

Phanerozoic geological evolution of the Equatorial Atlantic domain

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Abstract

The Phanerozoic geological evolution of the Equatorial Atlantic domain has been controlled since the end of Early Cretaceous by the Romanche and Saint Paul transform faults. These faults did not follow the PanAfrican shear zones, but were surimposed on Palaeozoic basins. From Neocomian to Barremian, the Central Atlantic rift propagated southward in Cassiporé and Marajó basins, and the South Atlantic rift propagated northward in Potiguar and Benue basins. During Aptian times, the Equatorial Atlantic transform domain appeared as a transfer zone between the northward propagating tip of South Atlantic and the Central Atlantic. Between the transform faults, oceanic accretion started during Late Aptian in small divergent segments, from south to north: Benin-Mundaú, deep Ivorian basin-Barreirinhas, Liberia-Cassiporé. From Late Aptian to Late Albian, the Togo-Ghana-Ceará basins appeared along the Romanche transform fault, and Côte d'Ivoire-Parà-Maranhão basins along Saint Paul transform fault. They were rapidly subsiding in intra-continental settings. During Late Cretaceous, these basins became active transform continental margins, and passive margins since Santonian times. In the same time, the continental edge uplifted leading either to important erosion on the shelf or to marginal ridges parallel to the transform faults in deeper settings.

1. Introduction

In the African and South American lithospheric plates, the Equatorial Atlantic domain is a peculiar area

where both Phanerozoic structures and geological evolution have been controlled by few but very long transform faults, still active since their initiation at the end of Early Cretaceous. From south to north, there are the Chain, Romanche and Saint Paul fracture zones (Figure 1). The continental basins that appeared along these transform faults are the Benue and Potiguar basins (Chain), Togo-Ghana and Ceará basins (Romanche), the Côte d'Ivoire and Pará-Maranhão basins (Saint Paul) (Figure 1). Between these transform faults, short segments of conjugated divergent margins are from south to north Benin-Mundaú, deep Ivorian basin -Barreirinhas, Liberia-Cassiporé (Figure 1).

Unfortunately, this area has been relatively poorly investigated for several reasons:

- as for many sedimentary basins, there are few aerial outcrops, especially along the African margin;
- the continental margins are mainly of transform-types, thus very narrow and potentially less interesting than wide divergent margins for oil prospection;
- vertical seismic lines does not provide good images of the numerous strike-slip faults;
- the geodynamic framework is poorly constrained because the oceanic accretion started during the Cretaceous quiet magnetic period, because the present position below the magnetic equator prevails good quality magnetic measurements, and finally because the numerous and wide fracture zones make the correlation of magnetic anomalies uneasy (e.g. Campan, 1995).

Most of the available geological informations on the continental shelf come from drill-holes and seismic lines performed by the oil industry. During the seventies, the scientific exploration was focused on the survey of fracture zones in the deep basins and dedicated to a first investigation of continental margins (Fail et al., 1970; Arens et al., 1971; Delteil et al., 1974; Emery et al., 1975). From the eighties, investigations were focused on the Côte d'Ivoire-Ghana margin, in the central part of the African equatorial margin, and along the intersection of the Romanche fracture zone with the deep Ivorian divergent basin (review in Basile et al., 1996). These investigations culminated with four scientific drill-holes performed during Ocean Drilling Program Leg 159 along this margin (Masclé et al., 1996).

From this data set, we describe in this paper the geological evolution from a pre-rift reconstruction (Figure 2a) to the present day stage.

2. Latest Proterozoic to Triassic: pre-rift

The Equatorial Atlantic margins extend over an assemblage of Proterozoic to earliest Palaeozoic tectonic domains, that mainly result from the PanAfrican-Braziliano orogeny (Black, 1984) which occurred between ca.

