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The role that plate tectonics, inferred stress changes and stratigraphic unconformities have on the evolution of the West and Central African Rift System and the Atlantic continental margins

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ABSTRACT

The Muglad rift basin of Sudan, is a good example of polyphase rifting, with at least three major phases of basin development. Each phase has resulted in the generation of source rock, reservoir and seal geology with structural traps often closely linked to basement highs. In this paper we investigate on a regional scale the tectonic processes that have contributed to rift basin development.

On a regional scale, the evolution of the Africa-wide Mesozoic rift system is intimately linked to relative movements of African sub-plates and to global plate tectonic processes and plate interactions. Changes in plate interactions are observed in the oceanic crust as azimuth changes of fracture zone geometries and by inference have caused significant modifications to both the orientation and magnitude of the motions of the African sub-plates. Such plate motion processes have controlled the polyphase development of the West and Central African Rift System. On the basinal scale, changes of sub-plate motions have resulted in changes in the stress field which have had a clear impact on the deformation and fault geometries of rift basins and on the resulting stratigraphy. The construction of the first unified stratigraphic chart for the West and Central African Rift System shows a close correlation in the timing of the major unconformities with the timing of changes in relative plate motion as observed in the changes of the azimuthal geometry of the oceanic fracture zones in the Central Atlantic. Since similarly timed unconformities exist along the continental margins of Africa and South America, we propose that the causative mechanism is change in relative plate motion which leads to an increase or decrease in the tension on the plate and thus controls the strength or effective elastic thickness, T_e, of the crust/plate beneath the margins. This results in a focused change in isostatic response of the margin during short-period changes in relative plate motion; i.e. more tension will mean that loads are not compensated locally resulting in local uplift of the margin.

1. Introduction

The Mesozoic plate tectonic link between the opening of the Atlantic Ocean and the development of the West and Central African Rift System (WCARS) via the Benue Trough and shear zones cutting Cameroon is not a new idea (Binks and Fairhead, 1992), nor is the polyphase development of the WCARS (Guiraud et al., 1992). What is new is the improved resolution and definition of the data sets used to establish the linkage. We now have for the Atlantic Ocean, the best available satellite derived free air gravity data set (Fairhead et al., 2009; Fig. 1) which has improved the spatial resolution down to ~6.5 km (half wavelength). The free air gravity data principally image the response of the bathymetry and near sub-seafloor structures, resulting from seafloor spreading processes at the mid-Atlantic ridge. Thus the enhanced resolution gravity data are able to improve our knowledge of the opening history of the Atlantic Ocean and to refine the associated plate reconstruction model. The message that comes repeatedly from the gravity field of the oceans is that the opening process at the mid-oceanic ridge clearly responds to changes in relative plate motions resulting from local and far field changes in plate interactions e.g. Africa–Europe and India–Asia plate collisions. This is recorded by both subtle and distinctive changes in the direction of the fracture zones (or flowlines) with an estimated response time of a few millions of years based on the smooth curvature of the fracture zones and the momentum changes that are needed to change the direction of motion of plates. The African plate has traditionally been considered as a rigid plate in plate reconstruction models. However, to explain the development and evolution of the Mezosoic rift systems in Africa there is a need to consider Africa as subject to intra-plate deformation by representing it as a set of three sub-plates — NW Africa, Nubia (NE Africa) and S Africa; the Somali Plate and the East African Rift System which divides it from

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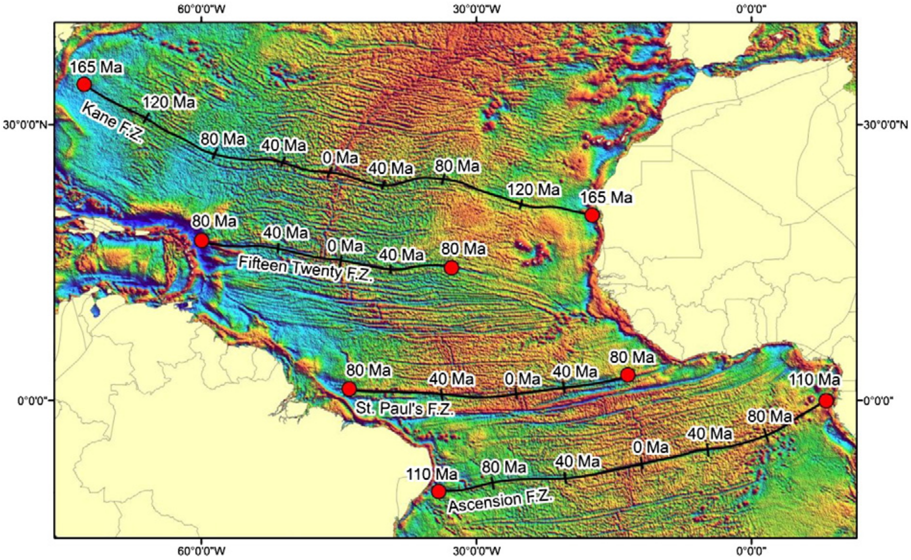

Fig. 1. Free air gravity map of the Central, Equatorial and northern part of the Southern Atlantic Ocean (Fairhead et al., 2009). The mid-Atlantic ridge (axis at 0 Ma) is clearly seen to be offset progressively by the fracture zones. Four named major fracture zones are identified and their curvature is seen to change as a function of distance away from the mid-oceanic ridge. The age of the oceanic crust is given in Ma along each of the four fracture zones.

the rest of Africa is more recent and inactive over most of the time period being considered here. Within our plate reconstruction model (Masterton et al., 2012), these sub-plates are allowed to move relative to each other. For this study, we consider the NW Africa and S Africa sub-plates as the most significant blocks — separated by the WCARS. We show that changes in plate motions, seen within the oceanic domain are replicated within the rift basins of the WCARS (sub-plate boundary between NW Africa and S Africa) in the form of changes in structural style (extension, shear and compression) such that extension in one basin can be associated with shear with little extension in another basin that is orientated perpendicular to it. Many of the basins show this change in tectonic style whereas the Muglad basin in Sudan shows only three major periods of extension. Using gravity studies we show that the fracture patterns of the basement within the rift has a distinct 'rhomb' geometry that is considered to have developed from repeated periods of trans-tension. We further show that the times of changes in plate motion correlate well with the timing of the stratigraphic unconformities found within the WCARS basins to indicate that there is both a cause and effect. We also show that the timing of plate motion changes correlate with the unconformities associated with the continental margin of the Atlantic. This suggests that changes in plate motion are the cause of these phenomena but their effect at sub-plate boundaries (rifts) is more tectonic than the response at continental margins, which are located within the heart of the sub-plate where vertical sedimentary loading has weakened the crust and made it more susceptible to converting horizontal plate stress changes into changes of flexural response. For the latter, it is proposed that during periods of change in plate motion the crustal/plate stress will change which will change the elastic strength of the crust beneath continental margins resulting in a change in the isostatic response of the margin.

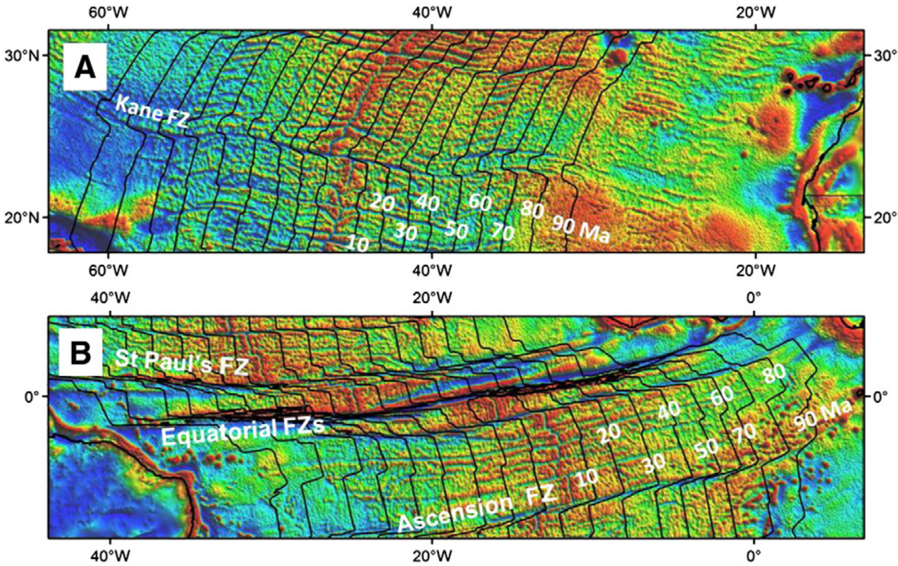

Fig. 2. Free air gravity map for A: the Central Atlantic and B: northern South Atlantic based on the satellite solution after Fairhead et al. (2009). The changes in curvature of the well-defined fracture zones indicate subtle changes in relative plate motions. Superimposed are the synthetic isochrons of Müller et al. (2008) at 10 Ma intervals with 0 Ma not shown. The tracking of the fracture zones by the offsets in the isochrons shows that the plate model closely follows the changes in fracture zone curvature.

