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ARTICLE

Exploratory plays of Pará-Maranhão and Barreirinhas basins in deep and ultra-deep waters, Brazilian Equatorial Margin

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ABSTRACT: *The Pará-Maranhão and Barreirinhas are exploratory frontier basins. After the discoveries in deep/ultra-deep water turbidites at the correlated African equatorial margin and French Guiana (Jubilee and Zaedyus plays), the exploratory interest was retaked for those basins. Using 2D seismic interpretation, it was search to identify hydrocarbon accumulations potential focusing on turbiditic reservoirs. Three plays types linked to three margin distinct segments were identified: shallow waters, faulted shelf border and deep/ultra-deep waters. The shallow waters and faulted shelf border plays are related to two petroleum systems: Caju-Travosas and Travosas-Travosas. The Caju Group (Late Albian-Early Cenomanian) and Travosas Formation (Cenomanian-Turonian) source rocks occur between 2,400 and 3,700 m below sea water bottom for shallow waters play, and between 1,300 and 4,800 m for faulted shelf border play. The deep/ultra-deep waters play is related to three petroleum systems: Codó-Travosas, Caju-Travosas and Travosas-Travosas. The source rocks from Codó Formation (Aptian) occur between 2,860 and 4,550 m, from Caju Group (Late Albian-Early Cenomanian) between 2,200 and 3,800 m and from Travosas Formation (Cenomanian-Turonian) between 1,430 and 2,860 m. In the African equatorial margin, the oil window top is located around 2,700 m below sea water bottom. Thus, it can be concluded that Pará-Maranhão and Barreirinhas source rocks would also be able to generate oil/gas in the specified depths.*

KEYWORDS: *Pará-Maranhão basin; Barreirinhas basin; petroleum geology; petroleum prospecting; plays.*

INTRODUCTION

The Brazilian equatorial margin includes Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará and Potiguar basins, with shows of oil and gas in exploratory wells along the whole margin, as well as well-known production fields at Potiguar and Ceará basins. However, when compared to Brazilian east margin, those basins are very poor studied, specifically Pará-Maranhão and Barreirinhas at deep and ultra-deep waters. Despite this, in recent years, these basins have attracted more interest in petroleum prospecting due to the significant discoveries in related African equatorial margin basins (Guinea Gulf) and in French Guiana. This interest emerge because both African and South American equatorial margin are considered analogous, since they were formed in the same geological context of transformant tectonic, culminating in the opening of equatorial Atlantic Ocean in Cretaceous.

The Jubilee play, located in Tano Basin at Ghana offshore, corresponds to one of the most important oil fields of Guinea Gulf, and comprises turbiditic fans and channels systems of the Cenomanian-Turonian, with shales of Late Cretaceous as source rocks. Jubilee discovery made exploratory investments increase significantly in the region of Guinea Gulf and lead to discovery of petroleum fields with the same characteristics in the margin of Ivory Coast, Sierra Leone and Liberia. Based on the theory of conjugated margins, the same play was successfully tested in the offshore region of French Guiana, where the Zaedyus field was discovered, also in turbiditic sandstones and very similar to Jubilee play. The success of Zaedyus discovery suggests that there may be a second, world-class petroleum system analogous to Jubilee along the South American side of the equatorial conjugate margin at deep and ultra-deep waters.

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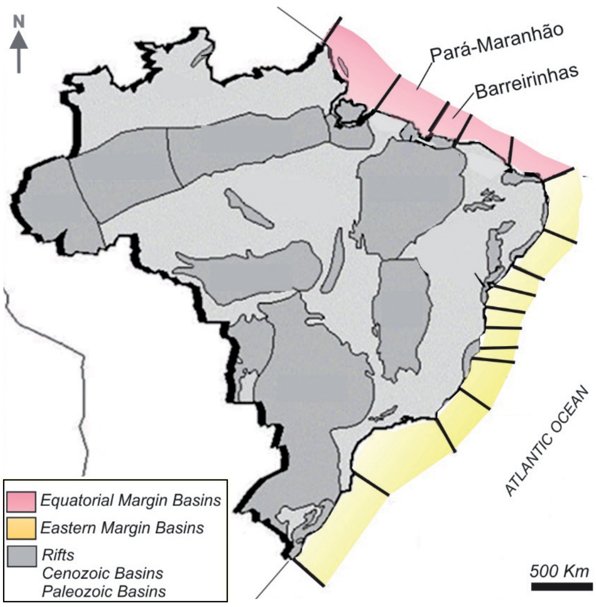
The understanding of transforming tectonics, as well as the evolution of the basins associated to this tectonic regime is of great importance, since there is still an exploratory frontier related to Brazilian equatorial margin basins. In addition, the seismic-stratigraphic interpretation and seismic geomorphology are indispensable tools for the offshore study of these basins, especially in deep and ultra-deep waters where there's no information from exploratory wells. Using seismic facies analysis and seismic geomorphology is possible to interpret the internal and external architecture of depositional elements in subsurface, and so help to identify possible plays related to turbiditic sandstone at deep and ultra-deep waters.

GEOLOGICAL SETTING

The Brazilian equatorial margin includes all West-Northwest (WNW) basins located in emerged and offshore areas along the states of Amapá, Pará, Maranhão, Piauí, Ceará and Rio Grande do Norte, and includes, from east to west, Potiguar, Ceará, Barreirinhas, Pará-Maranhão and Foz do Amazonas basins, besides the Marajó, Cassiporé, São Luís — Ilha Nova, Bragança-Viseu and Tacutu rifts. The Pará-Maranhão is exclusively offshore basin, located at Pará and Maranhão states, occupying an area of approximately 48,000 km^2 with elongated geometry at SE-NW direction as shown in Figure 1 (Brandão & Feijó 1994, Soares *et al.* 2007). The Barreirinhas basin covers part of the coast of Maranhão state and its adjacent continental shelf, occupying an area of 46,000 km^2 approximately, with 8,500 km^2 located at onshore portion (Feijó 1994, Trosdtorf Júnior *et al.* 2007). The limit between these basins is arbitrary since there is no geological feature that justifies their separation.



Source: modified from Mohriak (2003).

Figure 1. Map of the Brazilian basins with location of Pará-Maranhão and Barreirinhas basins.

The origin and evolution of Brazilian equatorial margin basins were considered analogous with Brazilian east margin basins for many years, where the most important offshore oil fields are located, including Santos, Campos, Espírito Santo and Sergipe-Alagoas basins, for example. However, while at the eastern margin the origin and evolution of basins are related to divergent tectonics and is where the three classical tectonic stages are recognized (rift, transitional and passive margin), the equatorial margin is characterized by directional and/or oblique tectonics associated with transformant faults zones, culminating with Atlantic Ocean formation.

The main characteristics of Brazilian equatorial margin basins include: late continental rupture when compared to basins of the eastern margin (with the exception of Potiguar basin continental rift); continental rupture controlled by transforming tectonics with dextral directional kinematics; subsidence and uplift events of diachronic character controlled by divergent, transtensive or transpressive tectonics of each margin segment; sub-basins present contrasting histories in terms of thermal flow, sedimentary facies distribution, magmatism and deformation episodes; the absence of transitional evaporitic sequence at Aptian, as well as the absence of structures and sedimentation associated with salt tectonics as found in the eastern margin basins (Françolin & Szatmari 1987, Szatmari *et al.* 1987, Matos 1999, 2000, Milani *et al.* 2000, Mohriak 2003, Zálan 2004, Basile *et al.* 2005, Brownfield & Charpentier 2006).

Matos (1999, 2000) proposed the systematization of an evolution model for Brazilian equatorial margin and defined three main tectonic stages: pre-transformant, sin-transformant and post-transformant. The same model can be applied to African equatorial margin basins, including the offshore basins of Sierra Leone, Liberia, Cote d'Ivoire, Ghana, Togo, Benin, and western Nigeria, and can also be applied to offshore basins of Guyana, Suriname and French Guiana on the South American margin. These east-west aligned basins of both Africa and South American are characterized by similar structural and sedimentary features, due to their common origin as transtensional rifting and wrench during the breakup of the African and American paleocontinents (Brownfield & Charpentier 2006).

The pre-transformant stage (pre-Albian) corresponds to rifting processes that preceded the formation of Equatorial Atlantic, including the Triassic-Jurassic stretching and fragmentation phase which formed the Tacutu, Marajó and Cassiporé rifts and associated magmatism, as well as Potiguar rift opening at Noecomian-Barremian (Matos 1999, 2000, Milani *et al.* 2007). The Neocomian rifting that occurred at Potiguar Basin coincided in time with rupture in eastern margin of Brazil and implantation of Recôncavo-Tucano-Jatobá and Sergipe-Alagoas rifts (Szatmari *et al.* 1987, Soares & Rossetti 2005). However, the Barremian-Aptian limit registers an important phase of shear and intracontinental fracturing, with sediments accumulation in several depocenters, such as Potiguar, Ceará, Barreirinhas, Pará-Maranhão, Bragança-Viseu/São Luís and Foz do Amazonas basins (Matos 2000). The rifting pattern along the equatorial margin presents E-W segments alternated with SE-NW segments.

The syn-transforming stage (Albian-Cenomanian) marks the period from the establishment of first oceanic accretion centers at equatorial margin until the end of control of transforming faults at basins. At this stage, the transtensive and transpressive processes acted concomitantly, generating simultaneous subsidence and uplift events in different basins (Matos 1999, 2000). The tectonic environment at equatorial margin in Albian was controlled by translational movement between South America and Africa, with dextral directional movement along the transforming faults. In addition, the Albian period is characterized by continental and shallow marine depositional environment with siliciclastic sedimentation in intracontinental basins. Open marine conditions occurred from Upper Albian, indicating the definitive disconnection between Africa and South America (Szatmari *et al.* 1987, Azevedo 1991, Matos 2000, Basile *et al.* 2005). According to Matos (2000), at Barreirinhas basin and Mundaú sub-basin (Ceará basin) the deformation was essentially transtensive, dominated by distension, while at Pará-Maranhão and Potiguar east the transtention were dominated by directional movement associated to São Paulo and Chain Faults. The Piauí-Camocim sub-basin (Ceará basin) has one of the most important transpressive deformation records, with compressive structures such folds and faults (Zalán & Warme 1985).

From Cenomanian, equatorial margin basins started the drift tectonic phase, which was given in a context of transforming passive margin until the Santonian. From the Upper Santonian to Recent, the drift phase occurs at divergent conditions. This last phase is characterized by a predominance of distensional deformation in addition to continuous thermal subsidence that is post-rupture lithospheric cooling consequence (Matos 1999, 2000, Basile *et al.* 2005).

The Pará-Maranhão and Barreirinhas basins are composed of five main mega sequences, as described by Soares *et al.* (2007) and Trosdtorf Júnior *et al.* (2007): intracratonic syneclise (Paleozoic), including Canindé Group; Rift II (Aptian), including "Inominate" Formation; Pre-Rift III (Aptian), including Codó Formation; Rift III (Albian), including Canarias Group; Drift (Late Albian to Recent), including Caju and Humberto de Campos groups, besides basaltic magmatism of Late Cretaceous, Eocene and Miocene.

