Foz do Amazonas and Pará-Maranhão Basins Ready to Replicate Guyana Success*

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Abstract

The Foz do Amazonas and Pará-Maranhão basins in Northern Brazil constitute the natural uninterrupted continuation of the Guyana-Suriname-French Guyana continental margin to the South. They are part of the Brazilian Equatorial Margin that straddles from Foz do Amazonas Basin to the Potiguar Basin in the extreme East. They are typical two-stage normal- to oblique-rift, followed by drift, extensional basins developed upon a magma-poor passive margin (Figure 1). Since the Zaedyus discovery in French Guyana, situated only 50 km to the North of the Brazilian maritime border, the hopes for further similar discoveries in the Brazilian side were high. Major oil companies acquired several blocks in Brazilian Bid Round 11 in 2013 and since then several exploratory locations had been defined. Drilling has not yet commenced due to hurdles in the Brazilian environmental licensing system. The recent extraordinary success of ExxonMobil in Guyana strongly reinforced such belief and points to urge resuming exploration in the Foz do Amazonas and Pará-Maranhão basins. New seismic surveys in these basins reveal leads and prospects similar to those played successfully in both sides of the Equatorial Atlantic.

Introduction

The Foz do Amazonas Basin is a large offshore Cretaceous to Cenozoic passive margin basin developed as a typical normal-rift, followed by drift, in the westernmost portion of the Equatorial Atlantic, in the northernmost portion of the continental margin of Brazil (Figure 1). The continental crust underlying the basin is constituted by a plastic Late Proterozoic terrane, the N-S-trending Tocantins-Araguaia foldbelt. This "soft" terrain allowed wide stretching and strong thinning of the crust during the rift phases that led to the breakup of Western Gondwana in this region. As a result, the profile of the Foz do Amazonas Basin is one of a wide margin presenting a low taper in the underlying continental crust. Mantle exhumation marks the passage from continental to oceanic crust, characterizing this margin as a magma-poor passive margin (Zalán, 2015a).

The location of the Foz do Amazonas Basin in the northernmost portion of the South American continent resulted in three rift phases affecting its early development (Figueiredo et al., 2007). As the Gulf of Mexico was opening, its distal effects ensued the formation of N-S-trending dykes and tabular lava flows of Late Triassic/Early Jurassic age. These were the first extensional evidence in the area and form the “so called” Pre-Rift Sequence. By the time the South Atlantic started opening, its far effects led to the development of few isolated grabens that trapped the older lava flows and syn-rift terrestrial siliclastics (Neocomian-Barremian). During the Aptian-Albian, extensive stretching and rupturing took place during the opening of the Equatorial Atlantic. New and large grabens were superimposed upon the older grabens. Their filling is mostly siliciclastic but, this time, marine in nature. Breakup took place around 100 Ma. The Drift Sequence started in the Late-most Albian and lasted until the Present (Figueiredo et al., 2007). Alternating, retreating and advancing carbonate platforms in the proximal areas and turbidites in the distal regions characterized this phase. The huge Amazon Cone was deposited during the last 10-9 Ma (Figueiredo et al., 2007). This huge Neogene pile of mostly muddy sediments down-warped the underlying stretched and thinned plastic continental crust in such a way that allowed the deposition of circa 11 km of sediments (Cone Sequence).

The Pará-Maranhão Basin is a large offshore Cretaceous to Cenozoic trans-tensional passive margin basin in the Equatorial Atlantic, situated immediately to the south of the Foz do Amazonas Basin (Figure 1). The basin developed as an oblique-rift, followed by oblique drift. The continental crust underlying the basin is constituted by rigid Mid Proterozoic foldbelt terranes surrounding an even harder Archean nucleus, the São Luiz Craton. These rigid terranes did not allow much stretching and thinning of the crust during the rift phase in this region. As a result, the profile of the Pará Maranhão Basin is one of a narrow margin presenting a high taper in the underlying continental crust (Zalán, 2015b). Mantle exhumation marks the passage from continental to oceanic crust, characterizing this margin as a magma-poor passive margin (Zalán, 2015a). The contact between the São Luiz Craton and the Tocantins-Araguaia foldbelt acted as the weakness zone that controlled the location and development of the mighty São Paulo Oceanic Fracture Zone, whose two parallel E-W-trending branches cross the entire Equatorial Atlantic. This feature also marks the geological boundary between the Foz do Amazonas and Pará-Maranhão basins.

