Tectonophysics, 213 (1992) 141–151
Elsevier Science Publishers B.V., Amsterdam

A plate tectonic setting for Mesozoic rifts of West and Central Africa

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(Received May 24, 1991; revised version accepted November 28, 1991)

ABSTRACT

Binks, R.M. and Fairhead, J.D., 1992. A plate tectonic setting for Mesozoic rifts of West and Central Africa. In: P.A. Ziegler (Editor), Geodynamics of Rifting, Volume II. Case History Studies on Rifts: North and South America and Africa. *Tectonophysics*, 213: 141–151.

Africa, by virtue of its central position within Gondwana, has recorded much of the complex history of plate interactions which have progressively fragmented this supercontinent since the Early Mesozoic. Continental reconstructions reveal both a temporal and spatial relationship between the development of the continental margins of Africa and the formation of rifted sedimentary basins deep within the African continent. The multi-stage opening of the Atlantic Ocean and associated rifting in West and Central Africa provide one of the most impressive examples of ocean–continent tectonic interactions. During the Early Cretaceous the onset of rifting along the future margins of the South Atlantic is contemporaneous with intra-continental rifting generating both strike-slip and extensional basins within West and Central Africa. The syn-rift phase of intra-continental basin development continued until the Santonian, by which time Africa and South America had been physically separated for approximately 10 Ma. Except for minor rifting during the Senonian and Tertiary, the short-lived phase of deformation at about 80 Ma marks the transition into the post-rift or "sag" phase of basin development. This deformational event can be correlated with a period of plate motion changes, recognised from fracture zone geometries, seen in both the Central and South Atlantic oceans. Using present day stress analogies, Cretaceous rifting in Africa can provide a means of indicating the regional palaeostress directions within Africa at this time.

Introduction

Since the Late Palaeozoic, the progressive fragmentation of Gondwana has led to not only major basin formation along the present-day continental margins but also to distinct phases of intra-continental rift basin development within the African continent. In this paper, we distinguish three major phases of basin development: (1) prior to 180 Ma, (2) 130–80 Ma and (3) 20–0 Ma and focus in on the second phase.

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Phase 1

This phase of basin development is associated with the breakup of Gondwana which commenced in the Middle Jurassic with the opening of the Central Atlantic (Klitgord and Schouten, 1986). There were no associated major intra-continental basins developed in North West Africa coincident with this phase of opening, probably due to the location of the stable West African cratonic block, although Permo-Triassic age rifts can be found in Morocco and East and South Africa. By the Middle Jurassic, the Indian Ocean had started to open with the drift of Madagascar, India and Antarctica away from Africa. This breakup is preceded by a significant phase of

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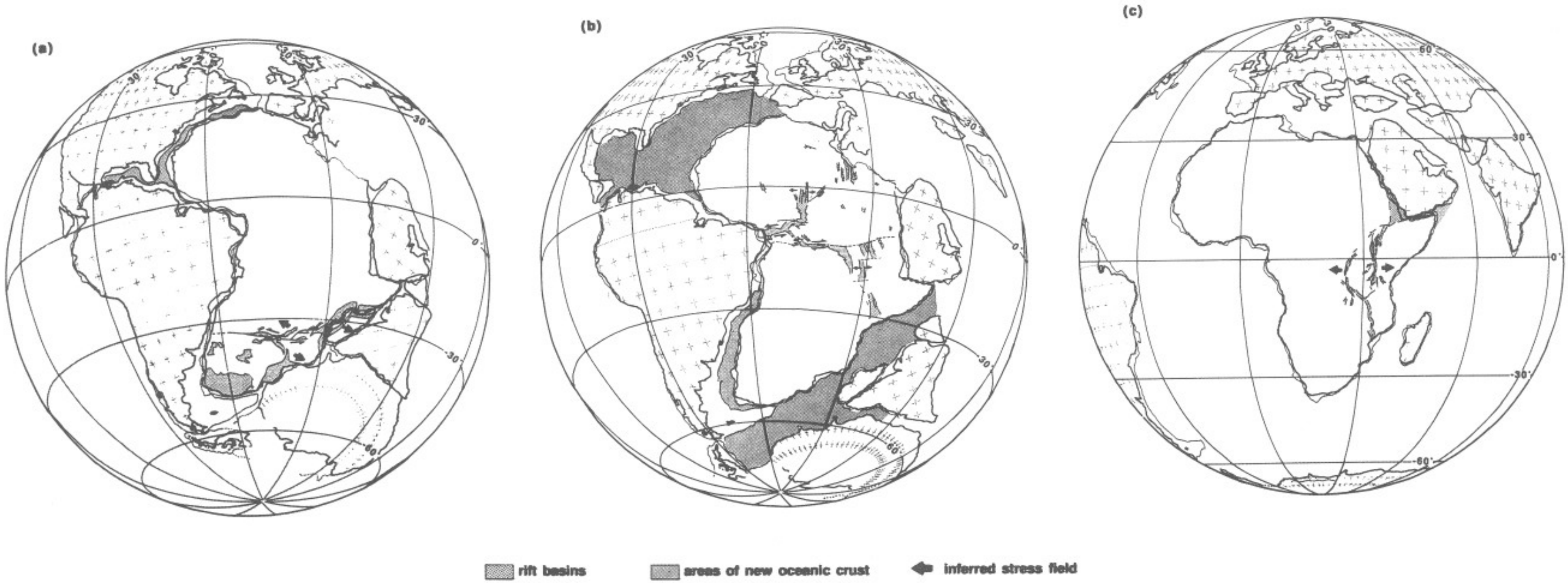