Those basins are considered analogous to Ivory Coast and Tano basins in Guinea Gulf, all of them located between Romanche and São Paulo Transform Zones.

The Brazilian equatorial margin basins have source rocks in five main stratigraphic intervals: marine shales of Devonian (Pimenteiras Formation in the Pará-Maranhão and Barreirinhas basins); lacustrine shales of Neocomian (Pendência Formation in the Potiguar basin); lacustrine and lagoons shales of Aptian (Cassiporé and Codó formations in the Foz do Amazonas basin, Codó Formation in the Pará-Maranhão and Barreirinhas basins, Mundaú and Paracuru Formation in the Ceará basin, Pescada and Alagamar formations in the Potiguar basin); calcilutites and marine shales of Albian-Cenomanian (Limoeiro Formation in the Foz do Amazonas basin, Caju Group in the Pará-Maranhão and Barreirinhas basins); marine shales of Cenomanian-Turonian (Travosas Formation in the Pará-Maranhão and Barreirinhas basins).

Thus, at Pará-Maranhão and Barreirinhas basins there are four main source rocks, corresponding to marine shales of the Pimenteiras Formation (Devonian), lagoons shales of the Codó Formation (Aptian), calcilutites and marine shales related to Caju Group (Late Albian-Cenomanian), and marine shales of the Travosas Formation (Cenomanian-Turonian) (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007).

The reservoirs occur at four main stratigraphic intervals at Brazilian equatorial margin: fluvial-deltaic sandstones of the Neocomian-Albian (Cassiporé Formation in the Foz do Amazonas basin, Canárias Group in the Pará-Maranhão basin, Bom Gosto and Barro Duro formations in the Barreirinhas basin, Mundaú and Paracuru formations in the Ceará basin, Pendência, Pescada and Alagamar formations in the Potiguar basin); shelf sandstones and turbiditic sandstones of Late Cretaceous-Paleogene (Limoeiro Formation in the Foz do Amazonas basin, Travosas Formation in the Pará-Maranhão and Barreirinhas basins, Ubarana Formation in the Ceará basin, Açu and Ubarana formations in the Potiguar basin); porous and fractured calcarenites of the Paleogene (Amapá Formation in the Foz do Amazonas basin, Ilha de Santana Formation in the Pará-Maranhão basin); shelf sandstones and turbidite sandstones of Neogene (Orange Formation in the Foz do Amazonas basin).

Therefore, at Pará-Maranhão basin there are three main reservoir rocks, including fluvial-deltaic sandstones of the Canárias Group (Albian), fractured limestones, banks, reefs, talus deposits and carbonate turbidites of the Ilha de

Santana Formation (Paleogene), and turbidite sandstones of the Travosas Formation (Late Cretaceous-Paleogene). At Barreirinhas basin there are three main reservoirs, including shelf sandstones of the Bom Gosto and Barro Duro formations (Albian) and turbiditic sandstones of the Travosas Formation (Late Cretaceous-Paleogene) (Soares *et al.* 2007, Trosdtorf Junior *et al.* 2007).

DATASET AND METHODS

The data used in seismic interpretation correspond to post stack 2D seismic lines and well informations, all of which provided by the National Agency of Petroleum, Natural Gas and Biofuels (ANP). The location of seismic lines and well informations used are presented in Figure 2.

Seismic data consist of 15 seismic lines, with 10 in dip and 5 in strike direction. Nine lines are located at Pará-Maranhão basin and six lines at Barreirinhas basin. In addition, information of eight wells were used, being five in the Pará-Maranhão basin and three in the the Barreirinhas basin, all of them located in continental shelf and shelf border, with no information at deep and ultra-deep waters. In these cases, seismic information available in literature and well informations of shallow waters was extrapolated to that region. The well informations used include geophysical profiles, lithological description, hydrocarbons shows, geochemical and chronostratigraphic data. For the eight wells available for this paper, two are considered subcomercial oil producers, one is considered subcomercial gas producer, one is considered to contain gas, and four others are considered non-commercial or dry. The OpendTect® software was used for the interpretation of seismic data.The main published papers of both Brazilian and African equatorial basins used to help seismic interpretation was: Black (1984), Françolin & Szatmari (1987), Szatmari *et al.* (1987), Azevedo (1991), Silveira (1993), Brandão & Feijó (1994), Feijó *et al.* (1994), Silveira *et al.* (1994), Anjos (1999), Matos (1999, 2000), Schiefelbein *et al.* (2000), Mohriak (2003), Pasley *et al.* (2004), Zalán (2004), Basile (2005), Brownfield & Charpentier (2006), Milani *et al.* (2007), Soares *et al.* (2007), Trosdtorf Júnior *et al.* (2007), Soares Júnior *et al.* (2008), Jewell (2011), Nóbrega (2011), Soares Júnior *et al.* (2011), Fabianovicz (2013), Ferreira (2013), and Borsato *et al.* (2016).

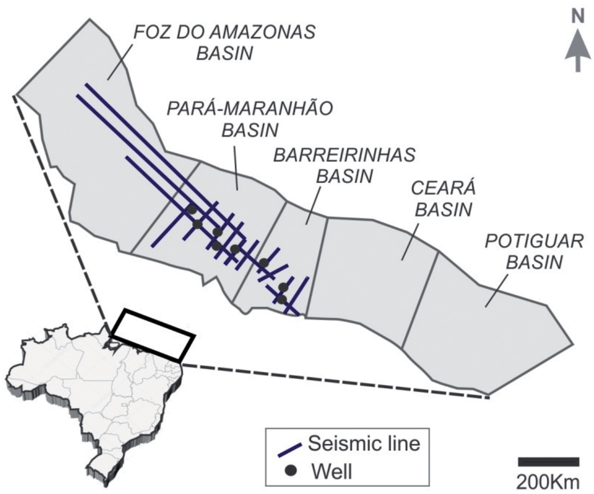


Figure 2. Location of seismic lines and wells.

Four main horizons and four main stratigraphic intervals were interpreted. The interpretation of possible sandy turbidites, considered as potential petroleum reservoirs, was made considering horizons with high reflectance, low frequency and lens geometry in 2D seismic data. Due to the quality of the 2D seismic data, the interpretation was mainly concentrated at deep basin and continental shelf, because the region of transition between these segments has noisy seismic data, making interpreting difficult and imprecise.

SEISMIC INTERPRETATION

Four major horizons were interpreted on studied seismic lines, which were chosen based on other seismic interpretations in the region, and based on the main unconformities present in the two basins (Silveira 1993, Silveira *et al.* 1994, Anjos 1999, Matos 1999, 2000, Brownfield & Charpentier 2006, Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007, Fabianovicz 2013, Ferreira 2013). A fifth horizon, the seabed, has not been interpreted since it is explicit, and consists in the top of the most recent sedimentary interval. The four interpreted horizons are Basement Top (BT), Albian Top (AT), Cretaceous Top (CT) and Oligocene Top (OT). These horizons delimit, respectively, the base of four sedimentary intervals, called Early Cretaceous (EK), Late Cretaceous (LK), Paleocene-Oligocene (P-O) and Miocene-Recent (M-R), whose top is the seafloor.

The oceanic basement is characterized by chaotic internal configuration and it is delimited on top by BT horizon (Fig. 3). The horizon is commonly cut by normal faults composing horsts and grabens (Fig. 4). An ocean ridge, a notable geomorphological feature, occurs at Pará-Maranhão basin seismic lines, attributed to São Paulo Transform Zone, which isolated the proximal depocenter of continental margin from its most distal portion towards the ocean basin. At seismic data of Barreirinhas basin does not occur the São Paulo Transform Fracture Zone because the basin is eastwards of its limit. The basement was better interpreted at deep basin region because the seismic lines lose resolution in deeper parts at continental shelf. According to Soares *et al.* (2007) and Trosdtorf Júnior *et al.* (2007), at continental shelf the basement of Pará-Maranhão basin is composed of São Luis Craton and Santa Luzia-Viseu Belt, while at Barreirinhas basin the basement is composed of São Luís Craton and Gurupi Belt. At deep/ultra-deep waters the basement is composed of basaltic rocks.

The EK interval overlays the BT horizon and presents subparallel to divergent internal reflections pattern with sheet and wedge external geometry, which are indicative of syn-tectonic deposition. The sequence top is the AT horizon, defined by reflectors with onlap terminations above its surface (Fig. 4). The Late Albian is characterized as the breakup, which is the moment when there was the rupture between South American and African paleocontinents. So this surface is characterized by a significant regional unconformity which occurs in both Pará-Maranhão and Barreirinhas basins, and is associated with eustatic fall caused by the South Atlantic opening (Matos 1999, 2000, Soares *et al.* 2007, Trosdtorf Júnior *et al*. 2007). The entire EK interval, as well as the underlying basement, is cut by normal faults, often showing horsts and grabens configuration, which is characteristic of the rift phase (Fig. 4).

In the seismic line 0275-09740 is possible to observe an abrupt change in reflectors inclination present in EK interval (Fig. 4), which can be attributed to an unconformity between the Aptian and Albian. This unconformity is well characterized in the literature and stratigraphic charts of the basins, and is attributed to change from an anoxic evaporitic marine environment to marine shelf, which marks the transition from sag basin pre-rift stage to rift stage (Soares *et al.* 2007, Trosdtorf Júnior *et al*. 2007).

The LK interval overlays the AT horizon, and presents internal configuration ranging from parallel to subparallel reflections of low continuity and sheet external geometry at continental shelf and deep basin, and also shows chaotic internal configuration which are characteristic of mass transport deposits (Fig. 5) at deep basin. In the context of studied area, this sequence is attributed to shallow marine deposition with high energy sands deposition of Areinhas Formation, and carbonates deposition of Bonfim and Ilha de Santana formations in low energy at continental shelf. At deep basin, this sequence is interpreted as uniform and predominantly pelitic deposition in conformity with underlying surface, in a low energy deep marine environment attributed to Travosas Formation. Moreover, is also common the presence of sandy turbidites attributed