2. Relative plate motions for the Atlantic Ocean

The free air gravity image of the Atlantic Ocean (Figs. 1 and 2) has been derived from satellite altimetry data (Fairhead et al., 2009) and principally images' lateral variations in upper crustal density and in particular the bathymetry; this provides important insights into the plate tectonic fabric of the ocean floor.

The fracture zones, emanating from the mid-Atlantic ridge are shown in Figs. 1 and 2 for the Central, Equatorial and northern part of the South Atlantic. For clarity the isochrons are shown at 10 Ma intervals, excluding the 0 Ma isochron in Fig. 2. This illustrates the change in curvature of the fracture zones about the mid ocean ridge axis (0 Ma) for the Central Atlantic (Fig. 2A) and the significant decrease in comparable curvature in the northern South Atlantic (Fig. 2B) for the same time periods.

Figs. 1 and 2 clearly image the fracture zones originating at the mid-Atlantic ridge and allow the flowline directions of relative plate motion to be identified. The fracture zones can be classified into two simple types, principal or major fracture zones that generally have a strong gravity signature and extend across the whole of the Atlantic Ocean, and secondary fracture zones that exist between these principal fracture zones. These secondary fracture zones tend to have smaller offsets at the mid-Atlantic ridge, smaller gravity responses and can be more discontinuous (broken up) along their length which relates to change in relative opening directions reducing the ridge offset to zero (Masterton et al., 2012).

Four of these principal or major fracture zones (FZ) are identified in Fig. 1 and characterise the three regions; the Central, Equatorial and South Atlantic as follows:

> *Kane and Fifteen Twenty FZs* are representative of the Central Atlantic FZs which represent relative plate motion of N America and NW Africa (sub-plate). It is important to remember that to the east of the mid-Atlantic ridge the oceanic crust forms part of the NW African sub-plate and all relative motions seen in the oceanic part reflect the motion of the whole sub-plate.
>
> *St Paul's FZ* represents the relative motion of S. America and the NW Africa sub-plate and is located to the north of the narrow complex set of Equatorial FZs.
>
> *Ascension Island FZ*, on the other hand, lies south of the Equatorial FZs and represents relative motion of S America and the S Africa sub-plate.

Thus the relative motions within the Atlantic are controlled by the interactions of at least four different plate pairs (including sub-plates) as well as the major collisional and anticlockwise interaction of the NW Africa sub-plate with the European plate.

To define the changes in these relative plate movements more clearly, Fig. 3 plots the azimuth of plate motion for the four major fracture zones shown in Fig. 1 against age of formation (black solid lines in Fig. 3). For each of these fracture zones, the analysis starts with a single selected point that is located on the fracture zone at the western flank of the Atlantic. The palaeo-position of this point is reconstructed relative to a fixed African reference frame from present day to the point of formation (at the mid-Atlantic Ridge), at 2 My intervals. The reconstruction uses the Getech global plate model V.1 (Masterton et al., 2012). The azimuth is calculated as the direction of motion of the point between each of these reconstruction age intervals, from past to present. This plot is hence a derivative of the spatial location of the fracture zone and thus identifies short period (high curvature) changes in relative plate motions more clearly. A period of uniform opening about a static Euler pole will appear as a linear segment in Fig. 3. Steep slopes relate to rapid rotation about a local Euler pole; shallow slopes relate to distant Euler poles and slow relative rotation of the plates.

Examining Fig. 3, there are a number of sub-linear segments seen in the azimuth-age plots. Some of these linear segments have a nearly constant azimuth, while others are linearly changing azimuth over short time periods. This is clearly seen in the Kane FZ (Fig. 3). The red dashed lines in Fig. 3 are an attempt to sub-divide the azimuth-age plot into a series of linear segments which are interpreted here as intervals of consistent smooth plate opening about a distant individual or slow moving set of Euler poles. These linear segments are linked together by short and rapidly changing azimuth segments (corresponding to highly curved fracture zones) and presumably represented by more local Euler poles or rapidly moving set of Euler poles. Such short and rapid changes in azimuth directions are considered to be the local response to near field plate interactions (NW Africa–Europe plate collision associated with the anticlockwise rotation of Africa relative to Europe) and

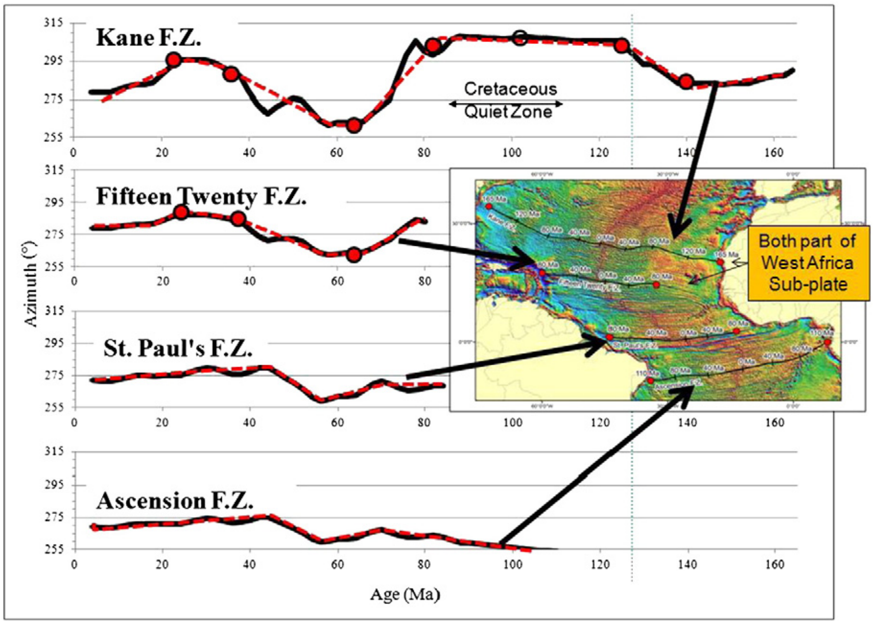

Fig. 3. Fracture zone azimuth against seafloor age: the solid black lines represent the azimuths along each of the four fracture zones (shown in Fig. 1); dashed red lines attempt to trace the linear segments of the azimuth-age plots representing smooth plate opening about an individual or slowly moving Euler pole. The red dots are times of the unconformities based in Fig. 6. The correlation between the dates of the unconformities and the timing of changes of the linear azimuth segments is discussed in Section 4.2.

less so to far-field plate interactions (India and Asia plate collision). Collisional interaction between NW Africa (sub-plate) and Europe (plate) will have maximum relative plate motion response in NW Africa and progressively a more damped response in more distant plates linked to NW Africa, due to differences in sub-plate motions being taken up by the crustal deformation (rifting extension/shear/compression) zones of the WCARS that divides the NW Africa and S Africa sub-plates.