Fig. 1. Reconstructions showing the timing and extent of the three major phases of rifting that have affected the African continent since the Early Mesozoic. (a) 180 Ma, breakup is just beginning along the African–North American margin while Karoo rifting in southern Africa is preceding the imminent separation of Madagascar, Antarctica and India from Africa. Geometry of the Karoo rifts and orientation of stress field from Daly et al. (1989). (b) 130 Ma, the Central Atlantic and Indian Ocean are well established, the South Atlantic has started to open but the Equatorial Atlantic remains closed. The rift systems of West and Central Africa are well established. (c) 20 Ma, rifting is taking place in East Africa associated with the development of the Red Sea as Arabia separates from Africa. Rift structure and stress field from Bosworth (1989) and Strecker and Bosworth (1991). All reconstructions generated using Terra Mobilis™ (Scotese and Denham, 1988).

intra-continental rifting and sedimentation within the extensive Karoo basins of East and Southern Africa (Fig. 1a). These Karoo basins began to develop in the Permo-Triassic (Lambiase, 1989), utilizing the weak zones of the Pan-African mobile belts which surround the cratonic blocks of Southern Africa. Present day seismicity in Southern Africa clearly indicates that these mobile belts continue to be weak crustal zones releasing plate stresses as narrow zones of earthquakes (Fairhead and Henderson, 1977; Daly et al., 1989). By ~180 Ma, when emplacement of oceanic crustal material began along this southeastern margin of Africa, active rifting within the Karoo basins had ceased although there was continued sedimentation in response to a thermal "sag" phase of basin subsidence (McKenzie, 1978).

Phase 2

From the Late Jurassic–Early Cretaceous onwards, rifting was taking place along the line of the proto-South Atlantic, as South America commenced it's separation from Africa (Fig. 1b). This is coincident with our second phase of intra-continental rifting, which led to the development of the West and Central African rift systems (Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume). Continental separation, as defined by the emplacement of oceanic crustal material, is dated at ~130 Ma for the Cape Basin area (Rabinowitz and LaBrecque, 1979) and becomes progressively younger northwards so that the equatorial region had only just begun to separate by ~119 Ma (Mascle et al., 1986). Prior to the opening of the Equatorial Atlantic, the Central and South Atlantic oceans were opening independently from one another resulting in considerable stress building up in the equatorial region. This stress was dissipated into the Caribbean (Pindell and Dewey, 1982), West and Central Africa (Fairhead, 1988b; Fairhead and Binks, 1991) and northeast Brazil (Chang et al., 1992, this volume).

Phase 3

The most recent phase of rifting to affect the African continent began in the Late Eocene and generated the structures of the Red Sea, Gulf of Aden and East African Rift System (Fig. 1c; Rosendahl et al., 1992, this volume).