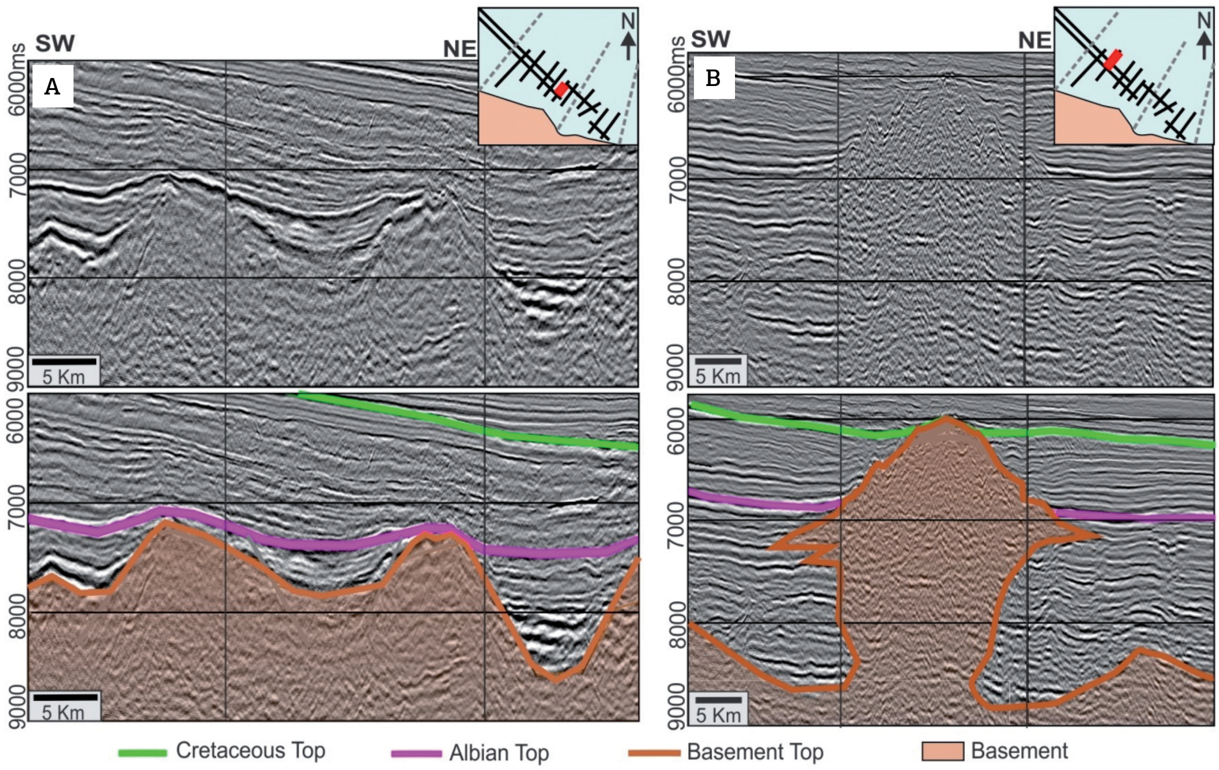


Figure 3. In (A) is presented 0270-3019 seismic line (Two Way Time—TWT vertical scale) showing basement with chaotic internal configuration. In (B) is presented 0270-3010 seismic line (TWT vertical scale) showing magmatic intrusion into overlying sedimentary package with chaotic internal configuration.

to Travosas Formation inside the pelites of the same formation (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007). The top of the sequence is the CT horizon, which is defined by onlap terminations above its surface and occurs as a regional unconformity in the stratigraphic charts of Pará-Maranhão and Barreirinhas basins (Fig. 5).

The P-O interval overlays the CT horizon and presents subparallel to complex sigmoid-oblique internal configuration with sheet and slope filling external geometry at continental shelf (Fig. 6A). Parallel reflections with medium to high continuity configurations occurs at deep basin, indicating lithological alternations and sheet external geometry, besides chaotic internal configuration which are characteristic of mass transport deposits (Fig. 6B). The continuity of the reflections decreases in continental shelf, probably indicating the greater presence of sands associated with depositional processes of higher energy. Unit top is the OT horizon, which is characterized by reflectors in conformity in continental shelf and by onlap terminations at deep basin (Fig. 6B). At the faulted shelf border the reflectors are often folded and may also show a disrupted pattern due to the large number of synthetic listric faults present in this margin segment (Fig. 6C). The interval is associated to deposition of sandy lithotypes of Areinhas Formation and carbonates of Ilha de Santana Formation at continental shelf, and deposition of pelites and sandy turbidites of Travosas Formation at the most distal segments (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007). According to mentioned authors, there is a regional unconformity present in Brazilian equatorial basins stratigraphic charts related to the Oligocene interval, which is assigned to OT horizon of this study.

The M-R interval overlays OT horizon and is characterized by parallel internal configuration, sometimes showing contorted configuration, with medium to high continuity and sheet external geometry (Fig. 7A). The relative continuous reflectors indicate existence of lithological alternation between fine sands and clays. The sequence may also present free pattern and sheet external geometry, which indicates the presence of homogeneous or non-stratified lithologies related to hemipelagites. As well as last intervals mentioned before,

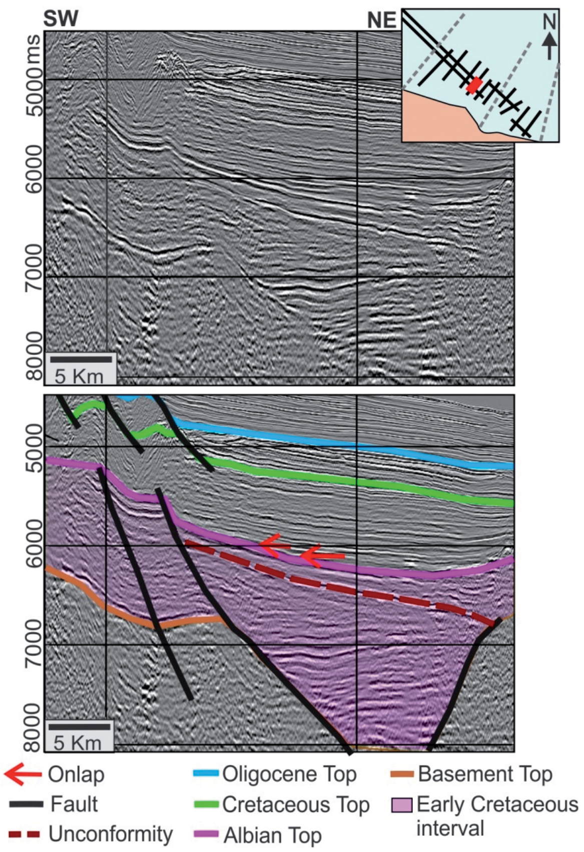


Figure 4. 0275-09740 seismic line (TWT vertical scale) with emphasis on Early Cretaceous interval and Albian Top horizon. The Early Cretaceous interval is characterized by subparallel to divergent internal reflections pattern, and Albian Top horizon is defined by reflectors with onlap terminations above its surface. The dashed red line is attributed to an unconformity between the Aptian and Albian. The basement and Early Cretaceous intervals are often cut by normal faults characteristics of rift phase.

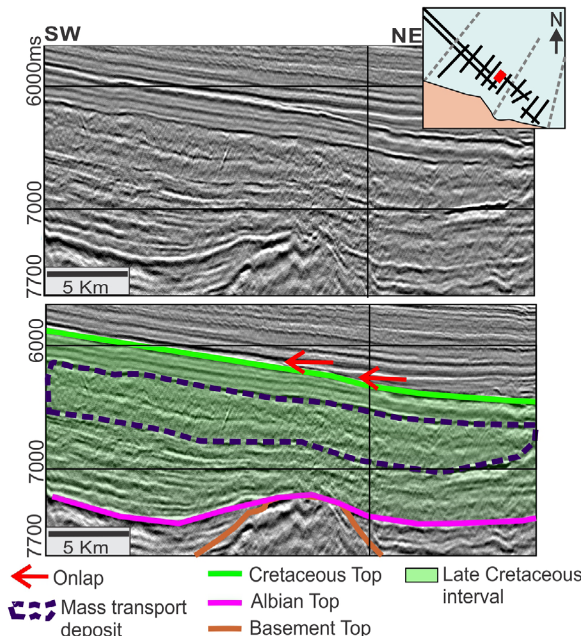


Figure 5. 0270-3019 seismic line (TWT vertical scale) with Late Cretaceous interval and Cretaceous Top horizon at deep basin. The interval is characterized by parallel to subparallel reflections of low continuity internal configurations, and chaotic seismic facies which are characteristic of mass transport deposits. The Cretaceous Top horizon is defined by reflectors with onlap terminations above its surface.

M-R interval is characterized by the presence of synthetic listric faults which occur predominantly at the shelf border, often showing reflectors with folded pattern (Fig. 7B). This interval is also related to deposition of sandy lithotypes of Areinhas Formation and carbonates of Ilha de Santana Formation at continental shelf, and deposition of pelites and sandy turbidites of Travosas Formation at the most distal segments (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007).

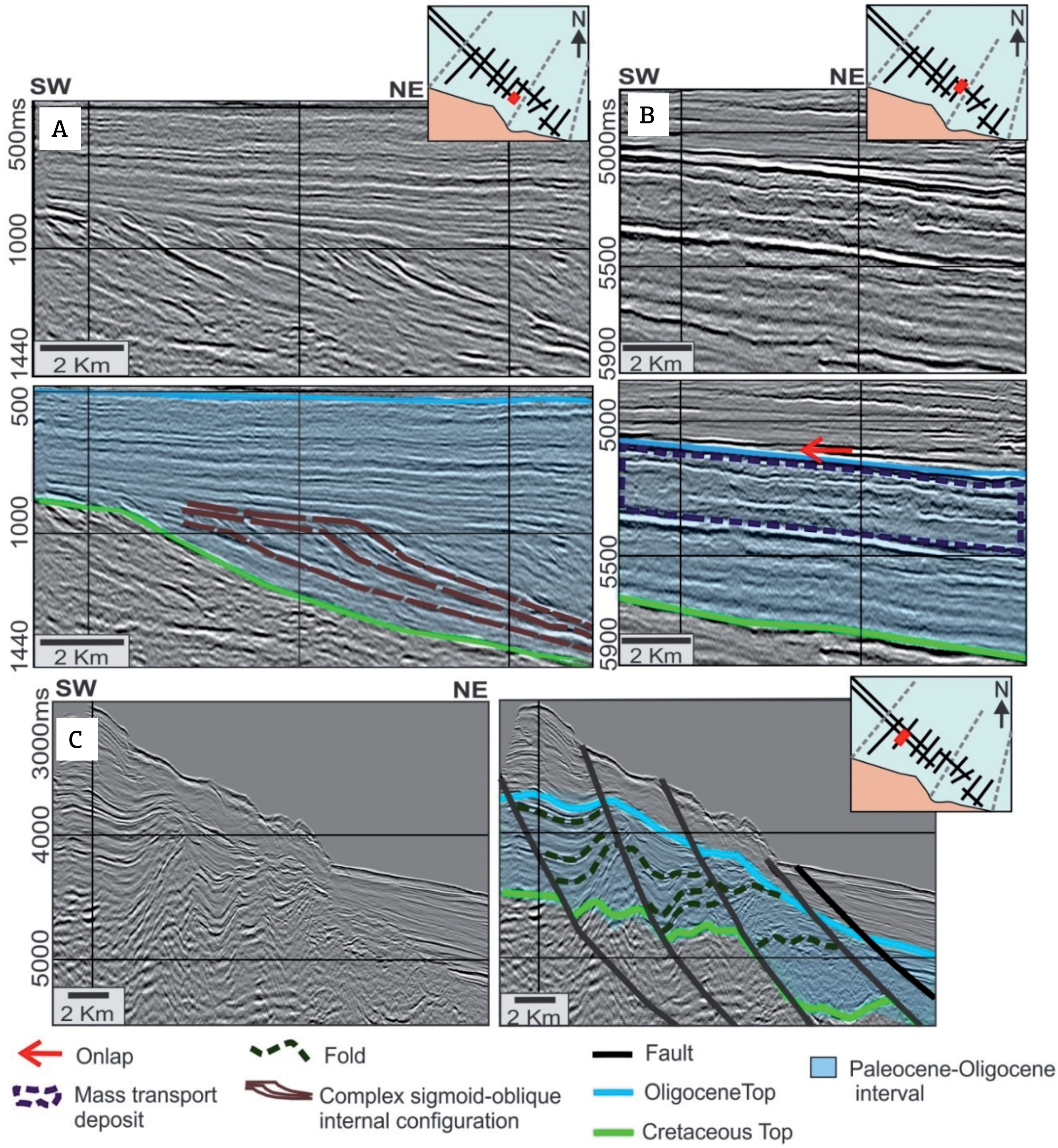


Figure 6. In (A) is presented 0275-01180 seismic line (TWT vertical scale) at continental shelf, showing Paleocene-Oligocene interval with internal configuration ranging from parallel to complex sigmoid-oblique. In (B) is presented 0275-01180 seismic line (TWT vertical scale) at deep basin, showing Paleocene-Oligocene interval with parallel internal configuration and chaotic internal configuration which are characteristic of mass transport deposits. The Oligocene Top horizon is characterized by onlap terminations above its surface. In (C) is presented 0270-3010 seismic line (TWT vertical scale) at shelf border, showing Paleocene-Oligocene interval with folded internal configuration due to listric faults present at this margin segment.