Changes in the direction of the linear segments (red dashed lines in Fig. 3) indicate changes in the relative plate motions which generate a modified stress field between the Africa sub-plates. The important conclusion that can be drawn from both Fig. 3 and the unified stratigraphic chart for WCARS (Fig. 6) is that the time of changes in the linear segments of the azimuth — age plot is very closely linked to the timing of the basin unconformities. The red dots superimposed on the Kane and Fifteen Twenty FZs (Fig. 3) indicate the dates of the basinal unconformities. Five of the seven unconformities identified are very closely linked to unambiguous azimuth changes. The 38 Ma unconformity is more subjective due in part to the short period changes in azimuth between 36 and 65 Ma. The absence of change in azimuth for the 100 Ma unconformity could be because the change in plate motion at that time only changed the rate of opening rather than the azimuth.

The magnitude of these azimuth changes shown in Fig. 3 significantly decrease from the Central Atlantic to the northern South Atlantic. This is interpreted to be due to the differential plate motion, on either side of the Equatorial FZs, being taken up by deformation within the WCARS (Fairhead and Binks, 1991). Changes in relative plate motion have resulted in the rotation of the African stress field and consequent changes in deformation regime, such as extension within the rift being changed to periods of extension in a different opening direction, or to strike slip movement parallel to the axis of the rifts, or to compression (e.g. Santonian; see Section 3.1) and/or to the stress field reducing below a threshold necessary to generate deformation. The most likely reason for such changes is the reordering of plate motions from near field plate interactions such as NW Africa colliding with Europe and its subsequent anticlockwise rotation closing the Tethyan Ocean (Guiraud and Bosworth, 1997) and less so from far field plate interactions (India collision with Asia).

3. West & Central African Rift System (WCARS)

3.1. Geology and tectonics

The plate tectonic link between the oceanic fracture zones and the continental West and Central African Rift System (WCARS) occurs beneath the Niger Delta. Here, at the southwest end of the Benue Trough, the gravity and magnetic data (Fig. 4) image the Chain and Charcot FZs, southern most of the Equatorial FZs, passing beneath the Niger Delta and entering the Benue Trough as tectonic structures of similar trend.

The overall tectonic model for the WCARS is a complex set of interconnecting pull-apart, wrench and extensional basins extending from Nigeria and Cameroon, on the Atlantic coast, eastwards via Chad and Central African Republic into Sudan through Kenya to the Indian Ocean and north from Lake Chad as the Tenere Rift and extending into southernmost Algeria (Figs. 5 and 9). The Euler pole shown in Fig. 5 for the Albian is consistent with early poles of opening of the South Atlantic while the Barremian pole is closely related to the internal deformation of Africa (i.e. sub-plate interactions) rather than any South Atlantic opening pole.

Detailed studies of the WCARS (Genik, 1993; Guiraud and Maurin, 1992; McHargue et al., 1992) have provided a comprehensive understanding of rift evolution which is summarised, with the help of Figs. 8 and 9, as follows:

Syn-Rift Stage 1 (142–120 Ma)

Rifting was initiated in the Early Cretaceous orthogonal to the extension direction E–W to N70E with half graben basins developing between northern Nigeria and western Sudan. Late Hauterivian to earliest Aptian has been identified as the start of rifting, but older possibly Neocomian and Late Berriasian sediments could be present.

Syn-Rift Stage 2 (119–101 Ma)

Rifting continued to develop in the Benue Trough, Sudan and Kenya as well as in the Termit/south Tenere basins, all providing evidence of NE–SW extension. The Benue Trough had clear sinistral strike slip movement. The termination of this stage is indicated by a regional unconformity identified by Genik (1993) that can be seen along the entire WCARS and represents a cessation of rifting. A similar unconformity is recognised within the Muglad Basin, Sudan by McHargue et al. (1992) and within the Benue Trough by Guiraud (1993) as well as along the margins of the Equatorial Atlantic by Mascle et al. (1988). Their study led Mascle et al. (1988) to name this major unconformity 'the post break-up unconformity'. Estimates of timing of the unconformity vary from close to the Albian–Cenomanian boundary (Mascle et al., 1995), to between the mid and late Albian (Genik, 1993), to within the Late Albian (Saint-Marc and N'Da, 1997) and to about 101/102 Ma according to the Gradstein and Ogg (1996) time scale.

Late Rift to sag basin stage (100–85 Ma)

This period is characterised by a decrease in the rate of subsidence and can be considered as thermal relaxation (Genik, 1993) with a

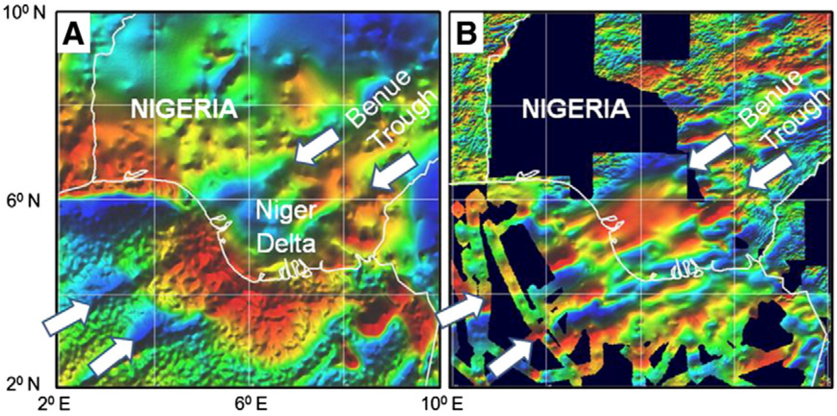

Fig. 4. A: The free air (offshore) and Bouguer (onshore) gravity field of the Niger Delta region showing that the oceanic fracture zones (Chain and Charcot FZs) can be identified beneath the Niger Delta and enter into and control the orientation of the Benue Trough structures. B: The smooth Total Magnetic Intensity (TMI) field response over the Niger delta is consistent with deep oceanic crust existing beneath a major portion of the Niger Delta with the same oceanic fracture zones identified in A seen in the gravity data. Further onshore the magnetic field responds to the shorter wavelength/shallow continental basement rocks.

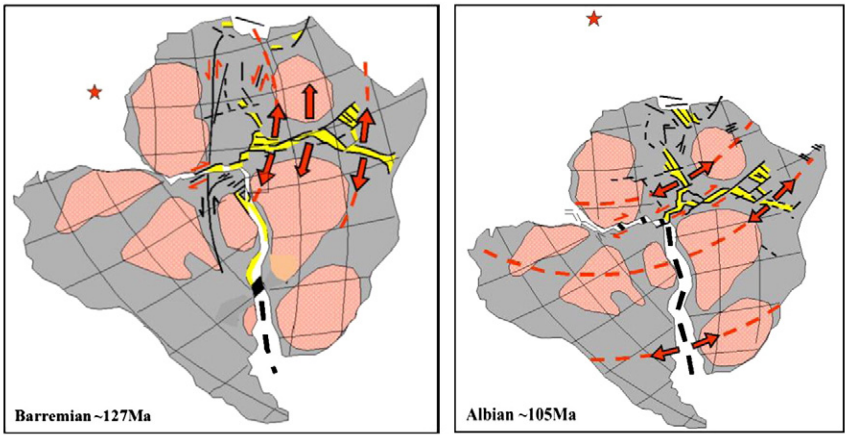

Fig. 5. The changing stress field of Africa has resulted in significant changes to the WCARS development as illustrated by the image in the left: the early extensional phase (pre-opening of the Equatorial Atlantic) of the WCARS during the Early Cretaceous (Barremian ~130 Ma) with opening in a more north–south direction requiring an African sub-plate Euler pole located off the coast of West Africa (red star). Right: by the Albian (~105 Ma) the plate motions have changed within Africa as a result of the advanced stage of plate separation from South America.

marine transgression commencing in the Late Cenomanian and covering the western WCARS. However in the Muglad Basin and along the Benue Trough rifting continued to develop. The development of a large seaway over the African continent from the north is explained as a combination of global sea-level rise of up to 300 m in the Late Cenomanian to Early Turonian and the extreme low relief of the topography along the elongate Cretaceous rift basins, due to both (1) the rift basin development closely following the McKenzie (1978) crustal extensional model (see Section 3.2), and (2) thermal subsidence within the basins.