As in the Foz do Amazonas, extensive Aptian-Albian stretching and rupturing took place during the opening of the Equatorial Atlantic. Narrow grabens encircling the São Luiz Craton were developed far offshore, to the north and east of the Ilha de Santana Platform (Oliveira et al., 2012), which is the shallow expression of the buoyant São Luiz Craton. Their filling is mostly siliciclastic and marine in nature. Breakup took place around 100 Ma. The Drift Sequence started in the Late-most Albian and lasted until the Present (Soares et al., 2007). Alternating, retreating and advancing carbonate platforms in the proximal areas and turbidites in the distal regions characterized this phase. The Drift Sequence is also affected by several gravitational cells exhibiting the complete zonation from the Extensional to the Compressional Domains, via the Translational Domain (Oliveira et al., 2012).

The Cretaceous Petroleum System

The Equatorial Atlantic was an exploratory area considered by the petroleum industry to be marginal in discoveries and production. With the exception of a few small fields producing oil in the order of a few tens of thousands of barrels per day, in Brazil (Ceará and Potiguar basins), Ivory Coast (Espoir and Baobab) and Ghana (Saltpond), no other significant discovery had been made. This all changed in 2007 when the Jubilee Field was discovered in Ghana by Kosmos Energy. This discovery led to a string of new discoveries in the deepwaters of Ghana and Ivory Coast that continues up to nowadays. Production from several of such fields is in the order of 200,000 bopd. The interest in the

Equatorial Atlantic was strengthened in 2011 when Tullow Oil announced the Zaedyus discovery in French Guyana, in a similar petroleum system that has been so successful in West Africa. Brazilian ANP took advantage of the timing and of the close proximity with the French Guyana maritime border and very successfully sold several exploratory leases in the Foz do Amazonas, Pará-Maranhão and Barreirinhas basins for a billion and half reais in bonus. Unfortunately, the follow up of the Zaedyus discovery led to a string of unsuccessful wells in French Guyana, and the interest in the South American side of the Equatorial Atlantic slowly diminished. Four years later, however, in 2015, the Equatorial Atlantic finally made his way up to the hall of fame of the petroleum industry. ExxonMobil announced the discovery of the Liza Field and, since then, more than 5 billion barrels of oil have been booked as reserves as ten more discoveries were announced. Production is slated to reach 1 million bopd in the next decade. The petroleum system played in all these discoveries is the same.

The successful petroleum system played in these deep and ultra-deep waters of the Equatorial Atlantic consists of Late Albian to Turonian (maybe Coniacian) anoxic marine shales as source rocks and Cretaceous (eventually Cenozoic) turbidite fans and channels as reservoirs. The trapping mechanism is invariably stratigraphic in nature, with lateral and updip pinchouts limiting the reservoirs containing hydrocarbons. From the results obtained in Guyana we can deduce that such individual accumulations may hold reserves in the order of several hundred million barrels of light oil. Clusters of such accumulations may contain several billions of barrels of oil reserves.

This exploratory model is analogous to the successful model applied in the deep Ghanian and Ivorian waters in the Equatorial Atlantic. The search is commonly focused towards packages of Late Cretaceous rocks displaying classical seismic-facies of submarine fans and channels in paleo-slope and basinal settings, filled by turbidite deposition, pinching updip towards the continental margins. Bright spots and flat spots should be expected since the major discoveries made in Ghana and Guyana presented plentiful Direct Hydrocarbon Indicators (DHIs).

New Seismic Surveys and Mapped Prospects

As discussed above, the Foz do Amazonas Basin is a large Cretaceous to Cenozoic passive margin basin, in the middle of which the huge Amazon Cone was deposited during the last 10-9 Ma. This huge Neogene pile of mostly muddy sediments may reach 11 km of thickness. It bent the underlying Paleogene and Cretaceous rocks by load flexing. The situation was ideal to force the source rocks gradually into the oil window and then into the gas window, where they stand today. Maturation and hydrocarbon generation is guaranteed. The Cretaceous turbidite reservoirs were already in place when maturation and migration took place. Oil was expelled from underneath the Cone in radial directions upwards towards regional highs. The load-induced flexure downwards created a compensation positive flexure between the Amazon Cone and the Pará-Maranhão Basin. A powerful migration route was established from the Southern margin of the Amazon Cone towards the Pará-Maranhão Basin.

