykes were deformed during the Santonian compressional tectonic event, which constrains their minimum age (> 80 Ma). In the basins of Figuil, Mayo Oulo and Koum it is difficult to prove that the magmas were emplaced during the progressive opening of the basins. However, in the Hama–Koussou basin basaltic lava flows are observed interbedded with shales whose age is well constrained palaeontologically.

South Chad

In the south of Chad there are a series of troughs including the Doba, Doseo, Salamat and Birao basins, aligned along the Central African Shear Zone (Browne and Fairhead, 1983). Half-graben trending N70°E to E–W were active from Neocomian to early Aptian, similar to those of north Cameroon and the Upper Benue (Guiraud and Maurin, 1992, this volume). A second set, active during the Late Aptian and Albian, are oriented N120°–N130°. In the Doseo basin there is minor evidence of magmatic activity in the form of sills of altered basalt and basaltic andesite, radiometrically dated at 97–101 Ma (Genik, 1992, this volume). A dolerite sill from the N120° oriented Bongor basin has been radiometrically dated at 52–56 Ma (Genik, 1992, this volume).

Sudan

The existence of deep NW–SE trending Mesozoic–Cenozoic sedimentary basins in southwest Sudan (Muglad, Blue Nile, Melut, Atbara; Fig. 2) has been demonstrated by Browne and Fairhead (1983), Browne et al.(1985), Schull (1988), Jorgensen and Bosworth (1989), Mann (1989), Bosworth (1992) and McHargue et al. (1992, this volume). Surface exposures of the rift sequences are rare and the total extent of the basins is known only from a combination of gravity studies and hydrocarbon exploration by major oil companies (Wycisk et al., 1990). The average amount of extension in the northern Sudan rifts is less than 10–30% (Jorgensen and Bosworth, 1989; Mann, 1989; Bosworth, 1992) and therefore they would not be expected to be characterised by significant magmatic activity. They appear to be passive rifts generated by crustal extension and lithospheric thinning, induced by regional tensile stresses.

The rifts terminate to the NW against the Central African Shear Zone (Fig. 2), which is a major continental scale transcurrent fault zone. Gravity and seismic data indicate that, in Sudan, this NE–SW trending structure consists of several small pull-apart basins connected by possible strike-slip faults (Bosworth, 1992). The largest basin on the shear is the Bagarra, which contains strata at least as old as Albian–Aptian (Bosworth, 1992), suggesting that the CASZ has been active since at least the Early Cretaceous. In south Sudan the rift basins are linked to their continuation in Kenya, the Anza rift, via the South Sudan Shear (Bosworth, 1992), which is believed to have been a major shear zone since at least the Late Jurassic. The Anza rift is one of the world's largest single rift basins, and one of the most highly extended (43–86%) in the Central African rift system (Bosworth, 1992). The age of initiation of rifting is not known, but is presumed to be Late Jurassic–Early Cretaceous.

Rifting in Sudan was initiated in the Late Jurassic (White and Blue Nile rifts; Fig. 3) when the principal extension direction was E–W, but shifted to a NE–SW orientation in the Late Cretaceous and Early Tertiary, involving all the known Mesozoic basins of Sudan and Kenya (Schull, 1988; Bosworth, 1992). Three distinct phases of rifting may be recognised; Late Jurassic–Albian, Turonian–Palaeocene and Eocene–Miocene (Bosworth, 1992; Fig. 3). The first phase may actually comprise two sub-phases, comparable with the observations of Guiraud and Maurin (1992, this volume) in the Benue Trough. The Blue Nile, Muglad and Anza basins underwent significant inversion in the Early Tertiary, related to E–W shortening (Bosworth, 1992; Fig. 3).

The oldest magmatic rocks drilled in the Blue Nile rift are extrusive basalts intercalated with lacustrine clays, suggested to be Late Jurassic in age on the basis of palynological data (ca. 155 Ma; Wycisk et al., 1990; Fig. 3). Basaltic lava flows encountered during drilling in the Khartoum sub-basin have been dated at 143 ± 6 and 125 ± 4 Ma. Wycisk et al. also note the existence of volcanic activity at ca. 80 and 38 Ma in the Blue Nile rift but do not indicate its nature. In the northwestern Muglad basin they report an age of 82 ± 8 Ma for a 90 m thick dolerite sill, encountered during drilling. These authors also note evidence for volcanic activity at approximately 4 and 2 Ma within alluvial fan sequences in the Muglad, which may represent air fall pyroclastic deposits from Cenozoic volcanic centres (e.g. Jebel Marra) outside the basin. T. McHargue (pers. commun., 1991) has described the presence of smectite as a cement in sandstones of the Aradeiba Formation (ca. 88–95 Ma) in the central Muglad which may be an alteration product of volcanic ash. Large Miocene–Pliocene dolerite sills have been identified in the Anza rift sequence (Bosworth, 1992).