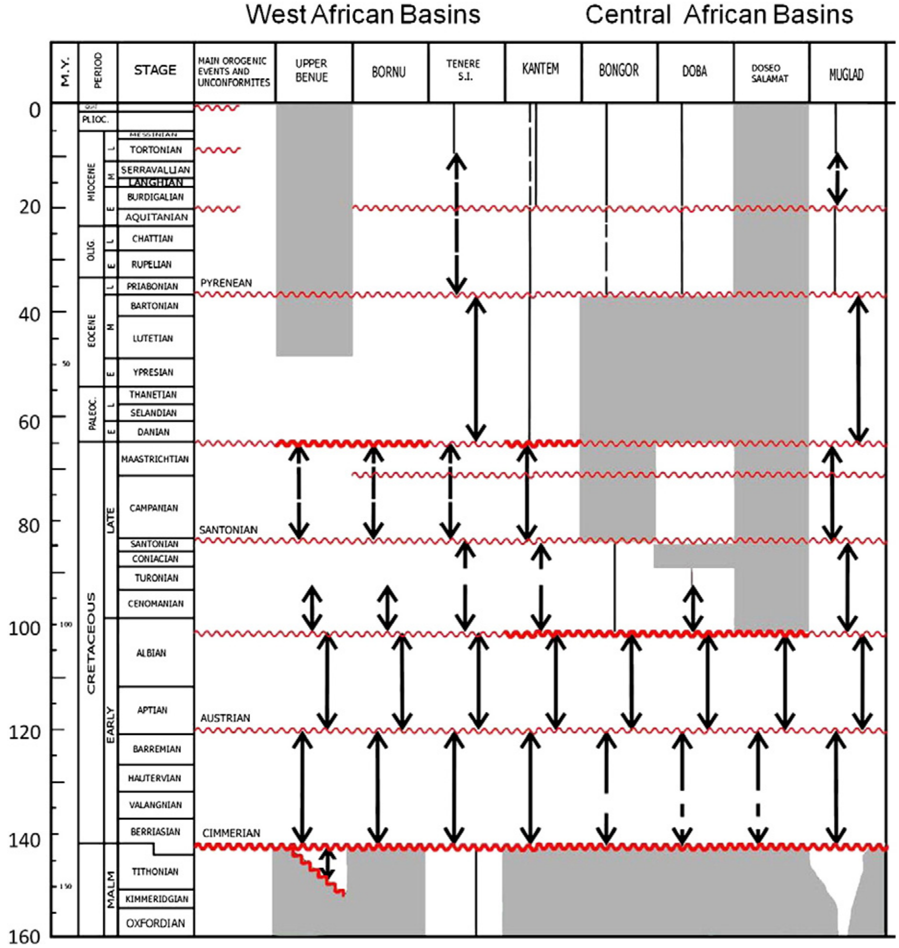

Fig. 6. Tectonic correlation chart of the late Jurassic to Recent for WCARS and neighbouring basins constructed by R Guiraud for GETECH (2002). Time scale in Ma after Gradstein and Ogg (1996). Unconformities are shown as red horizontal wavy lines with thicker red lines indicating major folding events. Double headed arrows show rifting events. Grey areas indicate erosion or very reduced sedimentation.

Late Santonian Basin Inversion (84 Ma)

A detailed overview of this inversion event is given by Guiraud and Bosworth (1997). This compressive event has been recognised in the Lower Benue Trough, in southern Chad, and extends along the length of the Central African Fault Zone. The shortening direction was NNW–SSE. In the Termit/south Tenere Trough and Sudan basins only slight transpressional deformation is identified.

Late Senonian Rifting (83–66 Ma)

Regression of the marine environment occurred during the Campanian and Maastrichtian although a sea way still existed west of the Hoggar. Sedimentation within the WCARS was dominated by continental terrigenous formations.

End Cretaceous Tectonics (65 Ma)

This event was similar to the shortening event in the Santonian and is associated with strong folding and strike-slip faulting. The shortening direction for the Benue Trough was NNW–SSE to N–S (Avbovbo et al., 1986; Benkhelil, 1988 — based on seismic data). Elsewhere in the Central African Rift System (CARS), shortening directions are difficult to identify due in part to erosion. In the Tenere basin NW–SE orientated normal faults were rejuvenated and minor faulting and folding occurred in the Sudan rift basins.

Palaeocene to Middle Eocene quiescence or rifting (65–38 Ma)

Rifting continued along the NW–SE trending Tenere and Central Sudan Troughs. Rifting in the Gongola basin, Benue Trough indicates an ESE–WNW to E–W extension direction.

Early Late Eocene transpression (~37 Ma)

A clear Late Eocene major compressional event is identified along the Tethyan African–Arabian margin (Guiraud and Bellion, 1995) and corresponds to the folding event for the NW African Maghrebian Belt and transpressional deformation all around the Hoggar Massif. The shortening event direction is ~N160°E.

Late Eocene to Recent Basin development (36–0 Ma)

There was general uplift resulting in the accumulation of only continental derived sediments called 'Continental terminal'. A brief compressional event interrupted basin development in earliest Burdigalian (~21 Ma) with shortening direction ~N40° to N70° E. Currently the region is considered to be in moderate ENE–WSW trending extension.

In summary, and with reference to Figs. 5 and 9, the geology and structure of the West and Central African Rift System (WCARS) basins are a complex response of the African sub-plate motion changes through time. Africa, as a whole, has been rotating anti-clockwise with respect to the Europe plate from at least 120 Ma (Guiraud and Bosworth, 1997) resulting in the closure of the Tethyan Ocean. During this time the Mesozoic phase of Gondwana break-up and Africa fragmentation has taken place. The African plate motion has been strongly influenced by near field perturbations (convergence of Africa–Europe) and less so from far field perturbations in the global plate circuit (convergence of India–Asia). The cumulative effect of these plate kinematic changes has resulted in the development of three main sub-plates in Africa: (1) NW Africa (west of the Benue Trough and the Termit–Tenere rift basins), (2) Nubia (NE Africa) and (3) S Africa (Africa south of the WCARS). Since the orientation of the WCARS basins range from NNW–SSE to WSW–ENE, while one basin may be experiencing a period of extension, another basin with different orientation could be experiencing wrench or strike-slip motion subject to the relative sub-plate movements/interactions. For example, a compressional event observed in one rift basin, perpendicular to the shortening direction e.g. Santonian event in the Benue Trough (shortening direction NNW–SSE), will be seen as either a strike-slip (Tenere rift basin) or extensional phase (Sudan rift basins) depending on the orientation between the rift axes and the principal stress field direction resulting from the differential movement of the sub-plates (NW Africa–S Africa). In such a plate model the stress trajectories can be considered to parallel small circles centred on the Euler pole that describes the relative motion of the sub-plates (Fig. 5). Stratigraphy studies of these basins show that significant and widespread synchronous unconformities occurred throughout the WCARS but for individual basins their dating is far from precise due to the lack of materials suitable for accurate age constraints (Guiraud et al., 1992). These unconformities represent hiatuses in basin development, correlate between basins within the WCARS and provide a means of timing of plate motion and stress changes within Africa. To bring order into the regional stratigraphy record GETECH (2002) made an attempt to generate a unified stratigraphic chart (Fig. 6) for the WCARS.

This unification of stratigraphic charts (Fig. 6) has allowed a more reliable dating of the numerous unconformities which have been superimposed in Fig. 3 as red dots on the Kane and Fifteen Twenty FZs azimuth-age plots. Of the seven unconformities identified in Fig. 6 five of them precisely fit the times of linear changes in the azimuth-age plot, while the 38 Ma unconformity is more subjective due to short period changes in azimuth between 38 and 60 Ma and the 100 Ma unconformity (open black circle) has no apparent azimuth change.