New ultra-deep two-dimensional seismic surveys (Figure 2) image in a very clear way the continental and oceanic crusts bent downwards underneath the Amazon Cone and upwards in the Pará-Maranhão Basin (Figure 3). Thick Cretaceous strata are harmonically folded with the Moho discontinuity. These Cretaceous sequences display source-rock seismic facies in the lower part and channels and lobes of turbidites highlighted by bright amplitude anomalies in the upper part. Vertical faults caused by the load flexure link the source rock strata to the Paleogene sequence underneath the Cone and around its margins (Figure 3 and Figure 4). The hydrocarbon kitchen is clearly seen below the Amazon Cone. The updip pinchout of turbidites towards the Southeast indicate optimal trapping conditions (Figure 3).

Figure 5 displays a different situation also favorable for stratigraphic trapping. The region situated between the two branches of the São Paulo Oceanic Fracture Zone shows strong deformation related to strike-slip movements along these former transform faults. During the Transform Fault Stage transpression was the dominant sliding mechanism. Mantle was pushed upward to exhumation amidst severely crushed oceanic crust, forming a positive flower structure. Later, during the early times of the Drift Stage the lateral movement of the blocks was such that trans-tension prevailed and a trans-tensional rift developed, creating a localized sag basin upon it. In this restricted basin source rocks were gradually subsided to depths between 7000-8000 m. This depression was also a locus for the concentration of turbidites sandstones, as it can be clearly seen by a package of >1000 m thick where seismic facies typical of lobes and channel complexes are abundant between 6000-7000 m.

Several leads of large areal extent and thickness were mapped (see examples in Figure 3, Figure 4 and Figure 5). They point towards the replication of the successful history of exploration in the nearby continental margins of the Equatorial Atlantic in South America and of the homologous margins of West Africa.

Conclusions

The Cretaceous petroleum system is a well-established successful play in the Equatorial Atlantic. Cretaceous source rocks ranging in age from the Late Albian to the Turonian, and maybe even Coniacian, sourced the rich accumulations of onshore Venezuela (La Luna Formation) and of the deep/ultra-deep waters off Guyana (Liza and satellites), French Guyana (Zaedyus), Ghana (Jubilee, Tweneboa, Eneyenra, Sankofa, etc.) and Ivory Coast (Ivoire, Saphir, etc.). The reservoirs are always Late Cretaceous turbidites, ranging in age from Late Albian to Maastrichtian. Miocene reservoirs have been successfully drilled at the Hammerhead discovery (Guyana). Most of the traps, if not all of them, are stratigraphic traps consisting of updip pinch outs of channelized turbidites and submarine fans. Since this petroleum system is situated in the Drift Sequences of those passive continental margins, that are devoid of salt and of the associated deformation, the turbidites that should be preferentially targeted are those situated closest to the source rocks. Turbidites interfingered with the source rock facies or immediately above should be the primary objectives of exploratory wells.

New 2D ultra-deep seismic surveys (FOZPh3 and PAMA) show the entirety of the Cretaceous petroleum system in deep/ultra-deep waters of the Foz do Amazonas and Pará-Maranhão basins. Tabular and parallel strong continuous reflections characterize the source rocks package at the base of the Drift Sequence. Channelized complexes and continuous single strong reflections indicate the presence of turbidite reservoirs in the Late Cretaceous and in the Cenozoic. Packages of faint parallel and continuous reflections occur above the Late Cretaceous and are suggestive of seal rocks. Bright spots, flat spots, gas chimneys and flags along faults are evidence of a working petroleum system. Several prospects, leads and clusters of leads of significant dimensions could be mapped in those surveys. All the indications point to the existence of great potential in these areas. The Foz do Amazonas and Pará-Maranhão basins are ready to replicate the exploratory successes of the nearby and homologous margins.