In Sudan and southern Egypt, there is evidence for a Triassic magmatic event (250–220 Ma; Vail, 1989; Franz et al., 1987; Schandelmeier and Kuster, 1991), which may be associated with the early stages of breakup of Gondwana. The expression of this event is mostly in the form of alkali ring complexes (Fig. 2). Schandelmeier and Richter (1991) record alkaline igneous activity in northern Kordofan, which ranges in age from Late Carboniferous (313 Ma) to Jurassic (165 Ma). This is intimately related to the reactivation of Pan-African basement shear zones which are subparallel to the CASZ (Fig. 3). Additionally, Schandelmeier and Kuster (1991) have suggested that major domal uplift in Kordofan, associated with the emplacement of Early Permian–Mid-Jurasic alkaline complexes, is related to the activity of a mantle plume beneath the area. Late Palaeozoic alkaline magmatic rocks, sealing reactivated basement structures, are also reported from an extensive E–W striking uplift zone, extending from Jebel Uweinat to the Red Sea (Klerx and Rundle, 1976; Schandelmeier and Darbyshire, 1984; Franz et al., 1987), which is subparallel to the Guinea–Nubian Lineament (Fig. 2).

Guinea–Nubian lineament

The Guinea–Nubian lineament (GNL; Fig. 2) is a major trans-lithospheric fault zone that can be traced across Africa, from the Senegal continental margin to the Red Sea (Guiraud et al., 1985). This is a pre-Mesozoic fracture system that has been reactivated periodically since the Triassic. In the Taoudenni basin of Mali, tholeiitic basalt dykes, sills and flows were emplaced parallel to this lineament, during the Early Jurassic (ca. 200 Ma; Bertrand, 1991) Central Atlantic rifting phase (Guiraud et al., 1987). However, in detail many different dyke directions are apparent and no priviledged fault direction clearly predominates (Bertrand, 1991). Permo-Triassic syenite ring complexes associated with this and subparallel lineaments (Tadhak 262–270 Ma; Bayuda Desert 233–237 Ma; Djebel Uweinat 235 Ma; Fig. 2; Vail, 1989; Franz et al., 1987) suggest that it may have provided an important pathway for magmas to reach the surface and may therefore affect the entire lithosphere (Guiraud et al., 1987). Permo-Triassic magmatic activity in the Air Massif (Valsardieu, 1971) may also be related. Kimberlite magmatism (83–120 Ma) in West Africa (Guinea, Mali, Senegal, Sierra Leone and Liberia) and the 80–105 Ma syenite magmatism of Los Island (Guinea) may also have been focussed by the Guinea–Nubian and subparallel lineaments (Haggerty, 1982; Moreau et al., 1986).

Niger–Chad basins

The NW–SE trending Tenere, Termit, Tefidet, Grein and Kafra basins of eastern Niger–Chad were initiated by Early Cretaceous rifting (Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume). The Termit is the largest basin, separated from the Tenere graben to the north by a major dextral shear zone (Agadez lineament), which forms part of the Guinea–Nubian lineament (Guiraud et al., 1985). The seismically defined depth to the Moho within the Termit basin is 25–30 km, with a maximum sediment thickness of approximately 14 km, suggesting a β-factor of approximately 2 (Genik, 1992, this volume). The stratigraphic record of the Tenere and Termit troughs suggests that there may have been continuous magmatic activity from Early Cretaceous to Recent times. However, no data are available concerning the geochemical characteristics or absolute ages of the igneous rocks. In the southern part of the Termit basin drilled rhyolite and basalt dykes and dolerite sills are constrained to be no older than 85–95 Ma (Genik, 1992, this volume).

NE Brazil–Gulf of Guinea

The main Mesozoic magmatic activity in Brazil is essentially restricted to a zone south of 16°S, roughly coinciding with the northern limit of the Parana tholeiitic flood basalt province (Chang et al., 1992, this volume). The Parana basalts, and their time equivalents in Southern Africa (Namibia), appear to have formed at about the same time (120–130 Ma) that the northward propagating South Atlantic rift reached the latitude of Namibia. The voluminous magmatic activity has been related to the activity of the Tristan da Cunha hotspot beneath the newly developing plate boundary (O'Connor and Duncan, 1990; Fig. 1). However, in northeastern Brazil (Fig. 2) there are widespread occurrences of magmatic rocks, mainly with tholeiitic characteristics, which can be correlated with the various phases of opening of the Central and Equatorial Atlantic (Fig. 3). Rifting in this area commenced during the Late Jurassic–Early Cretaceous (Castro, 1987) and, as in West and Central Africa, local reactivation of pre-existing basement fractures may have been important. Sedimentation and magmatic activity appear to cease by the mid-Albian (Fig. 3), coincident with the opening of the Equatorial Atlantic. The extensive occurrence of tholeiitic magmatic rocks in this area, preceding and concurrent with the Cretaceous rifting phase, strongly suggest the involvement of hotspot activity in the rifting process.

Fodor et al. (1990) have made a detailed geochemical study of tholeiitic basaltic rocks from the Maranhão basin (Fig. 2). These include low Ti Triassic?–Jurassic flood basalts from the western part of the basin (154–189 Ma) and high Ti Cretaceous hypabyssal intrusions from the eastern part (115–122 Ma). The low Ti basalts could relate to the opening of the southern part of the Central Atlantic, whereas the high Ti basalts could relate to the initial stages of opening of the Equatorial Atlantic at approximately 120 Ma. The Triassic?–Jurassic flood basalts may be related to the activity of a mantle hotspot, as Morgan (1983) places the St. Helena hotspot near Maranhão at 180 Ma. Relatively low initial $^{87}Sr/^{86}Sr$ ratios (ca. 0.7057) and O-isotope values ($\delta^{18}O$ ca. + 6.5‰) for some of the high Ti basalts suggest that they have experienced little crustal contamination, and therefore that their isotopic characteristics may reflect those of their mantle source. Geochemically they are similar to high Ti basalts from the Parana province, which have been considered by Hawkesworth et al. (1986) to be derived by partial melting of enriched subcontinental lithospheric mantle sources. In contrast the low Ti basalts may have experienced significant high level crustal contamination.