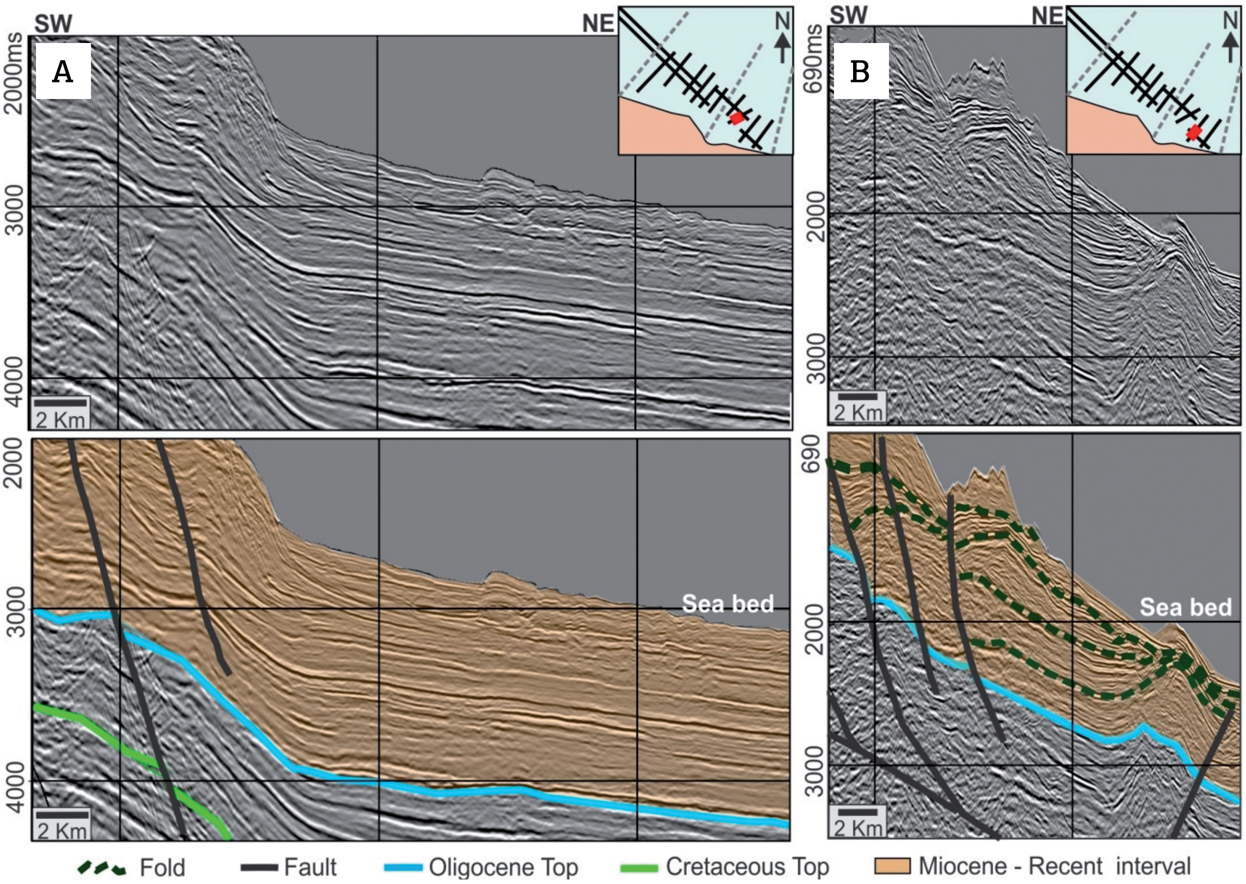


Figure 7. In (A) is presented 0239-247 seismic line (TWT vertical scale) at deep basin showing Miocene-Recent interval, which presents contorted and parallel internal configuration with medium to high continuity and sheet external geometry. In (B) is presented 0239-209 seismic line (TWT vertical scale) at shelf border, showing Miocene-Recent interval with folded internal configuration due to listric faults present at this margin segment.

CONSIDERATIONS ABOUT SOME IMPORTANT STRUCTURAL FEATURES

The analysis of the seismic sections suggests a difference in the structural styles of the intervals deposited above and below the AT horizon. The structural framework of Basement and EK sequences is characterized by the presence of large synthetic and antithetical normal faults, commonly configuring horsts and grabens (Fig. 8), which were formed during rift stage of Brazilian equatorial margin and persisted until the end of Albian (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007). The structural framework of LK, P-O and M-R sequences is characterized by synthetic and antithetic listric faults which occur mainly at the shelf border (Fig. 8). This same type of fault also occurs at SW and NE border of São Paulo Transform Zone. This set of faults generates a series of rollovers anticlines, apparently with axes in NW-SE direction, which can work as trap for hydrocarbons. The age of this set of faults is post-transformant stage because it affects almost all stratigraphic sequence of the basins, with the exception of post Oligocene thin sedimentary cover deposited during drift tectonics. In some seismic lines of Barreirinhas Basin, reverse faults at continental rise related to this same tectonic event were interpreted, as shown in Figure 9.

The São Paulo Transform Zone corresponds to one of the most expressive transformant fault zone of the planet. In the seismic sections of Pará-Maranhão basin this feature occurs as a notable ocean ridge which isolated the proximal depocenter of continental margin from its most distal portion towards the ocean basin (Fig. 8). At Barreirinhas basin this feature does not occur because the basin is located eastwards of São Paulo Transformant Zone limit.

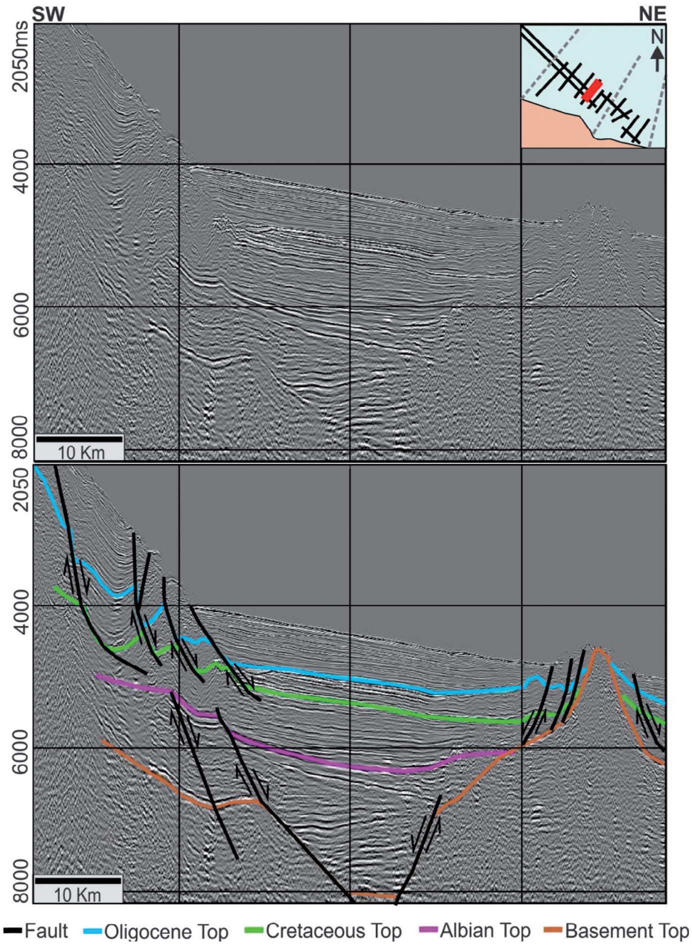


Figure 8. 0235-09740 seismic line (TWT vertical scale) showing two set of faults. The first one occurs in pre-Albian units and is related to rift phase, which is characterized by horsts and grabens configuration. The second occurs in post-Albian units and are related to listric faults at shelf border and to São Paulo Transform Zone border at deep waters.