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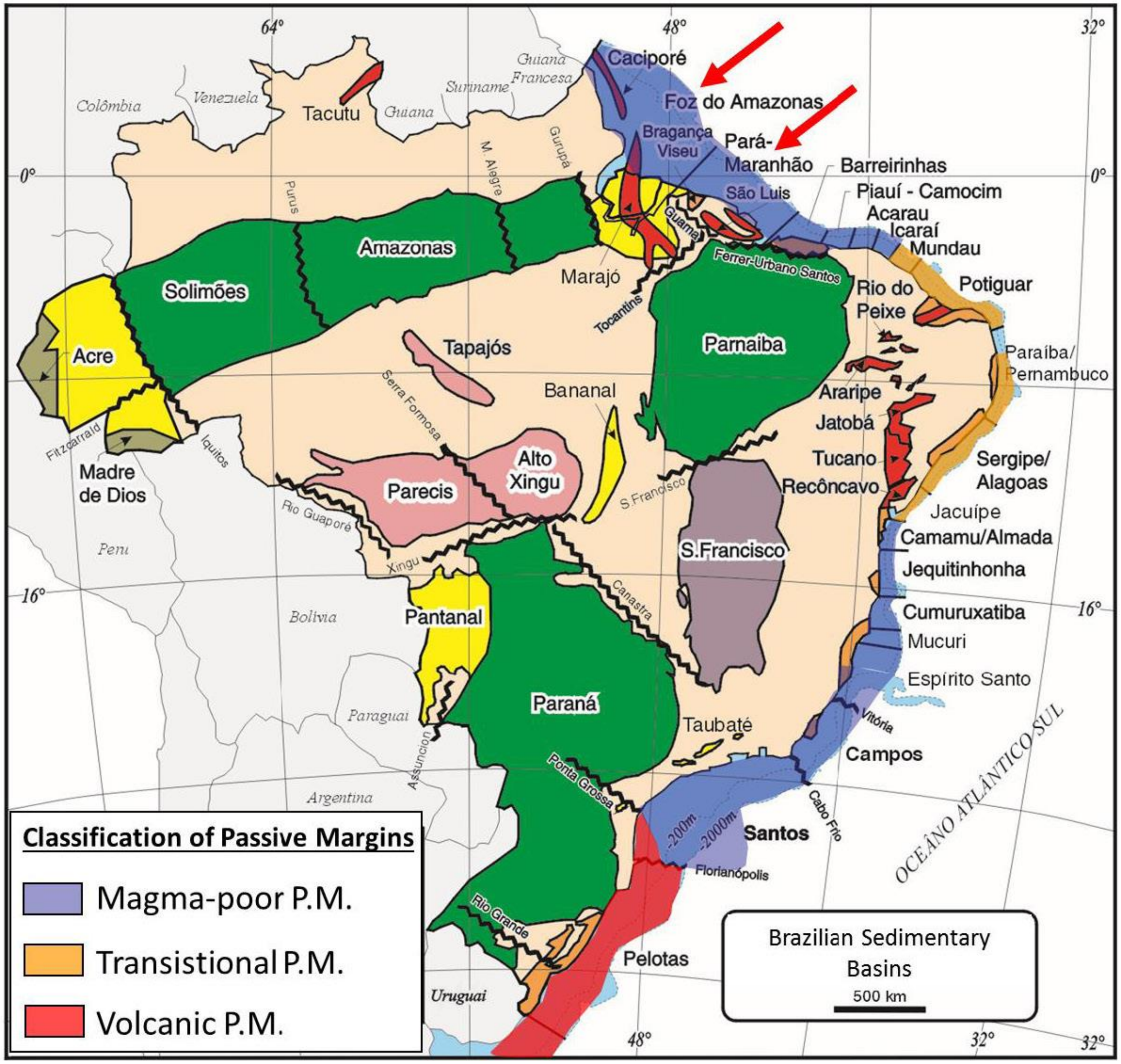

Figure 1. Map displaying the classification of the Brazilian passive margins (from Zalán, 2015a). Passive margins are classified as Magma-Poor Passive Margins (MPPM, in blue), Volcanic Passive Margins (VPM, in red) and Transitional Passive Margins (TPM, in orange). Typical VPM filled with SDRs run from Argentina, through Uruguay, into the Pelotas Basin. Typical MPPM displaying exhumation of mantle can be found in Santos, Campos and Espírito Santo basins in the Southeastern Margin and in the Barreirinhas, Pará-Maranhão and Foz do Amazonas basins in the Equatorial Margin. Transitional Passive Margins, displaying the coexistence of proximal sediment-filled grabens with distal SDR-filled grabens, are characteristic of the region encompassing the Jacuípe Basin to the Mundaú Basin in Northeastern Brazil. Red arrows point to the locations of the Foz do Amazonas and Pará-Maranhão basins.