Oliveira et al. (1990) present geochemical data for the N–NW trending tholeiitic Amapa dyke swarm of northern Brazil, which is temporally and spatially related to the opening of the Central Atlantic ocean (250–180 Ma). Individual dykes within this swarm can attain several hundreds of metres in width and can be traced over distances exceeding 250 km. In pre-drift reconstructions of South America and Africa the dykes are parallel to those of similar age in Liberia, Sierra Leone and Ivory Coast. Oliveira et al. (1990) consider that the range of compositions observed may be accounted for in terms of interaction between the Cape Verde mantle hotspot and the subcontinental lithosphere.

Fodor and McKee (1986) report whole-rock K–Ar ages of 185.4, 183.2 and 126.5 Ma for tholeiitic basaltic rocks cored in the offshore Amapa basin, northern Brazil. If these represent true crystallisation ages, then the older ages may relate to the opening of the Central Atlantic, while the younger ages relate to Equatorial Atlantic rifting. However, Mauche et al. (1989) have shown that K–Ar ages of similar tholeiitic intrusive rocks from Liberia may be unreliable due to the absorption of excess ^{40}Ar from the adjacent country rocks. If this is also the case here, then the youngest age (ca. 125 Ma) is the most reliable indicator of the age of emplacement. These basalts have geochemical affinities with the low-Ti tholeiitic Parana flood basalts of southern Brazil (Fodor et al., 1985) and are of a similar age. Horn et al. (1988) have obtained similar K–Ar ages (167–130 Ma) for an E–W striking tholeiitic dyke swarm in the Rio Grande do Norte, which extends for a distance of 200 km. Reyre (1984) documents the existence of 120–125 Ma volcano-sedimentary sequences on the continental shelf of Ghana and in the Potiguar basin there are 125–130 Ma dykes (Gouyet, 1988). Zalan et al. (1985) record the presence of slightly younger basalts in the Aptian syn-rift sequence of the offshore Piaui (Ceara) basin.

Long et al. (1986) give a Rb–Sr age of 104.8 ± 1.8 Ma for the magmatic complex of Cabo de Santo Agostinho, about 30 km south of Recife in northeastern Brazil. This consists of leucogranite and a variety of volcanic rocks including basalt, andesite, trachyte and rhyolite. Long et al. note that this complex lies on the extension of the trend of the Nigerian granite complexes of the Jos Plateau and may be synchronous with the initial stages of ocean basin formation in the Equatorial Atlantic. Chang et al. (1992, this volume) note the occurrence of basic dykes of similar age (105 Ma), associated with Precambrian NE–SW oriented mega-Riedel fractures, produced by sinistral movement of the Pernambuco shear zone (Fig. 2).

Almeida and Svisero (1991) and Castelo Branco and Lasnier (1991) describe the occurrence of kimberlite diatremes emplaced into the Palaeozoic and Mesozoic sediments of the Parnaiba basin (Fig. 2). These appear to be related to a regional basement lineament which, in predrift reconstructions, may connect with the Central African Shear Zone in West and Central Africa.

Cenozoic magmatism

Cenozoic magmatic activity is widespread in West and Central Africa (Fig. 4), particularly

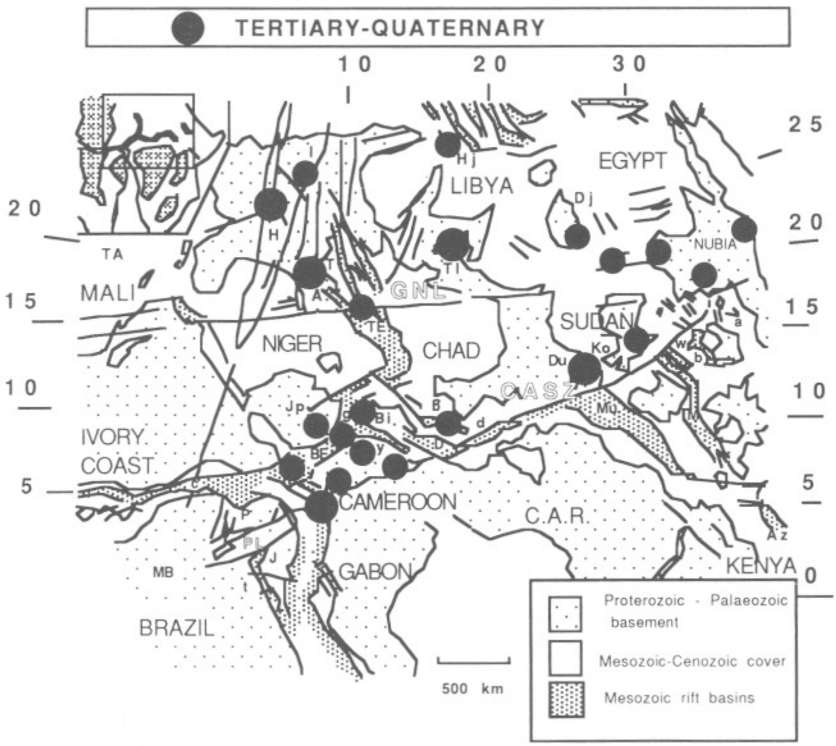

Fig. 4. Location of the major sites of Cenozoic magmatic activity in West and Central Africa. Activity associated with the Red Sea and East African rift system has been omitted for clarity. Symbols and data sources as Fig. 2.