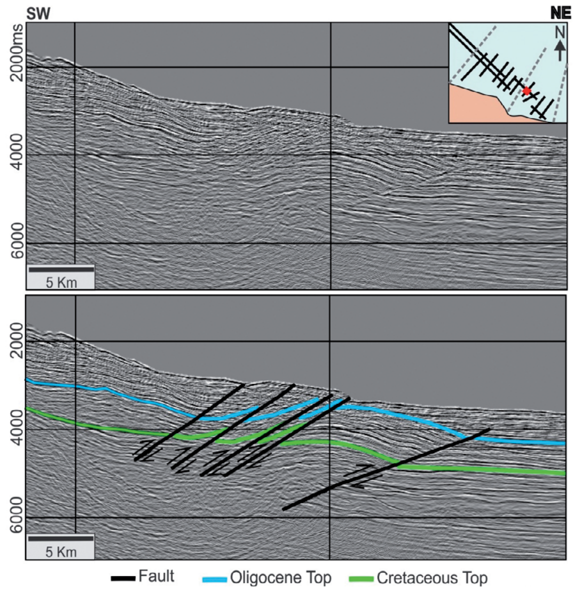


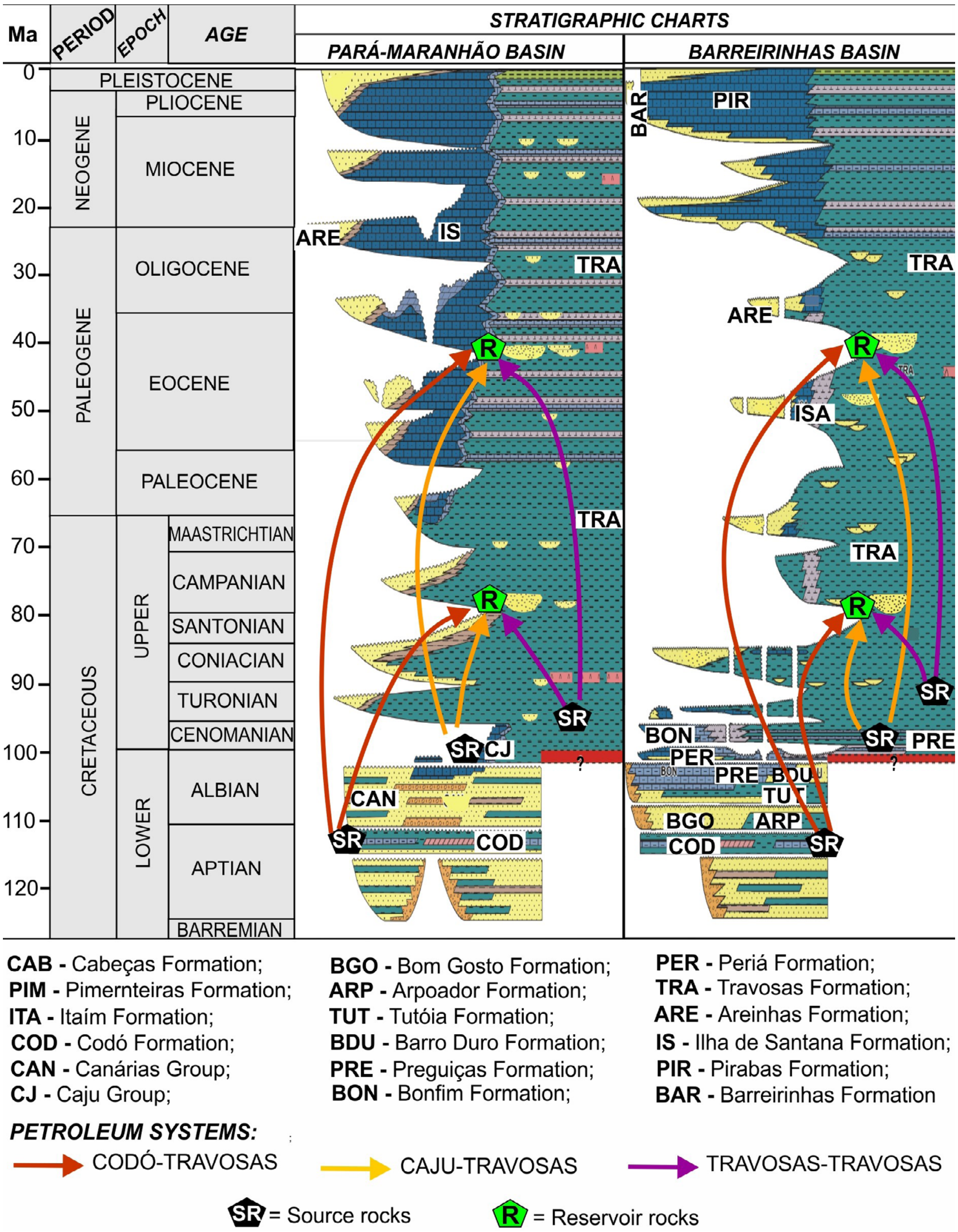
Figure 9. 0239-0163 seismic line (TWT vertical scale) showing reverse faults at continental rise of the Barreirinhas basin.

PETROLEUM SYSTEMS

The main source rocks of Pará-Maranhão and Barreirinhas basins are marine shales of Pimenteiras Formation (Devonian), lagoons and anoxic evaporitic marine shales of Codó Formation (Aptian); calcilutites and marine shales of Caju Group (Albian-Cenomanian) and marine shales of Travosas Formation (anoxic events of Cenomanian-Turonian) (Soares *et al.* 2007; Trosdtorf Júnior *et al.* 2007, Fabianovicz 2013, Ferreira 2013). According to Schiefelbein *et al.* (2000), correlated oil samples of these basins has transitional marine origin and mixture of organic matter of lacustrine and marine origin.

The main reservoirs of Pará-Maranhão basin are fluvial-deltaic sandstones of the Canárias Group (Albian), fractured limestones, banks, reefs, talus and carbonate turbidites of the Ilha de Santana Formation (Paleogene) and turbiditic sandstones of the Travosas Formation (LK to Paleogene). The main reservoirs of the Barreirinhas basin correspond to marine sandstones of the Bom Gosto and Barro Duro formations (Albian) and turbiditic sandstones of the Travosas Formation (LK to Paleogene) (Soares *et al.* 2007, Trosdtorf Júnior *et al.* 2007, Fabianovicz 2013, Ferreira 2013).

Although there are others possible petroleum systems, this research focused on identification of plays associated to turbiditic sandstones of Travosas Formation, which can be correlated to Jubilee play in Guinea Gulf and Zaedyus play in French Guiana. In this way, three possible petroleum systems were identified in the seismic lines of both Pará-Maranhão and Barreirinhas: Codó-Travosas (source rock from Aptian and reservoir from LK to Paleogene), Caju-Travosas (source rock from Albian-Cenomanian and reservoir from LK to Paleogene) and Travosas-Travosas (source rock from Cenomanian-Turonian and reservoir from LK to Paleogene). The Figure 10 shows the stratigraphic charts



Source: modified from Soares *et al.* (2007), Trosdtorf Júnior *et al.* (2007).

Figure 10. Pará-Maranhão and Barreirinhas basins stratigraphic charts showing the identified possible petroleum systems.

of Pará-Maranhão and Barreirinhas basins showing these petroleum systems identified in this research.

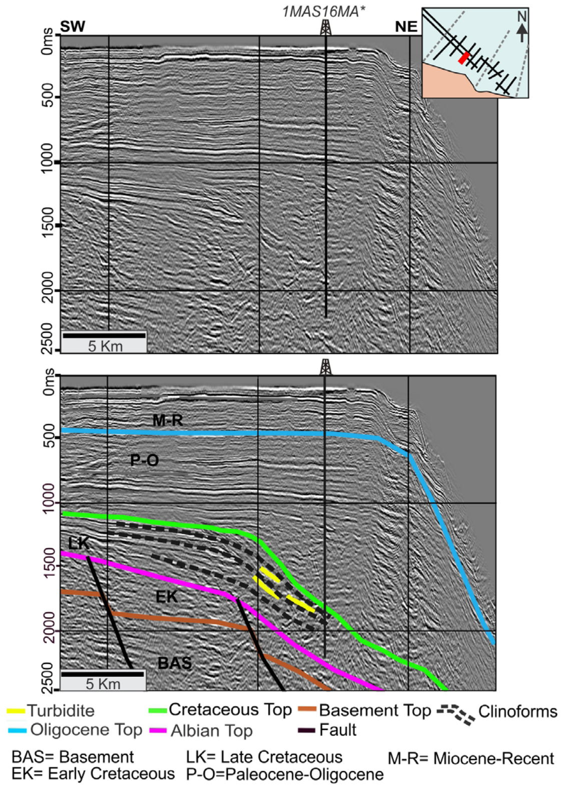
The interpreted turbiditic sandstones have reflectors with high acoustic impedance contrasts, low frequency, lense external geometry and longitudinal extension variable, ranging from 1 to 15 km. This seismic facies was identified in three distinct segments of the margin: shallow waters, faulted shelf border and deep/ultra-deep waters. Turbidites of shallow waters generally have the smallest extension and are identified at the base of progradant clinoforms, with internal configuration ranging from oblique tangential to oblique-sigmoidal complex. Turbidites associated to faulted shelf border are limited by listric faults and commonly occur at rollover anticlines. The turbidites of deep/ultra-deep waters are the most extensive, reaching up to 15 km, and are commonly associated with mass transport deposits.

In this way, as the main plays focused in this paper are associated to turbidites, such plays were also identified in three distinct segments of the margin: shallow waters play, faulted shelf border play and deep/ultra-deep waters play. The last one is the most importante in this research, since it is correlated to Jubilee play in Guinea Gulf and Zaedyus play in French Guiana.

Shallow waters turbidite plays

The plays of shallow waters occur as turbidites at progradant clinoforms base of continental shelf (Fig. 11) and belong to Travosas Formation (LK). The possible source rock could be the marine shales and calcilutites of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation (Cenomanian-Turonian), and migration occurs directly from source rock to reservoir as shown in Figure 12. The seal rocks are also the shales of Travosas Formation, and the trap is of stratigraphic type by depositional pinch-out.

Seven wells information available for this research present geochemical data obtained from lateral sample or drill cuttings, and 543 samples were analyzed for the percentage of Total Organic Carbon (TOC), corresponding only 245 samples to Albian to Turonian source rock interval. These measurements were obtained both in shales with intercalations of siltite, sandstones, marls, calcisiltites and limestones belonging to Travosas Formation. From these 245 samples, 116 present TOC below 0.5%, and there is no potential as source rocks; 62 samples present TOC between 0.5 e 1.0%, with low potential as source rock in the case of carbonate rocks; 58 samples present TOC between 1.0 e 1.5%, with some potential as source rocks; and only 9 samples present TOC above 1.5%, reaching a maximum of 1.66%.



*Well location is projected.

Figure 11. 0275-8780 seismic line (TWT vertical scale) showing the play associated to shallow water turbidites of Late Cretaceous at the base of progradant clinoforns.

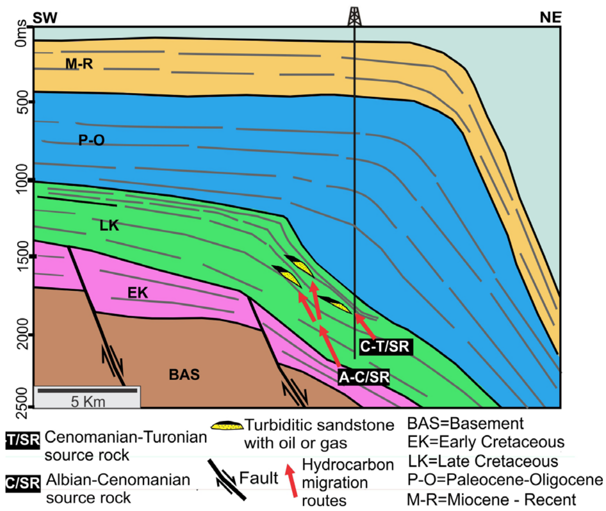


Figure 12. Schematic geological section based on the seismic line 0275-8780 (TWT vertical scale), showing the play associated to shallow water turbidites of the Late Cretaceous. The hydrocarbon generated by source rocks of the Caju Group (Late Albian-Early Cenomanian) and Travosas Formation (Cenomanian-Turonian) migrated to turbiditic sandstones of the Travosas Formation (Late Cretaceous). The trap is stratigraphic type, consisting in sandstones inside shales. The red arrows indicate the possible hydrocarbon migration routes. The well location is projected.

Considering the Hydrogen Index (mgHC/gTOC) versus Oxygen Index (mgCO2/gTOC) of the samples from Albian to Turonian obtained from the wells, it was verified that they have mainly Type II and Type III organic matter. According to Tissot & Welte (1984), Type II organic matter, which is derived from autochthonous marine organic matter deposited in a reducing environment, is favorable to oil and gas generation, while Type III organic matter, which are originated from terrestrial plants, is favorable to gas generation at great depths.

A total of 208 samples from six wells was used for Maximum Temperature (Tmax) analysis. Of these, 11 samples have Tmax below 400ºC, and 164 samples have Tmax between 400 and 440ºC and are considered immature according to Tissot & Welte (1984). On the other hand, 28 samples presented Tmax between 440 and 470ºC, and are considered at mature zone. Finally, only five samples presented Tmax above 470°C and are considered senile.