These three periods of rifting and breakup of Gondwana illustrate an intimate relationship between the plate tectonic evolution of the oceanic basins and continental tectonics, with a major phase of intra-continental rifting preceding each stage of break-up. Although many basins continue to deepen due to thermal subsidence, active rifting generally ceases around the time that oceanic crustal material begins to be emplaced along the line of crustal separation associated with that stage of development. All three phases of intra-continental rifting described above utilize, wherever possible, weak crust of the Pan-African mobile zones. This paper focuses on the Cretaceous development of the West and Central African rift systems and the associated opening of the South Atlantic Ocean, highlighting the evidence available which can relate these events.

Kinematic studies in the Central Atlantic (Klitgord and Schouten, 1986) have shown long periods of smoothly varying plate motion interrupted by short periods of rapid changes which include events dated at ~130 and ~80 Ma. For the South Atlantic, analyses of fracture zone geometries suggest a similar opening history (Cande et al., 1988; Fairhead, 1988a; Fairhead and Binks, 1991), although the ~80 Ma event is less well pronounced than in the Central Atlantic. The flowline event at ~130 Ma ties in well with the onset of our second phase of African rifting, whilst the ~80 Ma event correlates with a period of deformation seen within many of the Cretaceous basins of West Africa (Benkhelil, 1982; Benkhelil et al., 1988; Guiraud et al., 1987; Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume) which will be discussed more fully later. The spatial correlation between continental and oceanic tectonics is best illustrated in the Equatorial Atlantic where most of the major fracture zones appear to continue right up to the African margin and in some instances link up with major continental structures; e.g. the Charcot fracture zone can be seen to link with the strike-slip zone of the Benue Trough, in the region of the Niger delta (see Fig. 4). The continental extensions of these fracture zones are associated with historic seismicity (Sykes, 1978; Ambraseys and Adams, 1986), indicating that these fracture zones are weak and still able to dissipate stress into the adjacent continental areas.

The present day relationship between plate motion and intra-plate stress regimes, determined from focal mechanisms, in situ stress measurements and borehole breakout studies, has been studied by Zoback et al. (1989) as part of the World Stress Map Project. They observe that the maximum horizontal stress is subparallel to the direction of plate motion suggesting that irrespective of the varied individual stresses affecting an area (e.g. tectonic stresses resulting from plate boundary forces and flexure and localised stresses due to topography, erosion, etc.), the net balance of forces driving a plate also dominates the plate interior. It would therefore be expected that the geometry of rifted basins could provide palaeostress direction indicators for the plate tectonic processes acting at such times. An alternative way of viewing this relationship is to consider that stage poles which describe the progressive opening of an ocean basin, also provide the means of mapping the relative regional stress directions existing at that time.

Rift systems of West and Central Africa

The Cretaceous rift systems of West and Central Africa extend for over 4000 km from Nigeria northwards into Niger and Libya and eastwards through southern Chad into Sudan and Kenya. The Cretaceous rifts are, like the Karoo rifts, located within Pan-African zones of lithospheric weakness (Daly et al., 1989) and exhibit both strike-slip and extensional basin geometries (Fig. 2). The Mesozoic rifts can be divided into two sub-systems: the West African and the Central African, each of which consists of a set of strike-slip fractures which penetrate deep into the African continent before terminating by transforming motions along them into the development of extensional basins orientated perpendicular to the direction of strike-slip motion.

The West African sub-system extends from the Gulf of Guinea northeastward along the sinistral strike-slip "wrench" zone of the Benue Trough which splits in northeastern Nigeria into two branches: the Yola rift striking east into Cameroon and the Gongola rift striking northeast into the Lake Chad region. The Gongola branch has been shown from geophysical studies (Louis, 1970; Fairhead and Green, 1989) to join in the