during the Neogene. The volcanic fields are concentrated in Pan-African mobile belt zones, which have experienced tectono-thermal events within the past 650 Ma and which have generally higher heat flow and possibly thinner lithosphere than the adjacent West African craton (Lesquer et al., 1989). In some instances volcanism is closely associated with the zones of Cretaceous rifting (e.g. Benue Trough). However, many volcanic fields lie outside the Mesozoic rift basins. In several areas there is a strong correlation between Cenozoic volcanic activity and the location of major basement faults (Fig. 4), which may suggest that the rising magmas have utilised Mesozoic or older trans-lithospheric fractures/shear zones to ascend to the surface. Volcanic activity is particularly common in areas in which two or more differently oriented crustal lineaments or fault zones intersect (e.g. Hoggar). Many of the volcanic fields are associated with domal uplifts of the basement several hundred kilometres in diameter (e.g. Hoggar, Tibesti, Jebel Marra, Cameroon). This might suggest that they overlie localised diapiric mantle upwellings or hotspots, initiated at fairly shallow depths within the upper mantle.

Cameroon Volcanic Line

The 700 km long northeast trending Cameroon Volcanic Line (CVL), to the southeast of the Benue Trough, is the continental segment of a 1600 km long volcanic chain that straddles the West African continental margin, characterised by Maastrichtian–Recent alkaline magmatism (Figs. 3 and 4). It is partly superimposed upon a pre-existing fracture zone, the Central African Shear Zone, which cuts across a broad post-Cretaceous uplift, the Adamawa Uplift. Seismic refraction data indicate the presence of normal thickness continental crust (34 km) beneath the uplifted area (Dorbath et al., 1984). However, inversion of teleseismic travel time residuals indicates the existence of a well defined low velocity structure in the upper mantle in the depth range 40–140 km (Dorbath et al., 1986) which may indicate the presence of a zone of anomalously hot mantle beneath the region. The tectono-magmatic evolution of the line has been interpreted in terms of the development of en-echelon mega-tension gashes induced by transcurrent movement along the Central African Shear Zone (Guiraud et al., 1987; Moreau et al., 1987), but is not yet fully understood.

Magmatic activity has been reactivated several times along the length of the line. From the Maastrichtian to the end of the Eocene (73–35 Ma) anorogenic ring complexes of granite and syenite, with less abundant gabbro and occasional remnants of trachyte and rhyolite, were emplaced (Fitton, 1987). In north and central Cameroon these are generally older (73–60 Ma) than in central and south Cameroon (45–35 Ma) (Guiraud et al., 1987). Despite their Tertiary age, these have close geochemical affinities with the Younger Granites of Nigeria (Vail, 1989). Alkaline volcanic activity commenced around 35 Ma and has continued intermittently to the present day. Both the oceanic and continental sectors appear to have been active since the end of the Cretaceous and there is no evidence for any consistent migration of volcanic activity with time along the line (Fitton and Dunlop, 1985; Fitton, 1987). There are 12 main volcanic centres, three of which (Bioko, Etinde and Mt. Cameroon) straddle the seismically defined ocean/continent boundary.

Geochemical and isotopic data show no significant differences between alkali basaltic rocks erupted in the continental and oceanic sectors of the line (Fitton, 1987; Halliday et al., 1988). The continental lithospheric mantle beneath Africa should be chemically and isotopically very different from the young Atlantic ocean lithosphere, and, therefore if it had been involved extensively in the petrogenesis of the continental sector magmas they should bear a distinctive geochemical fingerprint, which they do not. This suggests that the primary magmas in the two sectors had similar sub-lithospheric mantle sources. However, the more evolved rocks in the two sectors are quite distinct. The continental magmas evolve towards peralkaline rhyolite whereas those of the oceanic sector evolve towards phonolite. Progressive crustal contamination of the continental sector magmas, accompanied by crystal fractionation, can explain this difference. In general there is a good correlation between the degree of silica-saturation of the primitive basalts and their $^{87}Sr/^{86}Sr$ ratio. Transitional basalts tend to have higher $^{87}Sr/^{86}Sr$ ratios than alkali basalts, nephelinites and basanites which suggests that they may have experienced crustal contamination en-route to the surface. Alternatively the transitional basalts may have incorporated partial melts derived from old enriched domains within the sub-continental lithospheric mantle.