The temporal correlation of the unconformities (Fig. 6) and azimuth changes of the FZs is remarkable. The correlation is best seen for the FZs of the Central Atlantic of which the eastern section of the Central Atlantic (east of the mid-oceanic ridge) is the growing part of the NW Africa sub-plate. These azimuth changes might be expected to be large if they originate from collision between the major plates of NW Africa and Europe. NW Africa has at least three plate and sub-plate interactions with N America (Central Atlantic), S America (Equatorial Atlantic) and S Africa (WCARS). The Central and Equatorial Atlantic plate margins would experience the largest effect of the NW Africa–Europe plate interaction, while the S Atlantic plate margin (relative motion between S Africa and S America) would see less of the effect due to the WCARS providing an effective structural barrier that dissipates and absorbs the NW Africa motions by internal deformation. This reduced plate motion is seen in the difference in the azimuth plots of the St Paul's FZ and the Ascension FZ (Fig. 3), which have similar shapes, but the Ascension FZ has lower amplitude changes. This difference is, of course, more subtle than the difference between the Central Atlantic FZs and the Equatorial Atlantic FZs which is related to plate interactions in the Caribbean; note especially the azimuth changes at 65 Ma and 84 Ma which are significant in the Central Atlantic, but virtually non-existent to the south.

Since the WCARS cuts Africa from the Atlantic to the Indian Oceans, the rift system appears to act as an effective west–east deformation barrier to stresses originating from the collision of the NW Africa–Europe plates. As with the adage "A chain is as strong as its weakest link", the WCARS is Africa's 'weakest link'. Changes in plate motion originating from the NW Africa–Europe plate collision have their greatest effect on the NW African sub-plate and have been, to a considerable extent, accommodated/absorbed within the WCARS by crustal deformation as compression, strike-slip shear and/or extension. Such plate processes are reflected in the differences in the shapes of the ocean floor FZs from the large azimuthal changes seen for the Central Atlantic (Fig. 3) to the weaker azimuthal changes seen in the South Atlantic Ocean. The southernmost FZs of the Equatorial FZs (Chain and Charcot FZs, Fig. 4) propagate the difference in plate motion between the Equatorial Atlantic and South Atlantic as shear-wrench movement into the African continent via the Benue Trough.

The dating of the magmatic activity (Guiraud et al., 1992) does not provide a simple fit with the changes in plate motion direction. The initial magmatic episode occurred in Late Jurassic–Neocomian times with rhyolites (147 +/− 7 to 127 +/− 6 Ma) in the Upper Benue. This was followed by Albian to Turonian basalts (104 +/− 5.2 to 90 +/− 4.5 Ma) and minor magmatic activity in the late Albian (110–97 Ma) in the Doseo basin (Genik, 1993; Guiraud, 1990; Guiraud and Maurin, 1992).

3.2. Geophysics

Each rift section of the WCARS exhibits the classic features of the McKenzie sedimentary rift basin model (McKenzie, 1978). In this model of rift basin under extension, the upper crust will undergo brittle failure resulting in rift basin development (tectonic phase) while the lower crust/upper mantle will deform by ductile stretching resulting in an overall isostatic subsidence of the ground surface and elevation of the Moho beneath the rift basin. Fig. 7 illustrates the crustal thinning under extension. This stretched crust thus provides the structural 'weak link' which can be exploited by changes in plate motion (and thus stress) leading, for example to basin inversion associated with the 84 Ma and 65 Ma unconformities in the Upper Benue.

The surface subsidence of the developing rift basin enhances drainage and sedimentation into the rifts. These low density rift basin sediments generate a negative Bouguer anomaly, which is superimposed on a longer wavelength positive Bouguer anomaly due to crustal thinning and elevated Moho (Fig. 8). Hot lower crust and upper mantle are brought closer to the surface by this tectonic phase of rifting; these cool and contract leading to a sag phase of subsidence. The most recent sag phase is clearly seen on seismic reflection data for NE Nigeria (Avbovbo et al., 1986). The McKenzie model is consistent with the gravity response seen over all segments of the WCARS (Fairhead and Green, 1989), for Sudan (Bermingham et al., 1983; Brown and Fairhead, 1983; Mohamed et al., 2001; Fig. 9) and Kenya (Reeves et al., 1986), not shown in Fig. 9. Evidence for the base lithosphere (plate boundary shown in Fig. 8) is lacking in both the present day topography and in the observed gravity data — thus indicating that the density contrast between the lithosphere and asthenosphere is very small or negligible.

4. The Muglad Basin, Sudan

4.1. Unconformities

Stratigraphic charts (Fig. 10) showing unconformities for the Muglad Basin, based on work by Chevron and GNPOC. These charts illustrate the difficulties of identifying unconformities and relating them to particular stages. What these charts do identify are at least three major extensional rift basin events with each event having both a tectonic subsidence and a sag phase (McHargue et al., 1992). Other stratigraphic charts (not shown) by Exxon (Genik, 1993) and Guiraud et al. (1992) show that whilst the unconformities seen in Sudan are widespread within the WCARS basins, their precise timing remains uncertain. The construction of the unified Tectonic correlation chart (Fig. 6), attempts to correlate the unconformity events within the WCARS basins and brings order to its tectonic evolution.

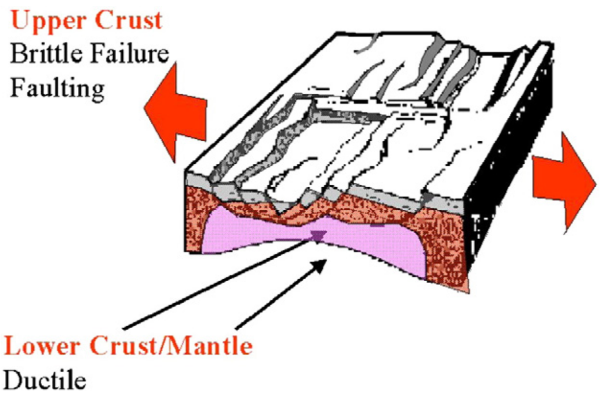

Fig. 7. Behaviour of the crust under extension.

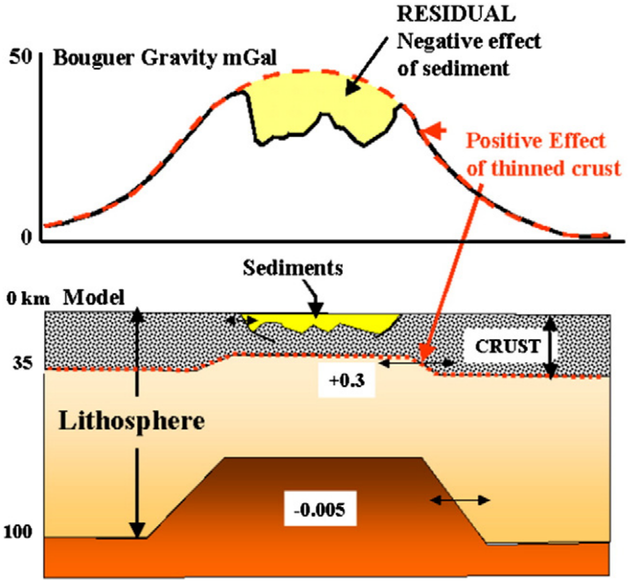

Fig. 8. Idealised gravity responses of the crustal structures, showing the long wavelength positive gravity response of the elevated Moho and the short wavelength negative gravity due to the sediments. For completeness the thinned lithosphere (plate) is included with slightly lower density asthenosphere beneath. The gravity effect of this lower lithosphere boundary to the plate has not been modelled in the gravity response since it is not seen in either the topography or gravity data (Fig. 9). The dominant gravity effects are generated by the crustal structure.

4.2. Structural style of the Muglad Basin

To undertake the construction of a detailed structure and basement map of the Muglad Basin requires a good quality compilation of all the available gravity and aeromagnetic data sets. These are the only data sets that completely cover the basin (Fairhead et al., 2012a,b) and through their inversion we have the ability to map the deep-seated structures and morphology of the rift basement surface.

To map the fault pattern of the basin we have used the total horizontal derivative of the Bouguer anomaly (Fig. 11) such that faults and contacts appear as local maxima (red). Tracking these maxima has enabled us to delineate most of the major structures. Since the study area straddles the magnetic equator, we did not use the magnetic data in any direct way to map these structures due to magnetic anisotropy effects, i.e. N–S trending structures are poorly imaged.