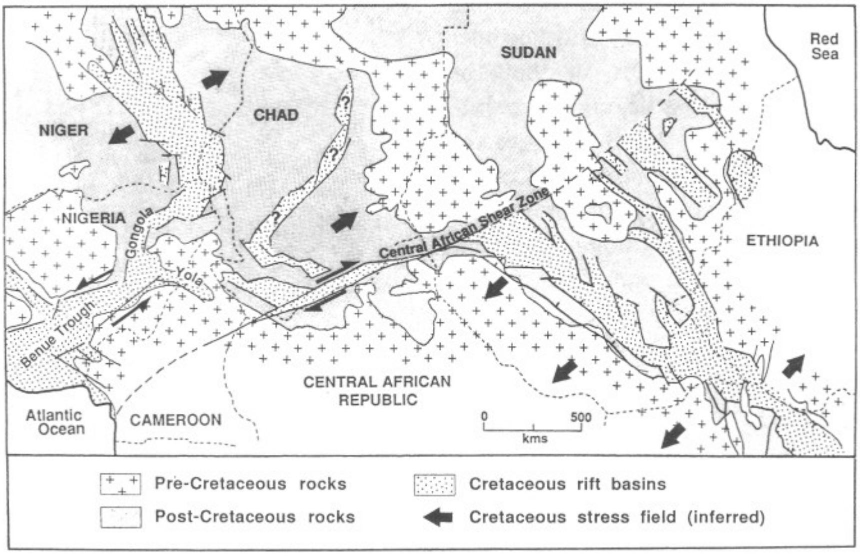

Fig. 2. Geometry of the rift systems of West and Central Africa based on Fairhead (1988a) and Guiraud and Maurin (1992, this volume).

Lake Chad area with the rift basins of eastern Niger which are orientated perpendicular to the Benue Trough (NNW–SSE). These eastern Niger basins have been shown by Guiraud et al. (1987) to be affected by a major N080° to N090°-striking lineament which crosses the basins at latitude 17°N. North of this lineament the eastern Niger basins are orientated in a NNW–SSE direction, dying out in southern Algeria. In the same area, a set of NNE faults could possibly provide a link through the Tibesti area to the Murzuk and Sirte basins of Libya.

The Central African sub-system exhibits a similar geometry, with a major ENE-oriented strike-slip zone showing in this case dextral movement (Ngangom, 1983; Cornacchia and Dars, 1983). Narrow "pull-apart" basins are located along the length of the strike-slip zone which extends from Cameroon through southern Chad and the Central African Republic into west-central Sudan. Movement along this fault system is dissipated into a series of NW–SE orientated rift basins which extend into southern Sudan and Kenya (McHargue et al., 1992, this volume). In Kenya, Cretaceous rifting rejuvenates the Jurassic Anza rift structures which have, in turn, been cross-cut by the Cenozoic East African rift system.

Each of the sub-systems contains many fault-bounded sub-basins, mostly of a "pull apart" nature; thus the stratigraphy exhibits significant variation from one area to another. Many papers have been published, giving detailed studies of the better known basins such as the Benue Trough (e.g. Burke, 1976; Petters, 1981; Benkhelil, 1982; Cratchley et al., 1984; Peterson, 1986; Avbovbo et al., 1986; Maurin et al., 1986; Popoff et al., 1986; Schull, 1988) while summaries of stratigraphy and structural setting of hitherto not yet described basins can be found in this volume (see Genik, 1992, this volume; McHargue et al., 1992, this volume; Guiraud and Maurin, 1992, this volume). The Cretaceous basins frequently contain very thick sedimentary sequences. For example, in the Lake Chad area and parts of Sudan, thicknesses in excess of 10 km have been recorded (Schull, 1988; Genik, 1992, this volume) while elsewhere values between 4 and 7 km are common (Carter et al., 1963; Cratchley et al., 1984; Genik, 1992, this volume). Regional post-rift subsidence (thermal sag) has resulted in most of the rift system being covered with up to 4 km of Tertiary and Recent sediments (Avbovbo et al., 1986). The oldest sediments found within the rifts of West and Central Africa are Neocomian–Barremian in age and are contained in narrow fault-bounded troughs in northern Cameroon and southern Chad (Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume). Compared to the rift system of East Africa, the rift systems of West and Central African are associated with only minor magmatic activity of which the volcanics of the Benue Trough are the best known. Transitional alkaline basalts from the Upper Benue Trough have been dated at 127 ± 6 Ma (Baudin, 1986) and basal volcanics have been found in the Bima Hills with an age of 147 ± 7 Ma (Popoff et al., 1983). By the Mid-Albian (104 Ma) marine sediments were deposited in the Benue Trough (Benkhelil, 1986; Guiraud and Maurin, 1991). This marine incursion is contemporaneous with the generation of oceanic crust in the equatorial parts of the Atlantic (Mascle et al., 1986); this is in agreement with the northward propagation of seafloor spreading in the South Atlantic Ocean.