Halliday et al. (1990) have shown that the primitive alkali basaltic magmas of the Cameroon line display a distinctive Pb isotope anomaly focussed at the continent/ocean boundary (Mt. Cameroon) which dimishes over a distance of 400 km to either side. Samples from the continent/ocean boundary volcanoes are characterised by elevated $^{206}Pb/^{204}Pb$ ratios similar to those associated with the oceanic island of St. Helena in the South Atlantic (Fig. 5). Such Pb-isotope characteristics are considered to develop in mantle source regions which have evolved for approximately 2 Ga with high U/Pb (μ) ratios and are commonly referred to as HIMU (high-μ). Halliday et al. (1990) consider that the Pb-isotopic anomaly in Tertiary–Quaternary volcanic rocks from the continent/ocean boundary in Cameroon is inherited from a zone at the base of the lithosphere (both continental and oceanic) that was metasomatically modifed by the St. Helena hotspot during the Cretaceous (ca. 130–100 Ma) opening of the Equatorial Atlantic. If correct, this would suggest that a broad zone of the continental lithosphere within West and Central Africa, extending over a radius of more than 500 km from Mt. Cameroon, may have been similarly modified, with the effect decreasing outwards from the axis of the plume head. HIMU characteristics are also apparent in Cenozoic alkali basalts from Hoggar (Algeria) and Jebel Marra (Sudan) (Fig. 5), which suggests that their source regions may have been similarly modified by the activity of HIMU mantle plumes. However, these are too far away from the postulated Cretaceous locus of the St. Helena hotspot (Figs. 1 and 4) to be related to that particular plume. An alternative explanation for the HIMU characteristics may be found in a recent proposal by Pavoni (1991) that a large scale dynamic upwelling of the mantle, originating in the lower mantle, has been focussed around 10°E, 0°N since the Mesozoic. This

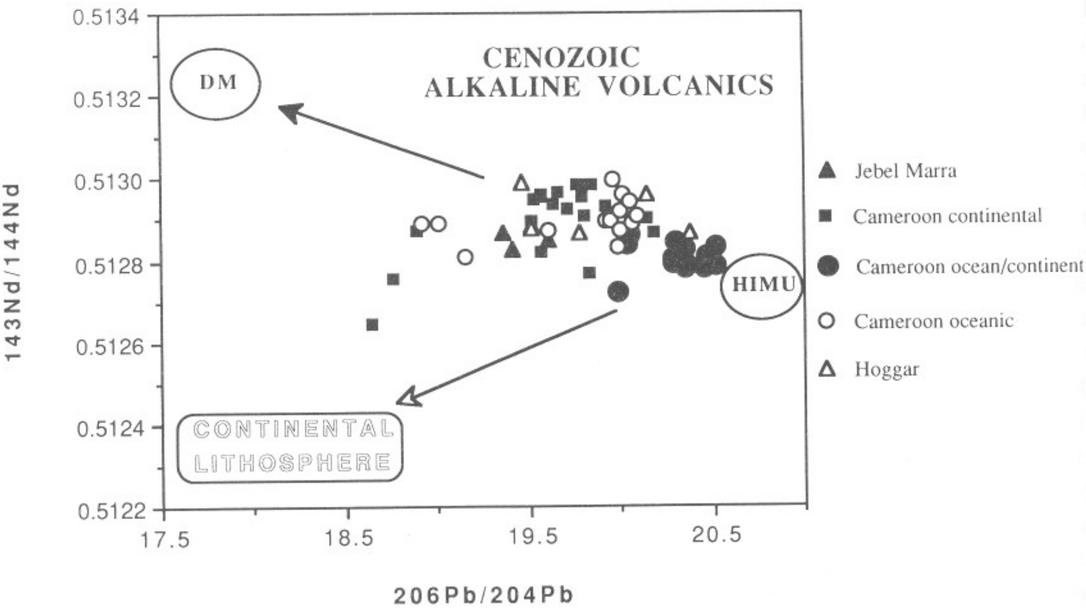

Fig. 5. Nd–Pb isotopic characteristics of Cenozoic alkali basalts. For data sources see text.

is an interesting idea which requires further investigation.

Benue Trough–Biu Plateau–Garoua Basin

During the Tertiary, basaltic magmas were emplaced throughout the entire Benue Trough, with the greatest concentration in the northeast (Fig. 4). More than 500 volcanic necks occur in this region, associated with the eruption of extensive alkali basalt lava flows on the adjacent Biu Plateau. Post-Cretaceous extension and volcanism in the Upper Benue corresponds to a period of general stress release after the Santonian or end Cretaceous compressional events (Benkhelil, 1989). In the Biu Plateau the distribution of volcanic necks appears to be controlled by a N–S alignment of Tertiary faults. In the Upper Benue, trachytes and phonolites have been dated between 11 and 22 Ma, while on the Biu Plateau basalts were emplaced from 23 to 7 Ma, and from 3 Ma to the present (Guiraud et al., 1987). Volcanism of this age also occurs on the nearby Jos Plateau and in the Cameroon volcanic line.

The development or rejuvenation of major fault systems, related to dominant E–W extension (Guiraud et al., 1987), took place during the Tertiary; in particular fractures at the contact between the Gongola branch of the Benue Trough and the Jos Plateau. These faults appear to control the localisation of Neogene–Quaternary volcanism in the Upper Benue and Jos Plateau. The emplacement of Palaeocene and Eocene alkali granite intrusions in Cameroon appears to be similarly fault controlled (Moreau et al., 1987). Activity in the southern part of the Jos Plateau occurred between 2.1 and 0.9 Ma (Grant et al., 1972) with the eruption of thin alkali basalt lava flows and the emplacement of rare phonolite domes.

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).