The fault pattern mapped in Fig. 11 shows distinct rhomb geometry, consisting of two distinct oblique fracture directions N to NNW and NW. Such geometry has probably resulted from the polyphase development with each phase having differing amounts of transtension (Wu et al., 2009). The extensional nature of the basin has been clearly demonstrated by the broad scale gravity response (Fig. 9) and by the known stratigraphy. The strike-slip component is more difficult to identify, but can be inferred from the development of the WCARS as a whole.

5. Unconformities on continental margins

The principal topic discussed has been the linkage between the timing of plate movements as seen in the FZ geometry and the stratigraphic unconformities found within the WCARS. In Fig. 3 the linear

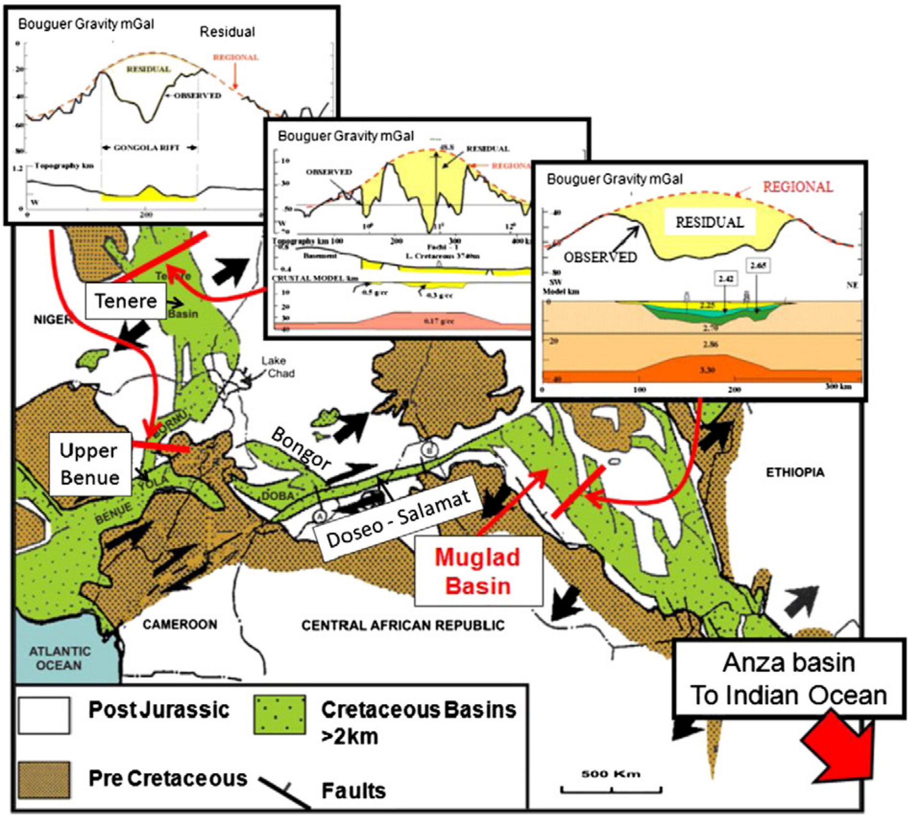

Fig. 9. The spatial geometry of the West Central African Rift System (WCARS) showing the strong regional positive gravity response over the rifts (due to the shallow Moho) from selected profiles across three segments of the rift system. The black arrows represent Albian phase of plate kinematics (Fig. 5) and not the more complex evolution of the rift system as a whole.

sections of the azimuth-age plot can be considered as uniform periods of plate motion resulting in periods of basin development, whereas changes in the azimuth reflect changes in plate motion and thus changes in basin formation leading to the development of unconformities. We now show that the timing of plate motion changes or timing of the unconformities (Fig. 6) correlates with the timing of continental margin unconformities. We propose these unconformities to have a common plate tectonic cause, resulting in different effects on the West African continental margin to those seen in the WCARS.

For continental margins, it is recognised that stratigraphic unconformities are an important part of sequence stratigraphy (Mitchum, 1977) which can be correlated on both regional and inter-continental scales and which help to underpin the concept of eustatic sea-level changes. Fig. 12 shows the chronostratigraphic chart for the Ivory Coast margin which is part of the NW African sub-plate and conjugate to the N margin of S America (Wells et al., 2012). The chart shows a distinct set of sedimentary sequences separated by short periods of non-deposition/unconformities. The gaps in the sedimentary sequence agree well with the times of WCARS unconformities — also shown in Fig. 12. Japsen et al. (2012) have also found striking coincidences between episodes of continental margin uplift and changes in plate motion and consider driving forces that can transmit across the spreading axis, probably at great depth i.e. in the asthenosphere (Japsen et al., 2012).

Based on our findings presented in this contribution, our favoured mechanism, or effect, for the development of the unconformities is periodic changes in the isostatic response of the plate due to changes in plate motion and thus in plate stress. The continental margins are intra-plate features whereas the WCARS is a sub-plate margin. As such it will respond differently to changes in plate motion (or plate momentum changes). Continental margins are considered here to have been weakened by the volume of sediments deposited and by the subsidence they have undergone and will focus horizontal stress changes when plate motion changes. The local effect is either isostatic uplift or subsidence depending on whether the plate motion generates tension or compression giving rise to vertical movements comparable in size to that previously attributed to eustatic sea-level changes (Mitchum, 1977). Watts and Fairhead (1999) have shown that flexuring of continental margins under sedimentary load is controlled by the effective elastic thickness, T_e, of the plate. We propose that during the short periods when plate motions are changing direction and velocity, the tensional stress field will change beneath the margin and either increase or decrease the T_e value beneath the margin and cause an isostatic response to occur (Fig. 13). The local nature and regional nature of unconformities are well documented by seismic stratigraphy mapping and we indicate in this study that the timing of these events is closely related to measurable plate tectonic processes; this calls into question the concept that eustatic sea-level changes are the principal cause of the unconformities rather than the plate tectonic driven mechanism proposed here. This study thus potentially opens up a range of new research studies to use deformable plates (or sub-plates) to quantify sub-plate motions and to test the different mechanisms of continental margin responses. To our knowledge the proposed isostatic response effect has not been tested by finite element models of continental margins (E Burov, per. com).

6. Discussion and conclusions

Although there remain some uncertainties in the age of the oceanic crust, and thus the timing of changes in relative plate motion, and even greater uncertainties in the dating of the basinal unconformities, this study shows a remarkable correlation in the timing of unconformities with the timing of changes in plate motion. We are therefore able to show at a macro-tectonic scale, the importance of stratigraphic

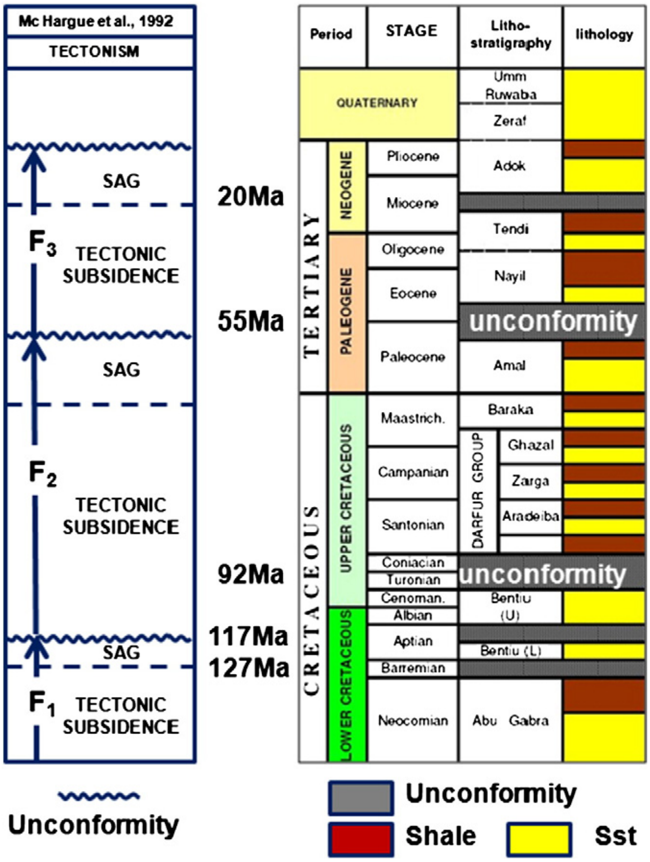

Fig. 10. Stratigraphic charts for the Muglad Basin, Sudan, after adjustment of Mchargue et al. (1992) (Chevron, left) to match the stage names of chart by Dr Zayad Awad (1999) (GNPOC, right).