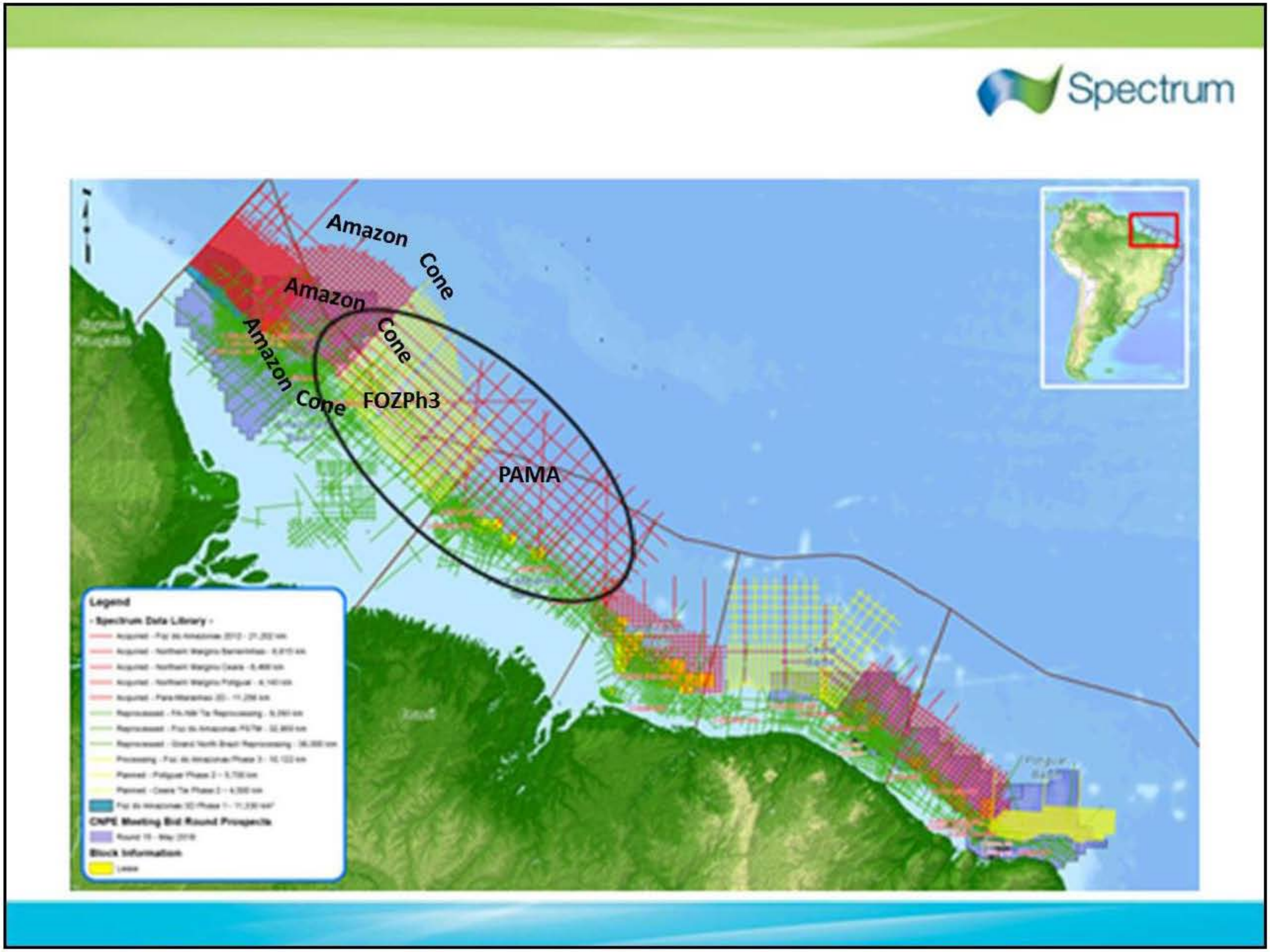

Figure 2. Map displaying the positioning of the new 2D seismic surveys object of this study. They were acquired in the southern part of the Foz do Amazonas Basin, including the southern extent of the Amazon Cone (FOZPh3, yellow lines), and in the Pará-Maranhão Basin (PAMA, red lines).