Hoggar

The Miocene–Quaternary volcanism of Hoggar indicates the important control reactivated basement faults may have on the location of magmatism (Guiraud et al., 1987; Dautria and Lesquer, 1989). The area is characterised by a broad domal uplift some 1000 km across (Dautria and Lesquer, 1989), with basement elevations of 350–400 m on the flanks rising to 1000–1200 m in the central part. Major NW–SE to NNW–SSE trending faults, which control the Tenere rift system to the southeast (Fig. 4), extend northwards into the Hoggar basement. These intersect the extension of N–S faults bounding Mid-Cretaceous rifts to the North of Hoggar, in the central part of the uplift, which is also a zone of strongly negative Bouguer anomalies and the focus of early magmatic activity (Dautria and Lesquer, 1989). The negative Bouguer anomalies suggest that thermal perturbations of the lithosphere are associated with the basement uplift (Lesquer et al., 1989). Unfortunately the timing of uplift is poorly constrained. A NE–SW trending late Pan African basement lineament also intersects the area and appears to have controlled the location of the main Miocene–Quaternary volcanic centres (Dautria and Lesquer, 1989). This is subparallel to the Guinea–Nubian lineament which stretches across Africa from the Senegal–Guinea coast to Egypt (Guiraud et al., 1985) and which may have influenced the location of magmatic activity in Egypt and in the Air and Tibesti massifs, as well as in Hoggar. The Miocene–Quaternary magmas appear to have used NE–SW and NW–SE trending faults to rise up to the surface, as evidenced by the orientations of dykes and chains of strombolian cinder cones. These trends correspond to a conjugate system of late Pan African strike slip faults, which may have been reactivated during the Cenozoic (Dautria and Lesquer, 1989).

Magmatic activity in the area began during the Late Cretaceous and Eocene (Fig. 3) with the emplacement of ring-complexes of carbonatitic affinity, including shonkinites, essexites, phonolites and monchiquites (Dautria et al., 1988) and the emission of basaltic lavas of possible tholeiitic affinity (Dautria and Girod, 1991). Miocene to Recent volcanism is focussed in five main areas (Tahalra, Atakor, Manzaz, Eggere and Adra N'Ajjer) with the main peak of activity in the Miocene. These areas correspond to zones in which the Precambrian basement has been domally uplifted (up to 2600 m in Atakor) during the Neogene (Lesquer et al., 1989; Dautria and Lesquer, 1989). These domes (up to 150 km across) are superimposed on a regional basement swell. The magmatism is alkaline and involves the eruption of predominantly mafic lavas (alkali basalts, basanites and nephelinites). The degree of silica undersaturation of the mafic rocks increases with decreasing age such that alkali basalts predominate in the Miocene, basanites in the Miocene–Quaternary and nephelinites during the Quaternary. On the basis of decreasing volcanicity from the Miocene to the Quaternary, and the present low heat flow of the area, Dautria and Girod (1991) suggest that the Quaternary basalts result from smaller degrees of partial melting at greater depths (ca. 150 km) than the Miocene basalts (80–100 km).

Studies of amphibole-bearing lherzolite and harzburgite mantle xenoliths entrained within the Plio-Quaternary basalts (Dupuy et al., 1986; Dautria et al., 1987; Dautria and Girod, 1991), suggest that the upper mantle beneath Hoggar is very heterogeneous and reduced in density compared to normal upper mantle. Most of these heterogeneities (due to partial melting, metasomatism and magma migration) could have been induced by successive magmatic events since the Late Mesozoic. Combined with gravity studies (Crough, 1981), these data suggest the occurrence of a low density body less than 60 km below the surface. Domal uplift could be the isostatic response to the presence of this body (Lesquer et al., 1989). Lesquer et al. (1989) present heat flow data for the area which do not reveal any large scale thermal perturbations of the lithosphere consistent with upwelling of the lithosphere/asthenosphere boundary on a regional scale. This is consistent with the conclusions of Crough (1981) on the basis of gravity data. The simplest explanation of these data is that the major thermal anomaly beneath the area was initiated in the Late Cretaceous–Eocene and that it has decayed significantly since the peak of volcanic activity in the Miocene (Dautria and Girod, 1991). The highest heat flow (61–63 mW m^{-2}) occurs within the fault bounded central Hoggar area and its extension to the south towards the Air Massif (Fig. 4), which may support the suggestion that deep seated basement fault zones control the major magma pathways to the surface.

Trace element and Nd–Sr–Pb isotopic studies of the Plio-Quaternary mafic volcanic rocks (Dautria et al., 1987; Allegre et al., 1981) suggest that their mantle source is highly enriched in incompatible elements and that this characteristic probably results from previous metasomatic events unrelated to the recent volcanic history of the area. Alkali basalts and nephelinites have $^{87}Sr/^{86}Sr$ ratios in the range 0.7031–0.7035; $^{143}Nd/^{144}Nd$ ratios range from 0.51287 to 0.51299 and $^{206}Pb/^{204}Pb$ from 19.46 to 20.37 (Fig. 5). Some of the Hoggar basalts show HIMU characteristics as extreme as those of the ocean/continent boundary Cameroon Line magmas. Thus it is possible that the metasomatism of their source region was similarly induced by the activity of a HIMU mantle plume, during the Mesozoic. Evidence for a major pre-Cretaceous uplift phase in the area, suggested by the unconformable relationship between Early Cretaceous strata and Precambrian–Palaeozoic basement rocks, may support such a model. However, it is equally possible that the Tertiary–Quaternary volcanism of Hoggar might be related to the upwelling of a HIMU mantle plume beneath the African plate since the Late Cretaceous.