720 and 520 Ma (Villeneuve and Cornée, 1994; Caby, 2003, Guiraud et al., this issue). This fold-thrust belt developed around the West African craton, the Guyana craton, the São Luis craton-Eburnean shield and the São Francisco craton (Figure 2a). It was associated with major strike-slip fault zones which rejuvenated during Phanerozoic times and more or less influenced the development of the Equatorial Atlantic, as the central African fracture zone (Cornacchia and Dars, 1983; Black, 1984), the Kandi-Transbrazilian fracture zone (Guiraud and Alidou, 1981; Caby, 1989), and the Guinean-Nubian lineaments (Guiraud et al., 1985) (Figure 2a).

Erosion and tectonic quiescence followed the PanAfrican-Braziliano orogeny. It resulted in a large sedimentary area trending WSW to ENE from northeastern Brazil to West Africa. In Ghana (Kjemperud et al., 1992) (Figures 3 and 4a) and Côte d'Ivoire basins (Tucker, 1992) as in Brazil (Solimões, Amazonas and Parnaíba basins, Milani and Thomaz Filho, 2000), continental terrigenous sedimentation took place from Ordovician times (Figure 2a). These basins registered marine invasions between middle Devonian and Early Carboniferous, when large marine platforms extended from the Proto-Pacific Ocean over South America during global sea level highstands (Isaacson and Díaz Martínez, 1995; Williams, 1995). Marine sediments included sandstones, silts, shales, carbonaceous shales and limestones. Poorly dated Late Carboniferous to Triassic continental sandstones overlaid the marine Carboniferous. The total thickness of the preserved Palaeozoic series can reach 1000 to 1200 meters (Figure 4a).

3. Late Triassic to Jurassic: rifting in the Central Atlantic

The Late Triassic rifting in the Central Atlantic extended southward in northern Brazil: Late Triassic terrigenous continental formations have been drilled in the offshore Caciporé (Brandão and Feijó, 1994) and Marajó basins (Milani and Thomaz Filho, 2000). The orientation of rifting in this northern area has been likely controlled by the PanAfrican Rokelides belt trend. This rifting stage was followed in the earliest Lias (around 200 Ma) by the development of the Central Atlantic Magmatic tholeiitic Province (Wilson and Guiraud, 1998; Burke et al., 2003). This province extended southward over the western part of the future Equatorial Atlantic. Tholeiitic volcanism occurred either intercalated within the sediments in Caciporé, Marajó, Solimões and Amazonas basins, or in NNW-SSE trending dykes in the western edge of Caciporé basin (Milani and Thomaz Filho, 2000), French Guyana (dated 196-200 Ma: Deckart et al., 1997), and Liberia (186-201 Ma: Mauche et al., 1989).

While oceanic accretion started during the Jurassic in Central Atlantic, the Guinean-Nubian/Ouachita-Wichita fault zone (Figure 2b) acted as a transfer zone between the divergent area northward and an almost

stable area southward. South of this fault zone indications of plate divergence are restricted to limited subsidence and some volcanism. Liassic to Tithonian continental sandstones and shales deposited along the NW-SE trending Liberia basin (Martin, 1982). Late Jurassic continental terrigenous formations also deposited offshore Côte d'Ivoire (Martin, 1982), in Ghana (Martin, 1982), Benin (Dray et al., 1989) and in upper Benue (Guiraud, 1993) basins (Figure 2b). In this equatorial area, the Mesozoic sedimentation seems to have been independent from the Panafrican structures, but was probably localized over Devonian basins. Basalt flows occurred in the eastern Ghana basin during the Callovian (Akpati, 1978) (Figure 3), in the Benue basin and in the western part of the Maranhão basin since 147 Ma (Popoff, 1988; Fodor et al., 1990; Maluski et al., 1995). Basaltic dykes intruded around the northwestern Brazil Potiguar basin during Middle Jurassic (Horn et al., 1988; Bellieni et al., 1992) (Figure 2b). They are trending N70° to N80°E as the Panafrican Adamaoua and Sanaga lineaments on the African side, or Patos and Pernambuco lineaments on the Brazilian side.