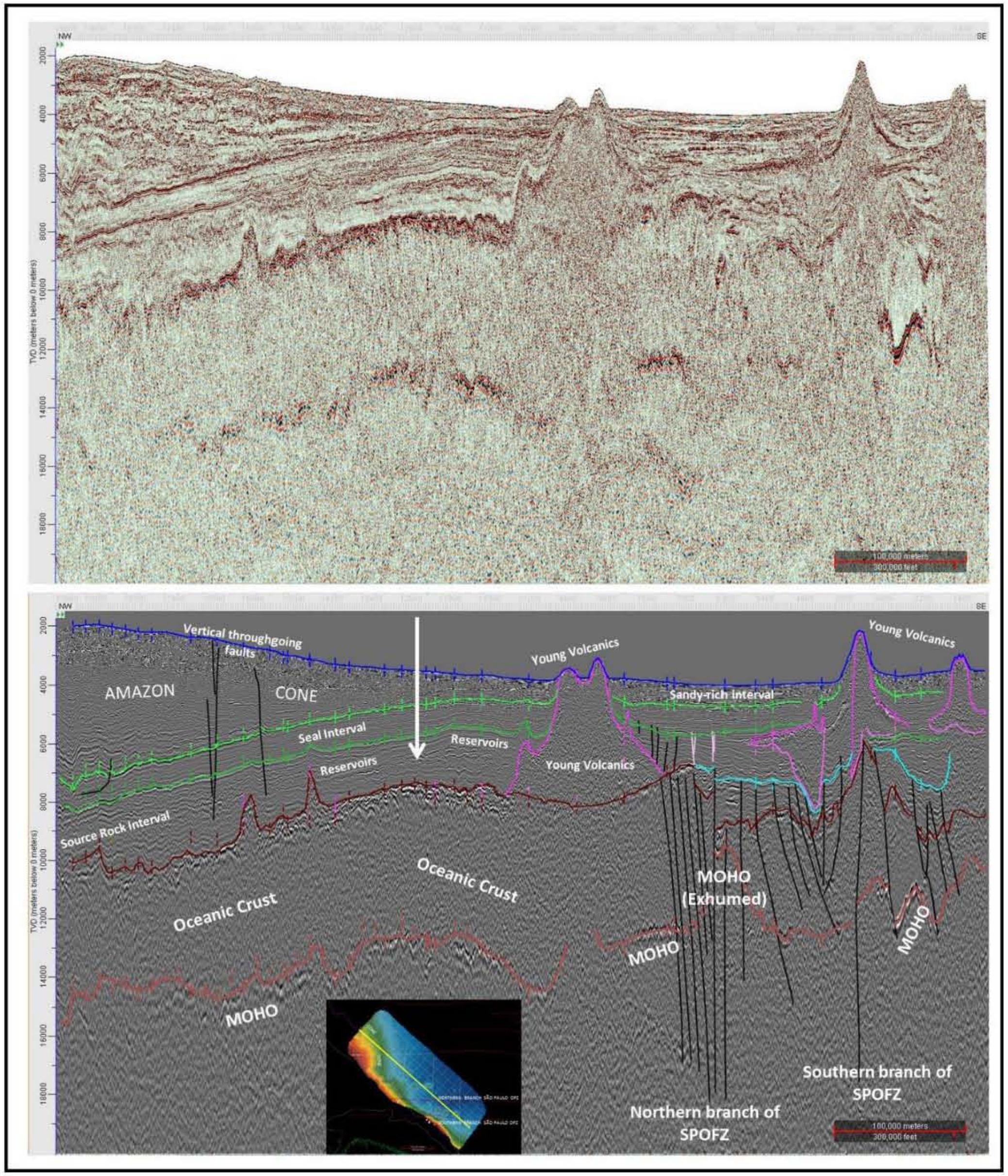

Figure 3. Strike-oriented seismic section (PAMA) crossing the entire study area, from the Foz do Amazonas Basin to the Pará-Maranhão Basin. The weight of the Amazon Cone clearly bends the entire Pre-Cone section as well as the oceanic crust. Source rocks were pushed to 8-10 km of depth. The bent oceanic crust created a compensation high that is a magnificent focusing high (white arrow). Reservoir seismic facies can be seen clustered to the right of the arrow creating a fantastic opportunity for an exploration well. The two branches of the São Paulo Oceanic Fracture Zone can be seen, as well as volcanics forming seamounts.