unconformities as a tectonic correlation tool. For Africa the unconformities, identified in the Muglad Basin and other basins within the WCARS, can be temporally correlated with the changes in azimuth direction of the oceanic FZs (Fig. 3). Detailed structural mapping of the West and Central African Rift System (WCARS) basins confirms this model (GETECH, 2002) with individual basins having periods of extension and strike-slip as well as short periods of compressional tectonics. The Muglad Basin, like other basins, has undergone a polyphase development which has resulted in three major phases of extension with

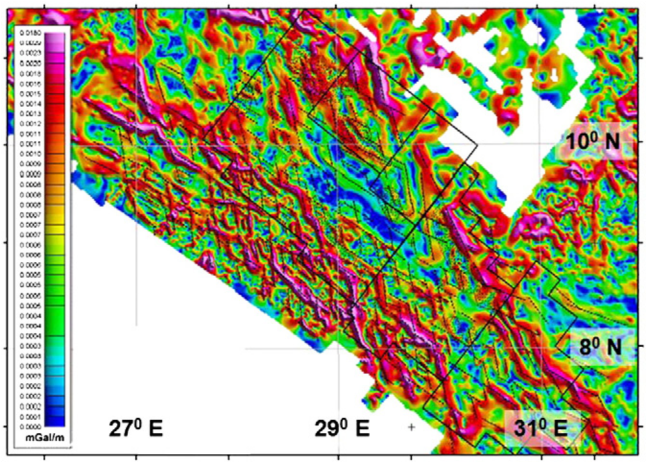

Fig. 11. The horizontal derivative of the Bouguer gravity showing the strong 'rhomb' geometry of fault pattern with fault trends N to NNW and NW.

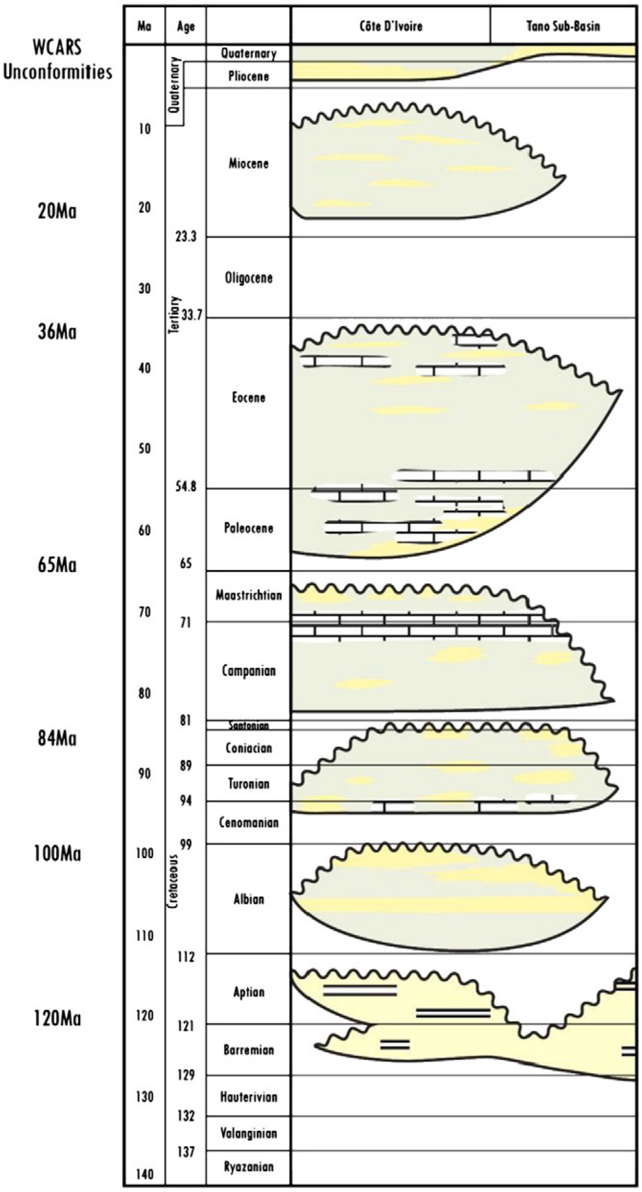

Fig. 12. Simplified stratigraphic chart for Cote d'Ivoire (redrawn from Wells et al., 2012) Equatorial Atlantic margins with dates of African basin unconformities indicated in bold black.

intervening periods (unconformities) when uplift and erosion or non-deposition have taken place. Since the Muglad basin is an integral part of the WCARS one can infer that it has undergone periods of transtensional deformation from the rhomb fault geometry seen in the basin. Thus the WCARS is shown to be intimately connected to regional plate tectonic processes; changes in plate motions have been recorded in great detail by the stratigraphy and fault geometries within the basins. How and why changes in plate motion link with the stratigraphical processes within the rift basins and continental margins is complex and not yet fully understood. It is possible that certain changes in African sub-plate motion will not necessarily generate an unconformity within all basins e.g. an extensional event followed by a further extensional event but with higher or lower stress could result in a basin to continue to develop without an unconformity. Equally a change in the African sub-plate motions could generate strike-slip deformation (or compressional folding) within one basin and result in a hiatus of its subsidence and generation of an unconformity, while in other basins it could be seen either as an extensional event due to the basin's differing orientation or as a period of quiescence when the stress field within Africa

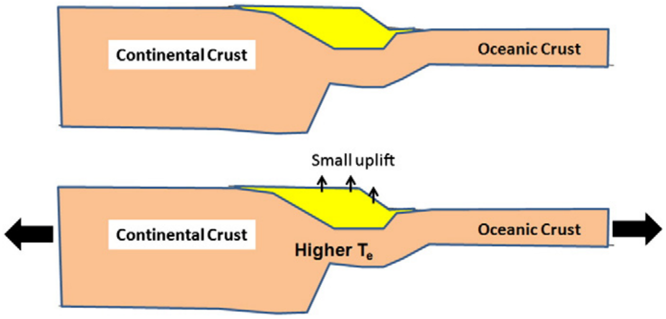

Fig. 13. Schematic diagrams of a continental margin with a small increase in tension applied to the underlying plate increasing the plate strength and effective elastic thickness T_e. The isostatic response to a higher T_e value is local uplift of the margin.

falls below a threshold value. This latter event is likely to occur when stresses change both in orientation and magnitude (Figs. 3 and 6). The sag phases of basin development seen in the stratigraphy of many basins (e.g. Fig. 10) are considered to be a response to reduced stress, cooling, thermal contraction and flexural isostatic subsidence of the basin. The current inactive state of the WCARS could be due to this cooling and associated crustal strengthening. The only current African plate activity is the Red Sea and East African Rift System — based on earthquakes and GPS plate motion vectors (Calais et al., 2006; McClusky et al., 2003). The development of the Red Sea and the East African Rift System (EARS) could be the reason that the WCARS is currently inactive. Any plate stresses which would previously have been dissipated in the WCARS are now absorbed by the hotter and more ductile EARS.

We show that the correlation of unconformity ages with plate motion is not restricted to the interior basins of Africa but matches, as far as dating permits, the boundaries of mega-sequences and sub-divisions of these sequences along the continental margins of the Atlantic. The proposed mechanism relates the change in African plate motion to isostatic response effects at the continental margins resulting in stratigraphic unconformities. It is proposed that the vertical loading of sediments onto the crust at the continental margins has weakened the crust so that small changes in plate motion will change the plate's elastic strength resulting in a small but focused isostatic uplift/subsidence of the margin. Seismic stratigraphy is possibly the most sensitive geological indicator we have to changes of plate strength and thus could provide a greater understanding of plate processes from a completely new perspective.