According to well data, the depth of Late Albian-Early Cenomanian and Cenomanian-Turonian source rocks at the continental shelf of Pará-Maranhão and Barreirinhas basins occurs approximately between 2,400 and 3,700 m below sea water bottom. At this depth, there is the possibility of oil and gas generation, and more details will be discussed in the next topics.

Faulted shelf border turbidite plays

The play of faulted shelf border occurs as turbidite lenses limited by a set of synthetic and antithetic listric faults and belong to Travosas Formation (LK to P-O) as presented in Figure 13. The possible source rock could be the marine shales and calcilutites of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation itself (Cenomanian-Turonian), and migration occurs through listric faults from the source rocks to the reservoir (Fig. 14). The seal rocks are also the shales of Travosas Formation and the traps are dominantly of mixed type, with depositional pinch-out and strong structural component of rollovers anticlines and associated faults.

The depth of Late Albian-Early Cenomanian and Cenomanian-Turonian source rocks was obtained by approximation, based on the horizons interpreted in seismic data. The sedimentary package as a whole has average seismic depth between 1,100 and 3,500 ms below sea water bottom at Pará-Maranhão basin, and between 1,000 and 3,700 ms at Barreirinhas basin. For conversion of time to depth, it was used an average velocity obtained from the Vertical Seismic Profile (VSP) well data of shallow waters. The average speed used for the sedimentary package as a whole was 2,600 m/s, while the average speed for water was 1,500 m/s. Based on this data, it was inferred that Late Albian-Early Cenomanian and Cenomanian-Turonian source rocks occur approximately between 1,400 and 4,500 m below sea water bottom at Pará-Maranhão basin, and approximately between 1,300 and 4,800 m below sea water bottom at Barreirinhas basin. In these depths, there is the possibility of oil and gas generation, however the possibility of oil biodegradation to the shallower reservoirs must be considered. More details will be discussed in the next topics.

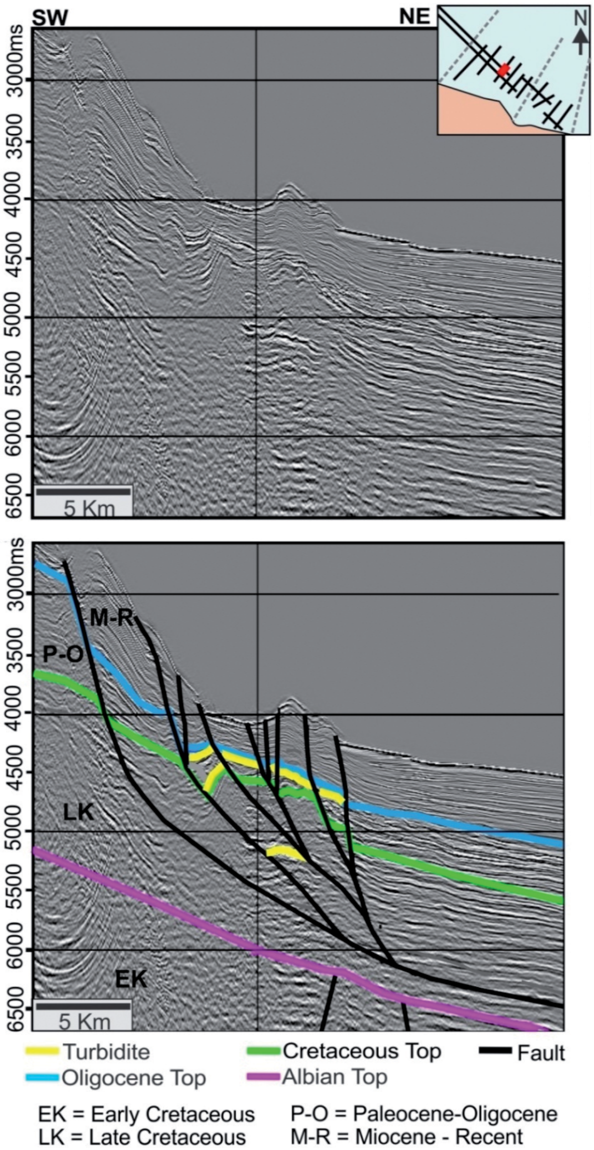


Figure 13. 0275-8780 seismic line (TWT vertical scale) showing probable play associated to faulted shelf border turbidites of the Late Cretaceous and Paleocene-Oligocene.

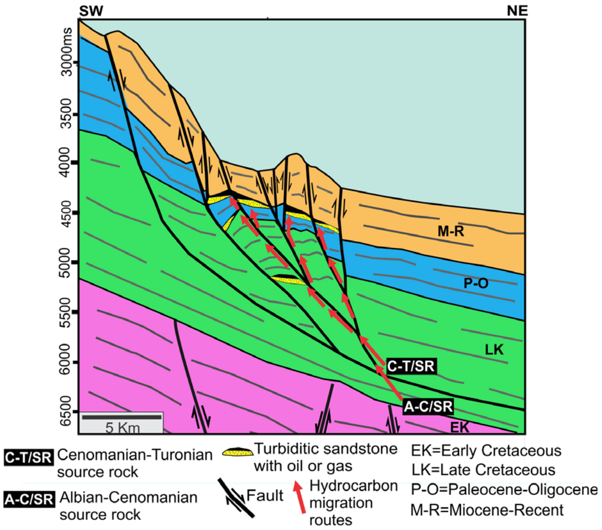


Figure 14. Schematic geological section based on the seismic line 0275-8780 (TWT vertical scale), showing the play associated to faulted shelf border turbidites of the Late Cretaceous and Paleocene-Oligocene. Hydrocarbons generated by source rocks of the Caju Group (Late Albian-Early Cenomanian) and Travosas Formation (Cenomanian-Turonian) migrated by listric faults to turbiditic sandstones of Travosas Formation (Late Cretaceous to Paleocene-Oligocene). The trap may be stratigraphic and/or structural type. The red arrows indicate the possible hydrocarbon migration routes.

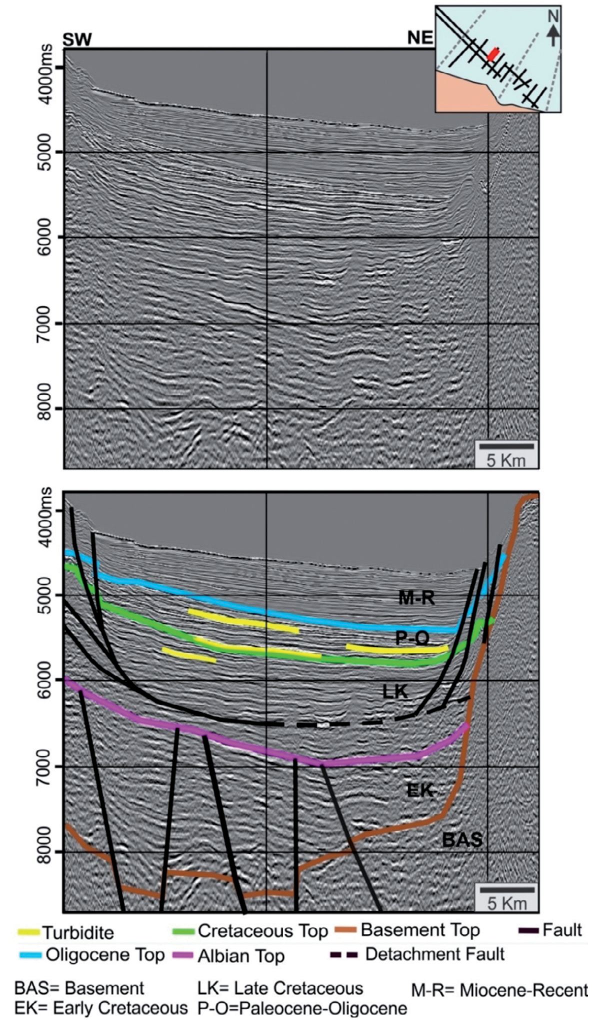


Figure 15. 0275-8780 seismic line (TWT vertical scale) showing the play associated to ultra-deep water turbidites of Late Cretaceous to Paleocene-Oligocene.

Deep/ultra-deep waters turbidite plays

The play of deep and ultra-deep waters occurs as lenses of turbidites and belongs to Travosas Formation (LK and P-O) as shown in Figure 15. There are three possibles source rocks for this play: the lagoon shales of the Codó Formation (Aptian), marine shales of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation (Cenomanian-Turonian). In the first case, the hydrocarbons generated by shales of the Codó Formation migrated through the contact between intrusive rocks of São Paulo Transform Zone and basin sedimentary package and then by listric normal faults towards turbidites of the Travosas Formation. In the second case, the hydrocarbons generated by shales of the Caju Group migrated through the listric faults to turbidites of the Travosas Formation or migrate directly from source rock to turbidites. In the third case, the hydrocarbons generated by shales of the Travosas Formation migrated through the listric faults to turbidites of the Travosas Formation or migrate directly from source rock to reservoir. The seal rocks are the shales of the Travosas Formation itself, and the trap is stratigraphic type (depositional pinch-out). The schematic geological section with this play is presented in Figure 16.

The approximate depth of source rocks from Aptian, Late Albian-Early Cenomanian and Cenomanian-Turonian was obtained by approximation, based on the horizons interpreted in seismic data. These source rock intervals were identified only in seismic lines of Pará-Maranhão basin, since the seismic lines of Barreirinhas basin have poor resolution in depth, and are not possible to make an accurate interpretation. The Aptian source rock has average seismic depth from 2,200 to 3,500 ms below sea water bottom, and the Late Albian-Early Cenomanian/ Cenomanian-Turonian source rocks have average seismic depth from 1,100 to 2,900 ms. For conversion of time to depth an average velocity obtained from the VSP wells data located at continental shelf was used. Thus, the average speed used to the sedimentary package as a whole was 2,600 m/s, while the average speed for water was 1,500 m/s. Based on this data, it was inferred that the Aptian source rock depth is aproximately from 2,860 to 4,550 m

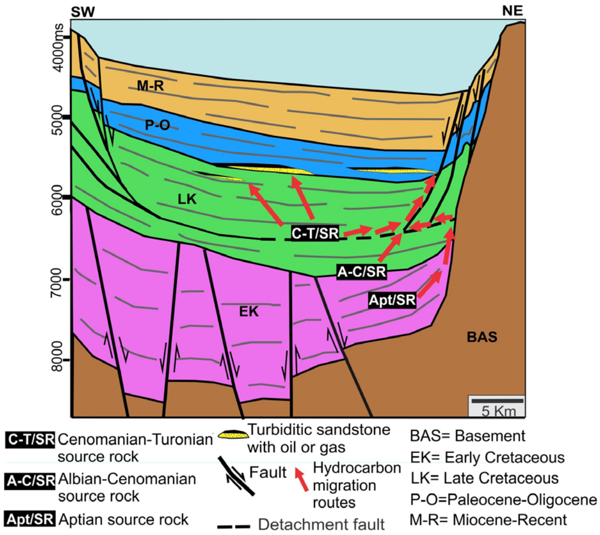


Figure 16. Schematic geological section based on the seismic line 0275-8780 (TWT vertical scale), showing the play associated to deep/ultra-deep water turbidites of the Late Cretaceous and Paleocene-Oligocene. The hydrocarbons generated by source rocks of the Codó Formation (Aptian) migrated through the contact between the intrusive rocks of São Paulo Transform Zone and basin sedimentary package, and then through the listric faults to turbidites of the Travosas Formation (Paleocene-Oligocene). The hydrocarbons generated by source rocks of the Caju Group (Albian-Cenomanian) migrated through listric faults to turbidites of the Travosas Formation. The hydrocarbons generated by source rocks of the Travosas Formation (Cenomanian-Turonian) migrated through listric faults to turbidites of the Travosas Formation or migrate directly from source rock to reservoir. The red arrows indicate the possible hydrocarbon migration routes.

below sea water bottom, the Late Albian-Early Cenomanian source rock depth should be approximately from 2,200 to 3,800 m, and Cenomanian-Turonian source rock depth should be approximately from 1,430 to 2,860 m.