This Callovian to latest Jurassic local rejuvenation or initiation of basin sedimentation and magmatism must be underlined as it is synchronous with similar events occurring along the Central African Rift System, e.g. the upper Benue, the central Sudan or the Anza basin in Kenya (cf. Guiraud et al., this issue). These different clues witness of a change in the paleo-stress field that affected the African-Arabian/south American plates, characterized by the occurrence of local tensional regimes which represent far-field effects of the opening of the Central Atlantic ocean and the Somali basin (western Indian Ocean). They predate the strong rifting activity that occurred since earliest Cretaceous times.

4. Late Berriasian to Late Aptian: rifting in the South and Equatorial Atlantic

During the Early Cretaceous, a new rift axis appeared in the South Atlantic, in relation with the emergence of the Paraná plume. The volcanic activity of the plume head started 138 Ma ago (Stewart et al., 1996), with a main magmatic episode between 134 and 129 Ma (Peate, 1997). Volcanism occurred in and around the Paraná area, as far as north Brazil in the East Maranhão (115-122 Ma: Fodor et al., 1990) and Potiguar basins (130-140 Ma: Bellieni et al., 1992), and in the Benue basin (Maluski et al., 1995; Coulon et al., 1996) (Figure 2c). From 130 to 120 Ma, rifting propagated northward to the Benue area, and across Africa to the Tethys realm (Guiraud and Maurin, 1991, 1992). Syn-rift sedimentation started in intracontinental basins since the Berriasian in the Potiguar basin (Araripe and Feijó, 1994) and probably along the Patos lineament in the Araripe (Baudin et al., 1996) and Rio do Peixe basins (Senant and Popoff, 1991; Françolin et al., 1994). During Early Barremian sedimentation started in the Benue Trough (Brunet et al., 1988), the Ghanaian Keta basin (Doyle et al., 1982) and Foz do

Amazonas (Brandão and Feijó, 1994). During this first stage of rifting in the equatorial area, the Niger delta area appears as a triple junction between the South Atlantic rift, the Benue transtensional rift and the transform zone of en échelon equatorial basins (Figure 2c). The rifting of the northeastern branch of the south Atlantic failed around 120 Ma, at the time of the final break up of Gondwana, when oceanic accretion started between Antarctica and India (Scotese et al., 1988). This incipient oceanic accretion imposed a kinematic plate reorganization (Nürnberg et Müller, 1991), and the connection between South and Central Atlantic by the en échelon Romanche and Saint Paul right-lateral transform faults, cross-cutting the Panafrican structures but localized on previously subsiding areas.

During Aptian times, intracontinental siliciclastic sedimentation occurred in fluvial to lacustrine environments all along these two transform faults, in strongly subsiding basins controlled by strike-slip or transtensional faults (Zalan et al., 1985; de Caprona, 1992; Chierici, 1996; Mascle et al., 1996, 1998; Basile et al., 1998; Attoh et al., 2004) (Figures 3, 4b, 4d, 4e). Between the two transform faults, the Côte d'Ivoire area represented a pull-apart structure, dominated by ENE-WSW extension and tilted blocks in the central part of the deep Ivorian basin (Blarez and Mascle, 1988; Basile et al., 1993; Sage, 1994). However, most crustal thinning and associated subsidence was localized along the curved coastal fault (de Caprona, 1992; Chierici, 1996), which was the termination of St Paul transform fault in the extensional area. Similarly, horsetail splay occurred at the connection between the Romanche transform fault and the southern side of the rifted Ivorian basin (Basile et al., 1993).