References

Avbovbo, A.A., Ayoola, E.O., Osahon, G.A., 1986. Depositional and structural styles in Chad basin of north eastern Nigeria. American Association of Petroleum Geologists Bulletin 70 (12), 1787–1798.

Awad, Zayad, 1999. Stratigraphy Chart (Personal Communications GNPOC).

Benkhelil, J., 1988. Structure et évolution géodynamique du basin intracontinental de la Bénoué (Nigéria). Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine 12 (1), 29–128.

Bermingham, P.M., Fairhead, J.D., Stuart, G.W., 1983. Gravity study of the Central African Rift System: a model of continental disruption. 2: the Darfur domal uplift and associated Cainozoic volcanism. Tectonophysics 94, 205–222.

Binks, R.M., Fairhead, J.D., 1992. A plate tectonic setting for Mesozoic rifts of West and Central Africa. Tectonophysics 213, 141–151.

Brown, S.E., Fairhead, J.D., 1983. Gravity study of the Central African rift system: a model of continental disruption. 1: the Ngaoundere and Abu Gabra rifts. Tectonophysics 94, 187–203.

Calais, E., Ebinger, C.J., Hartnady, C., Nocquet, J.M., 2006. Kinematics of the East African Rift from GPS and earthquake slip vector data. In: Yirgu, G., Ebinger, C.J., Maguire, P.K.H. (Eds.), The Afar Volcanic Province within the East African Rift System, GSL Special Publications.

Fairhead, J.D., Binks, R.M., 1991. Differential opening of the central and south Atlantic oceans and the opening of the Central African rift system. Tectonophysics 187, 191–203.

Fairhead, J.D., Green, C.M., 1989. Controls on rifting in Africa and the regional tectonic model for the Nigeria and East Niger rift basins. Journal of African Earth Sciences 8 (2/3/4), 231–249.

Fairhead, J.D., Williams, S.E., Fletcher, K.M.U., Green, C.M., Vincent, K., 2009. Trident — a new satellite gravity model for the oceans EAGE Amsterdam, extended abstract 6039. 71st EAGE Conference & Exhibition — Amsterdam, The Netherlands, 8–11 June 2009.

Fairhead, J.D., Mazur, S., Green, C.M., Yousif, M.E., 2012a. Regional tectonic controls on basement architecture and oil accumulation within the Muglad Basin, Sudan. Extended Abstract, 22nd Annual ASEG, Brisbane, p. 4.

Fairhead, J.D., Mazur, S., Green, C.M., Masterton, S., Yousif, M.E., 2012b. Regional plate tectonic controls on the evolution of the West and Central African rift system, with a focus on the Muglad Rift Basin, Sudan. SAPEG. Journal Sudanese Association of Petroleum Geoscientists (3), 14–29 (Feb 2012).

Genik, G.J., 1993. Petroleum Geology of cretaceous–tertiary rift basins in Niger, Chad, and Central African Republic. American Association of Petroleum Geologists Bulletin 77, 1405–1434.

GETECH, 2002. Central African basins study. Unpublished report pp. 253.

Gradstein, F.M., Ogg, J., 1996. A phanerozoic time scale. Episodes 19, 3–4 (and table).

Guiraud, R., 1990. Tectono-sedimentary framework of the Early Cretaceous continental Bima Formation (Upper Benue Trough; NE Nigeria). In: Kogbe, C.A., Lang, J. (Eds.), African Continental Phanerozoic sediments. Journal of African Earth Sciences 10 (1/2), pp. 341–353.

Guiraud, R., 1993. Late Jurassic rifting — Early Cretaceous rifting and Late Cretaceous transpressional inversion in the upper Benue Basin (NE Nigeria). Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine 17, 371–383.

Guiraud, R., Bellion, Y., 1995. Late Carboniferous to recent geodynamic evolution of the West Gondwanian cratonic Tethyan margins. In: Nairn, A., Dercourt, J., Vrielynck, B. (Eds.), The ocean basins and margins. The Tethys Ocean, vol. 8. Plenum, New York, pp. 101–124.

Guiraud, R., Bosworth, W., 1997. Senonian basin inversion and rejuvenation of rifting in Africa and Arabia. Synthesis and implications to plate-scale tectonics. Tectonophysics 282, 39–82.

Guiraud, R., Maurin, J.C., 1992. Early Cretaceous rifts of Western and Central Africa: an overview. Tectonophysics 213, 153–168.

Guiraud, R., Binks, R.M., Fairhead, J.D., Wilson, M., 1992. Chronology and geodynamic setting of Cretaceous–Cenozoic rifting in West and Central Africa. Tectonophysics 213, 227–234.

Japsen, P., Cobbold, P.R., Chalmers, J.A., Green, P.F., Bonow, J.M., 2012. Changes in plate motion and vertical movements along passive continental margins. EGU2012-7659, EGU General Assembly: Geophysical Research Abstracts, 14.

Japsen, P., Bonow, J.M., Green, P.F., Cobbold, P.R., Chiossi, D., Lilletveit, R., Magnavita, L.P., Pedreira, A.J., 2012. Episodic uplift and burial history of NE Brazil after opening of the South Atlantic. GSA Bulletin 124, 800–815.

Mascle, J., Blarez, E., Marhino, M., 1988. The shallow structure of the Guinea and Ivory Coast–Ghana transform margins: their bearing on the Equatorial Atlantic Mesozoic evolution. Tectonophysics 155, 193–209.

Mascle, J., Lohman, G.P., Clift, P., l'équipe embarquée, 1995. La marge transformante de Cote-d'Ivoire-Ghana: premiers résultants de la campagne ODP 159 (janvier-février 1995). 737–747 (Paris 320).

Masterton, S.M., Fairhead, J.D., Mazur, S., Green, C.M., 2012. The influence of oceanic fracture zones on the segmentation and structural control of continental margins. Extended Abstract EAGE Conference & Exhibition — Copenhagen, p. 4.

Mcclusky, S., Reilinger, R., Mahmoud, S., Sari, D.B., Tealeb, A., 2003. GPS constraints on Africa (Nubia) and Arabia plate motions. GJI 1551, 126–138.

Mchargue, T.R., Heidrick, T.L., Livingstone, J., 1992. Tectonostratigraphic development of the Interior Sudan Rifts, Central African. In: Ziegler, P.A. (Ed.), Geodynamics of Rifting, Vol. II. Case History Studies on Rifts: North and South America and Africa: Tectonophysics, 213, pp. 187–202.

Mckenzie, D.P., 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters 40.

Mitchum Jr., R.M., 1977. Seismic stratigraphy and global changes of sea level, part 11: glossary of terms used in seismic stratigraphy. In: Payton, C.E. (Ed.), Seismic Stratigraphy — Application to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir, 26, pp. 205–212.

Mohamed, A.Y., Ashcroft, W.A., Whiteman, A.J., 2001. Structural development and crustal stretching in the Muglad Basin, southern Sudan. Journal of African Earth Sciences 32 (2), 179–191.

Müller, R.D., Sdrolias, M., Gaina, C., Roest, W.R., 2008. Age spreading rates and spreading asymmetry of the world's ocean crust. Geochemistry, Geophysics, Geosystems 9, Q04006. http://dx.doi.org/10.1029/2007GC001743.

Reeves, C.V., Karanja, F.M., MacLEOD, I.N., 1986. Geophysical evidence for a Jurassic triple junction in Kenya. Earth and Planetary Science Letters 81, 299–311.

Saint-Marc, P., N'DA, V., 1997. Biostratigraphie et paléoenvironnements des dépots crétacés au large d'Abidjan (Golfe de Guinée). Cretaceous Research 19–8, 545–565.

Watts, A.B., Fairhead, J.D., 1999. A process oriented approach to modelling the gravity signature of continental margins. SEG. The Leading Edge 258–263 (February (1999)).

Wells, S., Warner, M., Greenhalgh, J., Borsato, R., 2012. Deepwater potential in Cote d'Ivoire. GEO ExPro 9 (3), 39–40.

Wu, J.E., Mcclay, K., Whitehouse, P., Dooley, T., 2009. 4D analogue modelling of transtensional pull-apart basins. Marine and Petroleum Geology, 26(8), pp. 1608–1623.