It is also important to consider the proximity of the deep/ultra-deep waters play with the intrusive rocks of the São Paulo Transform Zone, which may have warmed those source rocks constituting an atypical petroleum system. Thus, although the source rocks may be at maturity depth, it can also be senile due to the high anomalous temperatures.

DISCUSSION

As mentioned before, the Pará-Maranhão and Barreirinhas basins are considered correlate to Ivory Coast and Tano basins of the Guinea Gulf, and there are similarities between existing petroleum systems, including source rocks with similar characteristics and formed at same geological time interval, as well as reservoirs with the same characteristics related to turbiditic sandstones, as shown in Table 1.

Table 1. Comparison between the source rocks and reservoirs of Pará-Maranhã/Barreirinhas basins with Guinea Gulf basins.

Pará-Maranhão and Barreirinhas Basins	Guinea Gulf Basins
Source rocks	**Source rocks**
Devonian-transitional marine shales (Pimenteiras Formation)	Devonian-marine shales
—	Neocomian-lacustrine shales
Aptian lagoon shales (Codó Formation)	—
—	Middle Albian - terrestrial shales
Late Albian to Early Cenomanian - marine shales and calcilutites (Caju Group)	Late Albian - marine shales
Cenomanian-Turonian - marine shales (Travosas Formation)	Cenomanian-Turonian - marine shales
Reservoirs	**Reservoirs**
Late Cretaceous to Paleogene - turbidites (Travosas Formation)	Cretaceous – turbidites

Source: based on Brownfield & Charpentier (2006), Soares *et al.* (2007), Trosdtorf Júnior *et al.* (2007), Fabianovicz (2013), Ferreira (2013).

The Pará-Maranhão and Barreirinhas basins have marine source rocks from Devonian (Pimenteiras Formation), and Guinea Gulf basins also have Devonian marine source rocks known according to Brownfield & Charpentier (2006). According to the same author, there is a known source rock in Guinea Gulf from Neocomian lacustrines shales in the northern Dahomey Embayment, Congo basin and Ivory Coast basin, but which were not found in the studied Brazilian basins. The source rocks from Aptian of the Codó Formation present in both Pará-Maranhão and Barreirinhas basins have lagoon and marine evaporitic anoxic origin according to Soares *et al.* (2007) and Trosdtorf Júnior *et al.* (2007), and there is no source rock of this origin in the Gulf of Guinea. The source rocks related to Middle Albian in the Guinea Gulf, consisting of gas-prone terrestrial source rocks, and there is no correspondence in the Brazilian basins. The Late Albian source rock, consisting of marine transgressive oil-prone source rocks present in the Guinea Gulf basins (Brownfield & Charpentier 2006), may be correlated to the source rocks from Late Albian-Early Cenomanian of the Caju Group, present in both Pará-Maranhão and Barreirinhas basins, which is composed of shales and cacilutites deposited in a transgressive marine depositional environment according to Soares *et al.* (2007) and Trosdtorf Júnior *et al.* (2007).

Finally, the source rocks from Cenomanian-Turonian of the Travosas Formation present in Pará-Maranhão and Barreirinhas basins may be correlated to marine black shales related to anoxic events of Cenomanian-Turonian of the Guinea Gulf basins. According to Brownfield & Charpentier (2006), anoxic oceanic conditions that characterized the Middle Cretaceous and continued into the Turonian worldwide affected the Gulf of Guinea resulting in the deposition of black shale source rocks from Cenomanian-Turonian in the Ivory Coast and Tano basins. Samples analyzed from deep sea drilling sites both north and south of the Gulf of Guinea indicate that these source rocks contain more than 10% of organic matter consisting in Type II kerogen. According to Mello *et al.* (1989), the anoxic conditions also prevailed during most of the Cenomanian-Santonian interval in the Brazilian continental margin too. The anoxic events in the Brazilian basins were intermittent, rather than continuous, covering relatively short periods of time, most of them associated with sea level rises. The black shales of Cenomanian-Turonian present in both Brazilian and African margins were deposited under the anoxic conditions of the Second Cretaceous Global Oceanic Anoxic Event (OAE-2), characterized by periods of deposition of shale facies enriched in organic matter in almost every ocean of the world (Mello *et al.* 1989, Schiefelbein *et al.* 2000).

According to MacGregor *et al.* (2003) and Brownfield & Charpentier (2006), the most important source rocks within Guinea Gulf Province are Albian, Cenomanian and Turonian marine shales, with Type II and II-III oil-prone kerogen and Type III terrestrial kerogen. These source rocks are distributed throughout the offshore part of the Guinea Gulf Province, and are expected to increase in thickness and quality into deep waters. Two main areas of hydrocarbon generation were interpreted by MacGregor *et al.* (2003): the offshore of Ivory Coast and Tano basins; the offshore of Keta and Benin basins and the Dahomey Embayment.

These two probable "oil kitchens" are only present in deep waters, where the source rocks have reached a temperature of at least 100ºC and a vitrinite reflectance of 0.6%, which are values equivalent to source rock below 2,700 m of overburden. Heat flow may increase into the deep waters, as continental crust is thinner, giving shallower generation thresholds. According to MacGregor *et al.* (2003), for the Guinea Gulf basins the hydrocarbon generation started in the Late Cretaceous for the Albian to Cenomanian source rocks and continues to the present. For the Turonian source rocks, hydrocarbon generation possibly started in the Early Tertiary and also continues to the present. The reservoir rocks in Guinea Gulf are mostly Cretaceous turbidite sandstones with minor potential of limestone units, and the migration was either directly from adjacent source rocks or upward along faults from deeper source rocks. The seals correspond to marine shales with minor fault-related seals, while the traps include pre-transform traps related to fault blocks, syn-transform structural and stratigraphic traps, and post-transform stratigraphic traps (Brownfield & Charpentier 2006).

According to Dickson *et al.* (2016), total sediment thicknesses along both transform margins of South America and Africa exceed values associated with source maturity, depending on source position within the sediment column. According to the same authors, oils and other hydrocarbon evidence attest to the presence of working source rocks along both margins, and effective Cretaceous (Cenomanian–Turonian and possibly Albian) marine source rocks intervals have been demonstrated in oils sample set for both margins.

Assuming that the approximate oil window top depth occurs at 2,700 m bellow sea water bottom in the offshore of Guinea Gulf according to MacGregor *et al.* (2003), it can be inferred that source rocks of Pará-Maranhão and Barreirinhas basins must be at the oil window depth too, since the source rocks of those basins reached the burial depth equal to or greater than 2,700 m bellow sea water bottom in all the plays (shallow waters, faulted shelf border and deep/ultra-deep waters). The source rocks of Late Albian-Early Cenomanian and Cenomanian-Turonian, for example, would beat an approximate depth from 2,400 to 3,700 m below sea water bottom at shallow waters and from 1,300 to 4,800 m below sea water bottom at faulted shelf border. At deep/ultra-deep waters the source rocks from Aptian would be at an approximate depth from 2,860 to 4,550 m, the source rocks of Late Albian-Early Cenomanian would be from 2,200 to 3,800 m, while the source rocks of Cenomanian-Turonian would be from 1,430 to 2,860 m below sea water bottom.

It is also important to consider the proximity of the deep/ultra-deep waters play with the intrusive rocks of the São Paulo Transform Zone, which may have warmed those source rocks composing an atypical petroleum system. However, although the source rocks may be at maturity depth, it may also be senile due to the high anomalous temperatures.

Finally, although all interpreted plays (shallow waters, faulted shelf border and deep/ultra-deep waters) should reached the burial depth for oil /gas generation, it is important to emphasize that the greatest interest of this research are related to the deep/ultra-deep waters play, since Jubilee and Zaedyus plays are also located in deep/ultra-deep waters.

CONCLUSION

Four major seismic horizons were interpreted: BT, AT, CT and OT. These horizons delimit the base of four seismic stratigraphic intervals, named EK, LK, P-O and M-R, whose top of the latter is the seafloor.

The structural analysis of the seismic lines suggests two different structural styles. The first one occurs in the Pre-Albian interval and is composed by large normal faults, commonly configuring horsts and grabens, which were formed during rift stage of Brazilian equatorial margin and persisted until the end of Albian. The second occurs in Post-Albian interval and is characterized by synthetic and antithetic listric faults which occur mainly at the shelf border and also at São Paulo Transform Zone border. These listric faults compose a series of rollovers anticlines, apparently with axes in NW-SE direction, which can work as trap for hydrocarbons.

Although there are others possible plays in Pará-Maranhão and Barreirinhas basins, this research focused on identification of plays associated to turbiditic sandstones of the Travosas Formation, which may be correlated to Jubilee play in Guinea Gulf and Zaedyus play in French Guiana. So, three play types in three distinct segments of the continental margin were identified: shallow waters, faulted shelf border, and deep/ultra-deep waters. The deep/ultra-deep waters play is the most extensive and more important, since it is correlated to Jubilee and Zaedyus plays, which are also in deep/ultra-deep waters.

The plays of shallow waters occur as turbidites at progradant clinoforms base of continental shelf and belong to Travosas Formation (LK). The possible source rock could be the marine shales and calcilutites of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation (Cenomanian-Turonian), and migration occurs directly from source rock to reservoir. According to well data, the depth of the Late Albian-Early Cenomanian and Cenomanian-Turonian source rocks at the continental shelf occurs approximately from 2,400 to 3,700 m below sea water bottom.

The faulted shelf border play occurs as turbidites lenses limited by a set of listric faults and belong to Travosas Formation (LK to P-O). The possible source rock would be the marine shales and calcilutites of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation itself (Cenomanian-Turonian), and migration occurs through listric faults from the source rocks to the reservoir. The depth of the Caju Group (Late Albian-Early Cenomanian) and Travosas Formation (Cenomanian-Turonian) source rocks intervals was obtained by approximation, based on the horizons interpreted in seismic data, and occurs at depths approximately from 1,300 to 4,800 m below sea water bottom.