5. Late Aptian to Late Albian: post-rift, intracontinental transform

Rifting in the equatorial divergent basins stopped when the first oceanic crust accreted during the Cretaceous quiet magnetic zone (Figure 2c). Starting accretion correlates with a Late Aptian post-rift unconformity observed in the deep Ivorian basin (Basile et al., 1993; Basile et al., 1998) (Figure 4b) and in the conjugated Ceará basin (Zalan et al., 1985) (Figures 4d and 4e). However, between the divergent accretion axis, deformation was still active along the transform fault. Intracontinental rapidly subsiding basins (Ghana: Attoh et al., 2004; Côte d'Ivoire: de Caprona, 1992; Brazil: da Costa et al., 1990) developed along the transform faults, probably in structures similar to those developed during Cenozoic times along the Dead Sea transform fault. Sedimentation was still siliciclastic (Figure 3), probably feeded by the erosion of uplifted shoulders along the transform basins. First marine influences appeared in the Equatorial area during Late Aptian (Koutsoukos, 1982; Mascle et al., 1996; Maisey, 2000), but open marine connection between South Atlantic and Central Atlantic oceans occurred

only during Late Albian times, through narrow but locally deep basins (Pletsch et al., 2001).

While right-lateral transform faulting developed in the Equatorial Atlantic, left-lateral strike-slip faults were still active in the Benue trough (Guiraud, 1991), indicating that the Niger delta was still a triple junction up to Late Albian, even if displacements in the Benue area were probably very small when compared with displacements in the Atlantic area.

This intracontinental transform stage ended when the active transform fault brought into contact an oceanic lithosphere against a continental lithosphere. A second unconformity is associated to this event (Figures 4c and 4d), expected to have been diachronous along the transform fault, and older on the eastern termination of the transform faults on the African side (respectively on the western end on the Brazilian side) (Masclé and Blarez, 1987). Consequently, the ages of the unconformity vary along the margin, but are not younger than Late Albian, as at the African westernmost end of the Romanche transform, in the Côte d'Ivoire-Ghana marginal ridge area (Basile et al., 1998).

6. Latest Albian to Late Santonian: active transform margin

This stage started everywhere on the Equatorial continental margins by a diachronous unconformity that sealed the deformation. However, the reconstructions of the oceanic opening imply that transform faults were still active at that time between continental and oceanic lithospheres. This implies that the active transform zone shifted from the continental edge to the continent-ocean boundary, and that the deformation ceased on the continental margin (e.g., Basile et al., 1993; Basile et al., 1998). One of the most striking event at this stage is the uplift of the continental edge along the transform continent-ocean boundary. Where the continental crust was thinned and deep, as in the deep Ivorian basin or in Liberia, this resulted in the formation of a marginal ridge parallel to the transform fault (Figures 4b and 4g). Where the continental crust has not been thinned, the uplift resulted in tilting towards the continent and erosion (e.g. Costa et al., 1990; Attou et al., 2004) (Figures 4a and 4f). Since Masclé and Blarez (1987) and Todd and Keen (1989), this uplift along transform continental margins has been mainly explained as a consequence of transient heat transfer from the hot oceanic lithosphere to the coldest continental one. However, two of the most important results of ODP Leg 159 are that uplift occurred along the Côte d'Ivoire-Ghana marginal ridge since middle Albian times (Basile et al., 1998), i.e. during the intracontinental stage, and that there are no evidences of heating associated with the contact between oceanic and continental lithospheres (Basile et al., 1998; Wagner and Pletsch, 2001). Consequently, an alternate explanation has been proposed for transform uplift, based on the lithospheric flexure resulting from erosional unloading of

the continental crust along the transform fault, when plate displacement brings into contact continental crust at sea-level against deeper thinned continental crust, then oceanic crust (Basile and Allemand, 2002).

This stage ended when the oceanic accretion took place against the transform margin (Figure 2d). As for the beginning of this stage, this end is diachronous as the accretion axis moved along the transform fault. The last contact between the continental lithosphere and the accretion axis occurred during Late Santonian (84 Ma) (Figure 2d), and was coeval with a major kinematic change for the African plate (Guiraud and Bosworth, 1997).