Rifting and sedimentation continued, in a variety of tectonic settings, within the West and Central African systems throughout the Cretaceous. Prior to the Santonian, the Benue Trough shows sinistral transtensional movement which dissipates into the "pure" extensional basins of eastern Niger, while the Central African sub-system exhibits dextral movement, dissipating into the extensional basins of Sudan and Kenya. The final separation of the African and South American continents occurred at ~ 105 Ma (Mascle et al., 1988) but the thermal development of the intracontinental rifts continued until the Santonian when an important phase of basin inversion took place along the Benue Trough (Benkhelil, 1982; Benkhelil et al., 1988).

This Santonian deformational event at ~ 80 Ma is widely recognised in West and Central Africa as a short-lived period of compression producing folds parallel to the axis of the Benue Trough, Nigeria (Avbovbo et al., 1986; Benkhelil et al., 1988; Guiraud et al., 1987; Genik, 1992, this volume; Guiraud and Maurin, 1992, this volume) and NE–SW transpressional anticlinal structures in Niger and Chad (Genik, 1992, this volume). The compressional event, which is responsible for generation of these structures, is contemporaneous with widespread dextral strike-slip movements along the Central African sub-system, as evident by seismically imaged "flower" structures (Genik, 1992, this volume). Contemporaneous development of the Sudan basins, characterized by continued sedimentation and crustal extension, is consistent with this dextral movement along the Central African shear zone (Schull, 1988; McHargue et al., 1992, this volume). After the ~80 Ma event, major tectonic movements within the Central Africa sub-systems appear to have ceased (Fairhead, 1988b) although the basins continued to sag and deepen in response to post-rift thermal relaxation of the lithosphere, resulting in the accumulation of thick Tertiary to Recent sediments covering most of the Cretaceous rifts.

Gravity studies (Browne and Fairhead, 1983; Fairhead, 1988a; Fairhead and Green, 1989) have shown that the rift systems of West and Central Africa are associated with broad (regional) positive Bouguer anomalies located symmetrically over each basin. These anomalies are typically up to 450 km wide and have amplitudes of up to 80 mGal (Fig. 3a; Fairhead and Okereke, 1988). Refraction and reflection seismic studies across the Yola rift indicate that at least 11 km of crustal thinning has occurred (Stuart et al., 1985). Three-dimensional gravity modelling of the Benue Trough indicates that a crustal zone, 150 km in width, has been thinned by up to 18 km (Fairhead and Okereke, 1988). Superimposed on the regional positive gravity anomalies are smaller negative Bouguer anomalies, referred to as residual anomalies (Fairhead and Green, 1989). These