The deep/ultra-deep waters play occurs as lenses of turbidites and belongs to Travosas Formation (LK to P-O). There are three possible source rocks for this play: the lagoon shales of the Codó Formation (Aptian), calcilutites and marine shales of the Caju Group (Late Albian-Early Cenomanian) and marine shales of the Travosas Formation (Cenomanian-Turonian). In the first case, the hydrocarbons generated by shales of the Codó Formation migrated through contact between intrusive rocks of São Paulo Transform Zone with basin sedimentary package and then by listric normal faults towards turbidites of the Travosas Formation. In the second case, the hydrocarbons generated by shales of the Caju Group migrated through listric normal faults to turbidites of the Travosas Formation or migrate directly from source rock to turbidites. In the third case, the hydrocarbons generated by shales of the Travosas Formation migrated through listric normal faults to turbidites of the Travosas Formation or migrate directly from source rock to turbiditic reservoirs. The source rocks depths of the Codó Formation (Aptian) are approximately 2,860 to 4,550 m below sea water bottom, for the Caju Group (Late Albian-Early Cenomanian) should be approximately from 2,200 to 3,800 m, and for Travosas Formation (Cenomanian-Turonian) should be from 1,430 to 2,860 m. Those depths were obtained by approximation, based on the horizons interpreted in seismic data. It is important to consider the proximity of the deep/ultra-deep waters play with the intrusive rocks of São Paulo Transform Zone, which may have warmed those source rocks and composing an atypical petroleum system.

It is possible to affirm that there are similarities between the petroleum systems of the Gulf of Guinea and the Pará-Maranhão and Barreirinhas basins, including source rocks with similar characteristics, composed of marine shales of Late Albian to Turonian with Type II and III Kerogen, as well as reservoirs with the same characteristics related to turbiditic sandstones of Late Cretaceous at deep/ ultradeep waters. Considering that the top depth of the oil window occurs about 2,700 m the offshore of Guinea Gulf, according to litherature data, it can be concluded that at Pará-Maranhão and Barreirinhas basins there must be a generation of oil and/or gas at shallow waters, faulted shelf border and deep/ultra-deep waters plays based on the depths inferred.

Although the Pará-Maranhão and Barreirinhas basins are still relatively poorly explored, with few wells only in shallow waters, and none in deep/ultra-deep waters, they present a great exploratory potential due to the similarity with the Tano and Ivory Coast basins of Guinea Gulf. The recent discoveries in African Margin and French Guiana present a strong evidence for a major petroleum system working in the deep water areas and with source rocks and reservoirs common to both sides of the conjugate margin.

The drilling density in both Pará-Maranhão and Barreirinhas basins are still relatively low, and the majority of wells have been drilled in the shallow waters, with no information at ultra-deep waters. In addition, the 3D seismic data existing are scarce and confidential. So, the researches in the region are insufficient when compared to the other Brazilian basins of the eastern margin. The survey of 3D seismic, in addition to drilling of wells in deep/ultra-deep waters, would be of great importance for the opening of new exploratory perspectives along the Brazilian equatorial margin as a whole.

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REFERENCES

Anjos K.M. 1999. *Sismoestratigrafia de parte do projeto LEPAC Equatorial*. MS Dissertation, Laboratório de Engenharia e Exploração de Petróleo, Universidade Estadual do Norte Fluminense, Macaé, 143 p.

Azevedo R.P. 1991. *Tectonic evolution of Brazilian equatorial continental margins basins*. PhD Thesis, Department of Geology, Royal School of Mines, Imperial College of Science, Technology and Medicine, University of London, London, 455 p.

Basile C., Mascle J., Guiraud R. 2005. Phanerozoic geological evolution of the Equatorial Atlantic domain. *Journal of African Earth Sciences*, **43**:275-282. https://doi.org/10.1016/j.jafrearsci.2005.07.011

Black R. 1984. The Pan-African event in the geological framework of Africa. *Pangea*, **2**:6-16.

Borsato R., Greenhalg J., Wells S., Roberson R., Fontes C. 2016. Prospectivity of the equatorial conjugated margins of Africa and South America. Available at: <http://www.jhiassociates.com/uploads/4/2/8/1/42819539/pgs_equatorial_conjugate_margins_of_africa_and_south_america.pdf>. Acessed on: Aug. 15, 2018.

Brandão A.S.L., Feijó F.J. 1994. Bacia do Pará-Maranhão. *Boletim de Geociências da Petrobras*, **8**:101-102.

Brownfield M.E., Charpentier R.R. 2006. Geology and total petroleum systems of the Gulf of Guinea province of west Africa. *U.S. Geological Survey Bulletin*, **2207-C**:1-32.

Dickson W., Schiefelbein C.F., Odegard M.E., Zumberge J.E. 2016. Petroleum systems asymmetry across the South Atlantic Equatorial Margins. *In*: Nemcok M., Rybár S., Sinha S.T., Hermeston S.A., Ledvényiová L. (Eds.). *Transform Margins:* Development, controls and petroleum systems. London, Geological Society Special Publications, **431**:219-233.

Fabianovicz R. 2013. Bacia do Pará-Maranhão. *In*: Seminário Técnico Ambiental, 11. *Rodada de Licitação*...

Feijó F.J. 1994. Bacia de Barreirinhas. *Boletim de Geociências da Petrobras*, **8**:103-109.

Ferreira M.A. 2013. Bacia de Barreirinhas. *In*: Seminário Técnico Ambiental, 11. *Rodada de Licitação*...

Françolin J.B.L., Szatmari P. 1987. Mecanismo de rifteamento da porção oriental da margem norte brasileira. *Revista Brasileira de Geociências*, **17**:196-207.

Jewell G. 2011. Exploration of the transform margin of the West Africa: discovery thinking: Jubilee and Beyond. *In*: AAPG Annual Convention and Exhibition, Houston. *Short Paper*...

MacGregor D.S., Robinson J., Spear G. 2003. Play fairways of the Gulf of Guinea transform margin. ***In***: Arthur T.J., MacGregor D.S., Cameron N.R. (Eds.). *Petroleum geology of Africa:* New themes and developing technologies. London, Geological Society Special Publication, **207**:131-150.

Matos R.M.D. 1999. From oblique rifting to a transform margin: the opening of the Equatorial Atlantic. *In*: International Congress of the Brazilian Geophysical Society, Rio de Janeiro. *Short Papers*... **6**:1-4.

Matos R.M.D. 2000. Tectonic evolution of the equatorial south Atlantic. *In*: Mohriak W., Talwani M. (Eds.). *Atlantic rifts and continental margins*, p. 331-354. Washington, D.C., American Geophysical Union.

Mello M.R., Koutsoukos E.A.M., Hart M.B., Brassell S.C., Maxwell J.R. 1989. Late Cretaceous anoxic events in the Brazilian continental margin. *Organic Geochemistry*, **14**:529-542. https://doi.org/10.1016/0146-6380(89)90033-8

Milani E.J., Brandão J.A.S.L., Zalán P.V., Gamboa L.A.P. 2000. Petróleo na margem continental brasileira: geologia, exploração, resultados e perspectivas. *Brazilian Journal of Geophysics*, **18:**352-396. http://dx.doi.org/10.1590/S0102-261X2000000300012

Milani E.J., Rangel H.D., Bueno G.V., Stica J.M., Winter W.R., Caixeta J.M., Pessoa Neto O.C. 2007. Bacias sedimentares brasileiras: Cartas estratigráficas. *Boletim de Geociências da Petrobras*, **15**:183-205.

Mohriak W.U. 2003. Bacias sedimentares da margem continental brasileira. *In*: Bizzi L.A., Schobbenhaus C., Vidotti R.M., Golçalves J.H. (Eds.). *Geologia, tectônica e recursos minerais do Brasil:* textos, mapas & SIG, p. 87-165. Brasília, CPRM.

Nóbrega II M. 2011. *Mapeamento de estruturas do embasamento e seus limites crustais no Atlântico Equatorial, adjacente à margem brasileira*. MS Dissertation, Instituto de Geociências, Universidade Federal Fluminense, Rio de Janeiro, 81 p.

Pasley M.A., Shepherd D.B., Pocknall D.T., Boyd Q.P., Andrade V., Figueiredo J.P. 2004. Sequence stratigraphy and basin evolution of the Foz do Amazonas Basin, Brazil. *In*: AAPG International Conference & Exhibition, Cancun. *Short Paper*..., p. 257.

Schiefelbein C.F., Zumberge J.E., Cameron N.C., Brown S.W. 2000. Geochemical comparison of crude oil along the South Atlantic Margins. Petroleum system of South Atlantic margins. *AAPG Memoir*, **73**:15-26.

Silveira D.P. 1993. LEPAC equatorial: interessantes estruturas geológicas interpretadas em linhas sísmicas do LEPAC equatorial. *In*: Congresso Internacional de Geofísica, 3., Rio de Janeiro. *Short Papers*..., v. 2, p. 1231-1236.

Silveira D.P., Gomes B.S., Suarez C.R., Gomes P.O. 1994. Projeto LEPAC: Interpretação integrada dos dados geofísicos do LEPAC Equatorial. *In*: Congresso Brasileiro de Geologia, 38., Balneário Camboriú. *Short Papers*..., p. 35-37.

Soares U.M., Rossetti E.L. 2005. Tectonismo e sedimentação na porção SO do Rifte Potiguar - Bacia Potiguar emersa. *Boletim de Geociências da Petrobras*, **13**:149-166.

Soares E.F., Zalán P.V., Figueiredo J.J.P., Trosdtorf Junior I. 2007. Bacia do Pará-Maranhão. *Boletim de Geociências da Petrobras*, **15**:321-329.

Soares Júnior A.V.S., Costa J.B.S., Hasui Y. 2008. Evolução da margem atlântica equatorial do Brasil: três fases distensivas. *Geociências*, **27**:427-437.

Soares Júnior A.V.S., Hasui Y., Costa J.B.S., Machado F.B. 2011. Evolução do rifteamento e paleogeografia da margem atlântica equatorial do Brasil: Triássico ao Holoceno. *Geociências*, **30**:669-692.

Szatmari P., Françolin J.B., Zanotto O., Wolff S. 1987. Evolução tectônica da margem equatorial brasileira. *Revista Brasileira de Geociências*, **17**:180-188.

Tissot B.P., Welte D.H. 1984. *Petroleum formation and occurrence*. Berlin, Springer-Verlag, 699 p.

Trosdtorf Júnior I., Zalán P.V., Figueiredo J.J.P. 2007. Bacia de Barreirinhas. *Boletim de Geociências da Petrobras*, **15**:331-339.

Zalán P.V. 2004. Evolução fanerozóica das bacias sedimentares brasileiras. *In*: Mantesso-Neto V., Bartorelli A., Carneiro C.D.R., Brito-Neves B.B.B. (Eds.). *Geologia do continente sul-americano:* evolução da obra de Fernando Flávio Marques de Almeida, p. 595-612. São Paulo, Beca.

Zálan P.V., Warme J.E. 1985. *Tectonics and sedimentation of the Piauí-Camocim sub-basin, Ceará basin, offshore northeastern Brazil*. Rio de Janeiro, Petrobras/CENPES, Série Ciência-Técnica-Petróleo, 71 p.