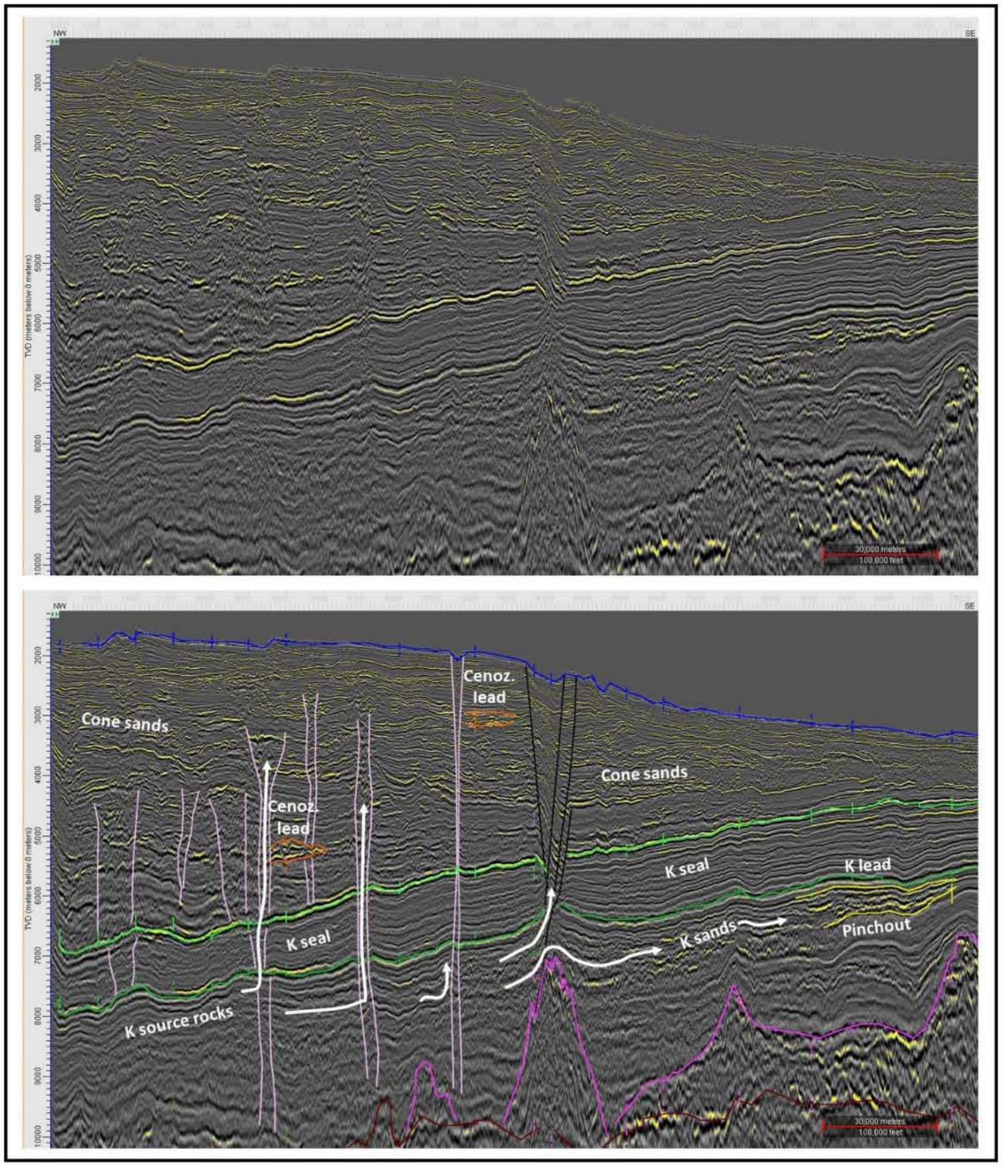

Figure 4. Strike-oriented seismic section (FOZPh3) clearly showing the functioning of the Cretaceous petroleum system. The Amazon Cone is the wedge-shaped package of rocks (up to 5 km thick) between the sea bottom and the light green reflector. Cretaceous source rocks are bent under the weight of the cone and sunken to >8000 m of depth. The updip migration to the right (southeast) is obvious. A pinched-out package of brilliant reflections suggest an excellent lead for Cretaceous turbidites. Vertical faults and gas chimneys (in pink) cross the Cretaceous seal package and may constitute routes for migration of hydrocarbons into the Cenozoic aged sands. Several leads could be mapped within the Cone Section; two of them are highlighted (orange reflectors).