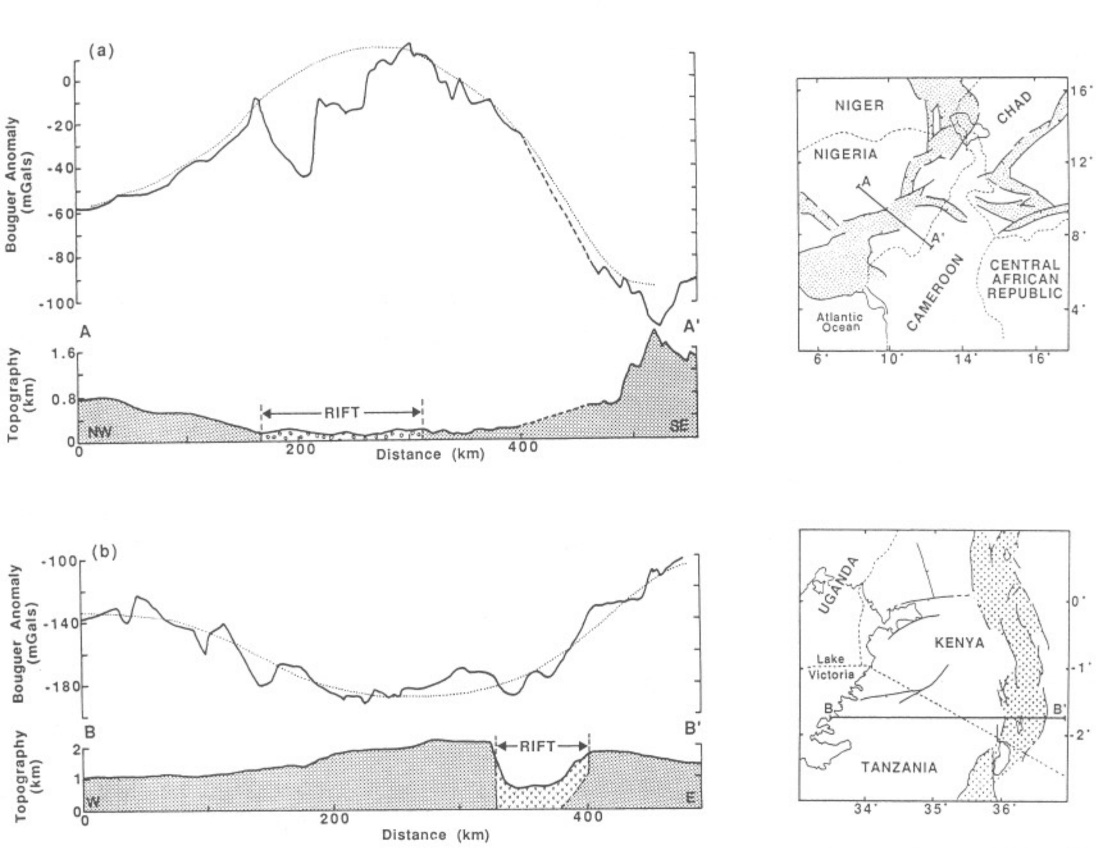

Fig. 3. Bouguer gravity anomaly and topography profiles across (a) the middle Benue Trough (after Fairhead, 1986) and (b) the eastern rift of the East African Rift System, Lake Magadi (after Fairhead, 1976). On the Bouguer gravity profiles the solid line represents observed values and the dotted line is the regional field.

smaller anomalies, which vary in their lateral extent and amplitude, reflect the spatial variability of the rift basin fill. Exploration well data provided by Exxon (Fairhead and Green, 1989) indicate that the rift basins of West and Central Africa have been subjected to rapid periods of subsidence and sedimentation with only minor magmatic activity. This contrasts sharply with the East African Rift System which is associated with crustal doming, uplift of the rift margins and major magmatic activity (Fairhead, 1986). The gravity signatures over the two rift systems are therefore not surprisingly very different with a broad negative gravity anomaly over the East African rifts, contrasting to the broad positive gravity anomaly observed over the palaeo-rifts of West and Central Africa (Fig. 3).

From both geological and geophysical observations it is suggested that the rifted basins of West and Central Africa are among the best examples of the McKenzie (1978) passive extensional basin model. The Early Cretaceous onset of basin formation in this area was associated with rifting along the margins of the future South Atlantic. This intra-continental rifting phase, which in the Benue Trough lasted for some 30 Ma, is evident by faulting and sedimentation (initially lacustrine, and later marine) which was accompanied by only minor volcanism (Wilson and Guiraud, 1992, this volume). Following the Santonian compressional event, which terminated rifting in most basins, the region continued to subside in response to post-rift thermal relaxation of the lithosphere ("sag" phase of McKenzie's 1978 model). The lack of shoulder uplift in West and Central African rifts, together with the geometry of the thermal sag basins, indicates that lithospheric extension was depth-dependent (non-linear; Fairhead, 1986). This is to say that the zone of extension increases in size (width) with depth or, in other words, that lower crustal thinning occurred over a broader zone than upper crustal extension by faulting, and that thinning of the lower part of the lithosphere occurred over an even broader zone. The East African rifts have not been subjected to as great a degree of crustal extension as the West African rifts. Crustal extension across the Kenya rift is of the order of 15 ± 10 km, increasing northwards towards Ethiopia and decreasing towards the south