Lesquer et al. (1990) note that to the north of Hoggar there is an E–W trending zone of anomalously high heat flow (80–120 mW m^{-2}), which correlates with a low velocity zone in the mantle down to depths of 150 km. The Illizi volcanic district (Fig. 4) is located on the southern edge of this heat flow high. Here some 20 explosion craters of probable Quaternary age eject lava fragments of melilitite and abundant spinelphlogopite harzburgite and rare phlogopite-garnet lherzolite mantle xenoliths. Combined petrogenetic and geophysical studies of this area may provide important constraints for models of intra-continental plate magmatism.

Air–northern Termit

Neogene–Quaternary volcanism in eastern Niger (Air and northern Termit areas; Fig. 4) has been related to intra-plate extension along NW–SE trending structural lineaments which extend from Hoggar to Lake Chad (Pouclet and Karche, 1988). Volcanism began in the early Miocene, with the main phase of activity in the Plio-Pleistocene, associated with ENE–WSW extension. The magmatism is predominantly alkaline involving nephelinites, basanites, alkali basalts and transitional basalts and their differentiates.

Four stages of volcanic activity have been recognised on the basis of K–Ar dating (Pouclet and Baubron, 1988): (1) Late Oligocene–Early Miocene (28–20 Ma)—involving basanitic to trachytic plugs, dykes, necks and flows. (2) Middle–Late Miocene (15–8 Ma)—scarce dykes and flows. (3) Pliocene (4–1.8 Ma)—abundant basanitic to basaltic volcanism in the form of necks and flows; also some trachytic and phonolitic flows in central-eastern Air. (4) Early–Middle Pleistocene (1.8–0.7 Ma)—similar to stage 3 but separated from it by an important phase of uplift in the Air massif in the Late Pliocene. In the northwestern Termit basin the Gosso Lorom volcanics (0–10 Ma alkali basalts, dolerites and tuffs) were emplaced along a major dextral basement shear zone (Agadez lineament; Genik, 1992, this volume). Slightly further south in the Termit basin an alkali dolerite sill has been dated at 8.6 ± 0.5 Ma (Guiraud et al., 1987). Within the Tefidet basin basaltic volcanics were emplaced from the Miocene–Quaternary along N–S oriented fractures.

The Cenozoic magmatic activity shows a chronological succession of the different magma types (Pouclet and Baubron, 1988; Pouclet and Ahmed, 1990). The most alkaline lavas were erupted in northern and central-eastern Air and subsequently in the southern part. These are related to the breakup of the uplifted eastern margin of the Air massif, associated with the subsidence of the Tefidet trough. The less alkaline lavas are the youngest and are scarce in eastern Air but very abundant in its central and southern parts. The same succession occurs in the Termit basin with older basanitic flows followed by younger transitional types.

In terms of their geochemical characteristics the volcanic rocks strongly resemble those of the Hoggar area to the north (Pouclet and Karche, 1988) and are similarly derived from an enriched mantle source region. This area was previously subjected to intense magmatic activity in the Palaeozoic with the emplacement of alkali ring-complexes (Vail, 1989; Demaiffe et al., 1991) which may have resulted in metasomatic enrichment of the lithospheric upper mantle. Magmatic activity also occurred in the Mesozoic (Valsardieu, 1971; Pouclet and Baubron, 1988).

Tibesti

The Tibesti massif of northern Chad is an area of domally uplifted basement rocks capped by Tertiary–Quaternary volcanic rocks. There is little published data on the area and the following brief description is based on that of Vincent (1970). The massif has been the site of intense volcanism since the Early Tertiary (Middle Eocene) and a major part of the volcanic activity is of Quaternary age. The initial phase of volcanic activity involved the eruption of mildly alkaline plateau basalts and their differentiates (trachyte, phonolite and rhyolite). In the central part of the massif these are surmounted by four large shield volcanoes, which erupted subalkaline basalts and their differentiates. These were followed by large scale eruptions of alkali rhyolitic ignimbrite. The final phase of Quaternary volcanism involved the eruption of silica poor potassic alkali basalts and their derivatives. The first phase of uplift in the area, which resulted in the erosion of thick Palaeozoic formations, is thought to be post-Carboniferous but pre-Early Cretaceous in age.

Sudan

Within Sudan, the Central African Shear Zone appears to control the distribution of Cenozoic volcanic centres distributed along its northern side, extending from Darfur to the Bayuda desert (Browne et al., 1985; Breitkreuz et al., 1991; Fig. 4). In the Darfur region a major central volcanic complex, Jebel Marra, developed in Miocene–Recent times above a domally uplifted area, whose main phase of uplift is thought to be Cretaceous (Birmingham et al., 1983). Two volcanic series, ranging in composition from alkali basalt to phonolite, have been recognised and are separated by an unconformity (Davidson and Wilson, 1989). Ages of 23 and 14 Ma have been reported for the first phase of activity (Breitkreuz et al., 1991). The climax of the second phase of activity (2 Ma–present) resulted in the formation of a large caldera (Deriba) at approximately 0.06 Ma. Volcanic activity persisted to at least 3500 years B.P. as determined by ^{14}C dates on carbonised wood fragments within pyroclastic rocks.