7. Post-transform evolution: passive continental margin

From Late Santonian to present times, the continental margins experienced continuous subsidence, increased above previous basins by differential compaction, and reduced above the previously uplifted continental edges. In the deep parts of the margins, changes in sedimentation indicate an increasing influence of deepwater circulation, probably as the consequence of the establishment of a N-S circulation through the Equatorial Atlantic gateway (Pletsch et al., 2001). In the shallower parts, the Oligocene unconformity (e.g. Chierici, 1996) (Figures 3, 4b and 4c), known in all West African coastal basins, appears as the most important event in the sedimentary section, and was probably related to a main sea-level fall. Anyway, because of their very steep continental slopes, the transform margins of the Equatorial Atlantic were not widen as divergent margins during the post rift stage: progradation of the shelf break by sedimentary accumulation is restricted to the narrows divergent basins as the Mundaú or deep Ivorian basins; along transform margins, shelf sediments by-passed through the continental slope directly to the abyssal plain.

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Figure captions:

Figure 1: Main structures in Equatorial Atlantic. Brazilian basins from Milani and Thomaz Filho (2000); cratons and intracontinental shears modified from Villeneuve and Cornée (1994). C1: West African craton; C2: Eburnean shield; C3: São Francisco craton; C4: São Luis craton; C5: Guyana craton. S1: Kandi lineament; S2: Guinean-Nubian lineaments; S3: South Adamaoua shear zone; S4: Sanaga shear zone; S5: Patos shear zone; S6: Pernambuco shear zone; S7: Trans-brazilian fault zone. Conjugated divergent basins: b1 (Liberia) and b2 (Caciporé); b3 (deep ivoirien basin) and b4 (Barreirinhas); b5 (Benin) and b6 (Mundaú). Intracontinental divergent basins: b7 (Solimões), b8 (Amazonas), b9 (Marajó), b10 (Tacutu). Conjugated transform continental margins: b11 (Côte d'Ivoire) and b12 (Pará-Maranhão); b13 (Ghana-Togo) and b14 (Ceará). Strike-slip basins: b15 (Benue), b16 (Potiguar).

Figure 2: Geodynamic evolution of the Equatorial Atlantic. Same legend as for figure 1. 2a: Pre-rift (latest

Proterozoic to Triassic) reconstitution. Continental fit after Unternehr et al. (1988), modified from Campan (1995). Africa is supposed fixed. 2b: Oxfordian reconstitution. V indicates Early Liassic volcanism in Guyana, Liberia, NE Brazil and Benue basin. 2c: Late Aptian reconstitution. Plate boundaries modified from Campan (1995). V indicates Early Cretaceous volcanism in NE Brazil, Potiguar and Benue basins. 2d: Santonian reconstitution. Plate boundaries modified from Campan (1995).

Figure 3: Composite stratigraphic framework of Keta basin (Ghana margin) (from Akpati, 1978).

Figure 4: Line drawing of seismic sections across continental margins in the Equatorial Atlantic. Same vertical (in second two-way travel time) and horizontal scales for figures 4a to 4e, with vertical exaggeration 3 for water velocities. 4a: Ghana margin (b13 in figure 1), modified from line 47 (Attoh et al., 2004). 4b: Deep Ivorian Basin (b3 in figure 1) and Côte d'Ivoire-Ghana marginal ridge (b13 in figure 1), modified from line MT02 (Basile et al., 1996). 4c: Côte d'Ivoire margin (b11 in figure 1), modified from figure 7-17 (de Caprona, 1992). 4d: Ceará margin (b14 in figure 1), modified from line 53-280 (Zalan et al., 1985; da Costa et al., 1990). 4e: Mundaú basin (b6 in figure 1), modified from lines 222-529 and 58-319 (da Costa et al., 1990). 4f and 4g are crustal sections of Ghana margin and Côte d'Ivoire-Ghana marginal ridge, respectively (same scales, vertical exaggeration 2.5). 4f modified from Edwards et al. (1997), in the area of figure 4a; 4g modified from Sage (1994), along the same section as figure 4b.