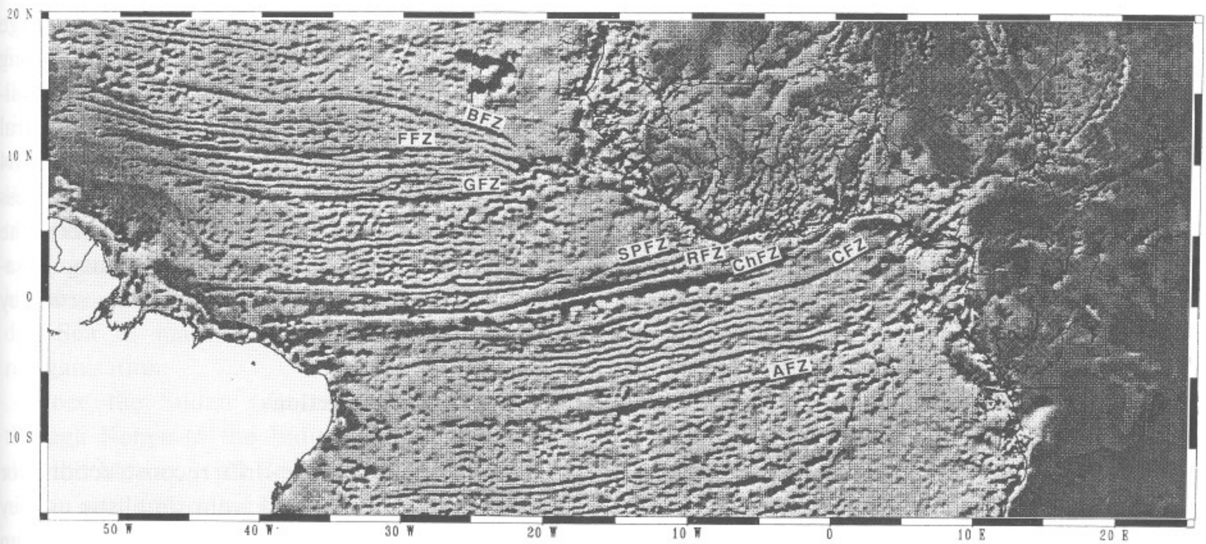

Fig. 4. Shaded relief image (lit from SE) of Haxby's (1989) $5' \times 5'$ gridded free-air gravity map derived from *Geosat/Seasat* data (oceans) combined with the Bouguer gravity field over Africa compiled by the African Gravity Project (Fairhead and Watts, 1988) illustrating the relationship between the fracture zones of the Equatorial Atlantic and the rift structures of West Africa. *BFZ* = Bahamas fracture zone; *GFZ* = Guinea fracture zone; *FFZ* = Four North fracture zone; *SPFZ* = St. Paul's fracture zone; *RFZ* = Romanche fracture zone; *CFZ* = Chain fracture zone; *ChFZ* = Charcot fracture zone; *AFZ* = Ascension Island fracture zone.

(Fairhead, 1986); this compares to estimates of 40 to 90 km in the West African rift (Browne and Fairhead, 1983; Fairhead and Okereke, 1988). In combination with the highly anomalous (hot) state of the upper mantle beneath East Africa, this has resulted in a totally different response of the crust (Fairhead, 1986).