The basaltic lavas of Jebel Marra show a restricted range of Sr–Nd–Pb–O isotopic compositions, whereas the more differentiated magmas show a wide range, consistent with the effects of crustal contamination (Davidson and Wilson, 1989). The primitive alkali basalts display HIMU Pb isotopic characteristics similiar to those of the Cameroon Line and Hoggar (Fig. 5), suggesting that they too may have been derived from a lithospheric mantle source, metasomatised by the activity of an earlier mantle plume. In general, however, the HIMU characteristics of the Jebel Marra basalts are rather weak (Fig. 5) which may be consistent with the location of Darfur on the periphery of the St. Helena plume head, when its axis was located beneath the Niger delta–Mt. Cameroon area at approximately 120 Ma. However, the distance from Jebel Marra to Mt. Cameroon is more than 1500 km, which would imply greater dimensions for the plume head than those envisioned by White and McKenzie (1989).

Associated with Jebel Marra in the Darfur province are two further volcanic fields in the Tagabo and Meidob Hills (Pudlo and Franz, 1991; Breitkreuz et al., 1991; Fig. 4). In the Tagabo Hills a bimodal basanite-phonolite/trachyte suite forms numerous scattered outcrops in an area of 70×20 km. The phonolites are about 16 Ma old and the basanites 11 Ma. The mode of emplacement of these rocks suggests shear controlled magma ascent along numerous deep seated fractures. There is no evidence for explosive volcanism in contrast to Jebel Marra where large pyroclastic eruptions are recognised within the sequence. In the Meidob Hills there are some 400 monogenetic cones of alkali olivine basalt and subordinate differentiated rocks (phonolite/rhyolite) which are much younger (6.5–0.25 Ma).

Volcanic rocks of Tertiary age are abundant in the areas near the Red Sea in Egypt, Sudan and Ethiopia (Cahen et al., 1984; Franz et al., 1987) and there is little doubt that 26–20 Ma volcanic activity is related directly to the opening of the Red Sea. These have been omitted from Fig. 4 for clarity. Tertiary magmatic activity also occurs in the northern part of the Anza rift (P.H. Nixon, pers. commun., 1991).

Summary

Magmatic activity was widespread in West and Central Africa and in northeastern Brazil during the Early Mesozoic (Triassic–Jurassic) prior to the development of major intra-continental rift systems in the Cretaceous. Some of this activity (e.g. Maranhão Basin, Brazil; Jos Plateau, Nigeria) may be related to the activity of mantle plumes which acted to pre-weaken the lithosphere and enhance the effects of deviatoric stresses on the subsequent rifting of Gondwana to form the proto-Atlantic ocean. Unfortunately the geochemical characteristics of these early magmatic rocks, particularly the tholeiites of Brazil, give little information about the geochemical identity of such mantle plumes, as their isotopic and trace element characteristics are largely dominated by components derived from the continental lithosphere.

There is strong evidence that the St. Helena hotspot was active beneath the Niger delta–Mt. Cameroon region of West Africa during the Early Cretaceous (O'Connor and Duncan, 1990). This must have considerably modified the lithosphere in the region of the proto-Equatorial Atlantic, both thermally and chemically. However, plume activity did not lead to voluminous tholeiitic flood basalt eruptions within the region. This is in marked contrast to the Tristan da Cunha hotspot, active at broadly the same time beneath the developing South Atlantic plate boundary, which is associated with the Parana flood basalt province of Brazil. The St. Helena and Tristan da Cunha plumes have different geochemical characteristics, which may relate to different sources and depths of initiation within the Earth's mantle (Wilson, 1989), and their dynamics remain incompletely understood. A comparative study of the different tectono-magmatic responses to lithospheric extension above the two plumes remains an important area for future studies. Unfortunately there is little geochemical data available for the Cretaceous phase of magmatic activity in West and Central Africa, apart from a small amount of unpublished Nd–Sr isotopic data for alkaline and tholeiitic basalts from the Benue Trough (Baudin, 1991). Pb isotopic data for these samples are urgently required to test the involvement of the St. Helena hotspot in their petrogenesis. The available Nd–Sr isotopic data do not provide conclusive evidence for this, but are consistent.

In the Cenozoic, alkaline magmatic activity has occurred widely within West and Central Africa, both within the Cretaceous rift system and outside it. Much of this magmatism is alkali basaltic in composition and can be related, at least in part, to the reactivation of major deep seated lithospheric fracture zones. Several of the volcanic fields are associated with broad domal basement uplifts, with diameters which suggest that uplift may have been initiated by diapiric upwelling within the upper mantle (< 670 km depth). The timing of uplift in these areas is, in general, poorly constrained and this remains an area for further research. However, in several areas (e.g. Kordofan, Hoggar) there is evidence to suggest that basement uplift may have been related to Mesozoic plume activity. The Nd–Sr–Pb isotopic characteristics of some of the Cenozoic basalts strongly suggest that they may have been derived from a zone at the base of the continental lithosphere, which had been metasomatically enriched in incompatible elements by the activity of mantle hotspots during the Mesozoic. This demonstrates that the relationship between the activity of mantle plumes and the geodynamics of rifting is complex, with some mafic magmas being derived from plume-modified mantle sources more than 100–150 Ma after the actual activity of the plume ceased beneath a particular part of the African plate.

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