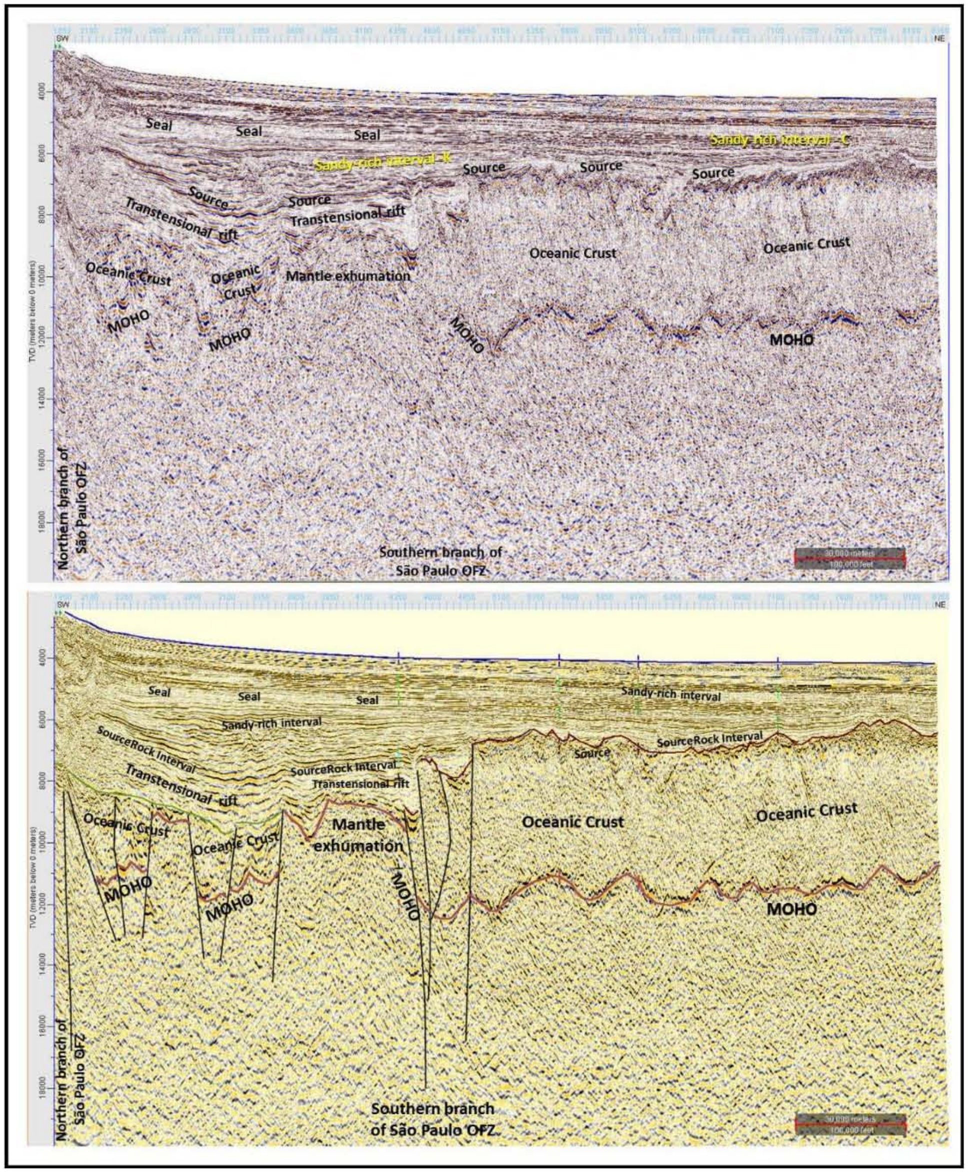

Figure 5. Dip-oriented seismic section in the Pará-Maranhão Basin (PAMA) showing strong deformation related to strike-slip movements along the two branches of the São Paulo Oceanic Fracture Zone. The oceanic crust is crushed between the branches and mantle exhumed as a result of a pop-up structure. A trans-tensional rift basin developed at the early stages of drifting. The source rock interval was sunken to depths > 7000 m. The down-warped basin above also collected a larger amount of turbidite sandstones (sandy rich interval) that pinch out to the southwest and to the northeast. Two bright spots related to such pinch outs to the southwest are clearly seen at around 6000 m.