Opening of the Atlantic Ocean

The development of the Atlantic Ocean began in the Jurassic with the opening of the Central Atlantic at ~ 180 Ma (Klitgord and Schouten, 1986); this was followed by the opening of the South Atlantic in the Early Cretaceous. The Equatorial Atlantic remained closed until the Aptian (~ 119 Ma). This entire history of relative plate movements is preserved in the seafloor spreading pattern as reflected by fracture zone traces and magnetic anomalies. Since fracture zones delineate spreading centre offsets (transforms) through time, they provide an approximate "flowline" trace. Thus, by combining fracture zone traces with the age of the oceanic crust, as determined from the geochronology of the seafloor magnetic anomaly pattern, an accurate picture of plate motions can be obtained. The gravity map, given in Fig. 4, is derived from combining a $5' \times 5'$ gridded *Seasat/Geosat* data set (after Haxby, 1988) with the African Gravity Project Bouguer (onshore)/free air (offshore) data set (Fairhead and Watts, 1988); it shows the Equatorial Atlantic to be an anomalous area in which the fracture zone gravity signatures are unusually strong, even on older oceanic crust, and in many instances can be traced across the entire Atlantic from the west coast of Africa to South America and the Caribbean. In the equatorial region, the mid-ocean ridge crest is dramatically offset by a series of transform faults, including a 100 km offset at the Romanche fracture zone. The Equatorial Atlantic has been defined as the area bounded by the Bahamas fracture zone to the north and the Ascension fracture zone to the south and is considered to be distinct from the Central and South Atlantic (Fairhead and Binks, 1991). Its northern boundary, to the west of the Guinea plateau, is associated with strong flowline divergence interpreted to be the result of differential opening between the Central and South Atlantic oceans (Jones, 1987), while its southern boundary is more diffuse. It is apparent from the gravity map of the area that many of the oceanic fracture zones appear to link up with the major fracture systems in Africa. For example, the Charcot fracture zone (ChFZ) is aligned with the northwest side of the Benue Trough (Fig. 4). The northern and southern boundaries of the Equatorial Atlantic are considered to be the principal sites for dissipating stresses into the Caribbean and African continents. Fairhead and Binks (1991) utilised published stage pole data for the Central and South Atlantic to assess the effects of dissipating all the stresses arising from the differential opening of the Central and South Atlantic oceans along the northern and southern boundary of the Equatorial Atlantic. They concluded that between 84 and 0 Ma the geometry of the seafloor is consistent with major stress release along the northern boundary; however, the correlation is not so good for major stress release along the southern boundary, except for the period about 80 Ma when the opening vectors for the Central and South Atlantic are coincident. During the Santonian, the fracture systems of Central Africa form small circles about the stage pole, thus permitting strike-slip movement along the ocean and continental fracture zones to dissipate differential opening between the Central and South Atlantic. Plate motions older than 84 Ma are more difficult to determine due to less well defined flowline traces, coupled with the Cretaceous period of single positive magnetisation, and are the subject of an ongoing study by one of us (RMB).

Plate tectonic interactions

Early attempts at pre-drift reconstructions for Africa and South America were simplistic as they consided the plates to be rigid, thus suffering no internal deformation during their breakup (Bullard et al., 1965; Rabinowitz and LaBrecque; 1979; Sibuet and Mascle, 1978). Consequently it was not possible to obtain a satisfactory fit for the whole length of the South American–African margins. It is now accepted that continents are subjected to intra-plate deformation during their breakup and collision. This must be taken into account when carrying out palinspastic reconstructions. Geological and geophysical studies have shown that the fault geometry, associated with the rift systems of West and Central Africa, consists of two sets of fractures which emanate from the Gulf of Guinea and penetrate deep into the African continent: one set strikes northwards through Niger towards Libya and the other eastwards through southern Chad into Sudan and Kenya. This geometry avoids the necessity to invoke compressional tectonics in northeast Africa as proposed by Pindell and Dewey (1982). By considering the continent to consist of a number of rigid "blocks" separated by deformable zones, stage poles must not only satisfy the oceanic flowline geometries but must also be compatible with the observed type of deformation along these intra-continental "mobile zones". From comparisons between seafloor opening and rifting in Africa there exists a simple temporal and spatial link between the various stages of opening of the Atlantic and the development of the rift systems within West and Central Africa. The most striking correlations are the changes in flowline direction at 130 and 80 Ma (Klitgord and Schouten, 1986) which correlate respectively with the onset and termination of major Cretaceous rifting in West and Central Africa. The 80 Ma event produced inversion along the axis of the Benue Trough, dextral strike-slip along the Central Africa sub-system and a period of further extension in the Sudan rifts. Elsewhere, this event has been recognised by Haxby (1989) in the Weddell Sea as marking a major period of plate reorganisation.

Since the Sudan rifts extend southeastward through Kenya to the Indian Ocean, it is likely that the Mesozoic rift development of Africa was also in part controlled by plate tectonic processes controlling the opening of the Indian Ocean. The plate tectonic setting of Mesozoic rifting in Africa is further complicated by the Late Cretaceous northward movement of African and it's collision with Europe (Ziegler, 1992) which must have modified the stress field and thus influenced the rift geometries within Africa. The significance of these interactions have yet to be determined.

Acknowledgements

RMB gratefully acknowledges financial support from a NERC research studentship and the Basin Analysis of Africa Project (Leeds University).

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