Unlocking hydrocarbon potential in the underexplored Brazil Equatorial Margin: Role of 2D seismic reimaging

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This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October 2023.

Abstract

Recent reprocessed 2D seismic data from pilot projects in Foz Do Amazonas and Para Maranhao and from the full 2D seismic reprocessing of Ceara basin show a significant improvement in seismic imaging. These reprocessing projects were completed in 2022. They demonstrate that the reimaging of the 2D legacy data with advanced signal processing and depth imaging applications can be an effective way to enhance the existing seismic data over the deepwater and ultra-deepwater areas of the underexplored Brazil equatorial basins.

Having a similar geological evolution to the prolific Guyana and Tano basins, where Cretaceous plays are successfully proven, expectations to find significant hydrocarbon accumulations in the Brazil equatorial margin are high. However, in order to conduct future reliable prospectivity assessments leading to optimal exploration programs over this extensive region, it was important to uplift the seismic imaging of existing 2D data.

The resulting seismic images from the 2D reprocessing projects show a remarkable enhancement in terms of definition and resolution at both deep and shallow intervals. It enables better mapping of trap geometries, unlocking new leads and prospects even in untested plays. Current results of the ongoing regional seismic interpretation using this reprocessed seismic data and the available information from the shallow water wells are presented in this work. The improved seismic imaging of the reprocessed data is key to document the diversity of play types identified in the Brazil equatorial margin and encourages the idea that this frontier exploration region may have great hydrocarbon potential.

Introduction

The Brazil Equatorial Margin (BEM) can be considered the next exploration frontier in the Atlantic offshore. Relatively recent discoveries in the Atlantic equatorial segment such as the giant Liza and Jubilee fields in the Guyana and Tano basins, respectively, increase the expectation of finding important hydrocarbon accumulations in the Brazil equatorial basins. This is especially so if we keep in mind the Atlantic conjugate margin concept, and realize that the African and South American equatorial basins evolved in the same geological context, going from a transform tectonic setting to an eventual opening of the Atlantic Ocean in the Cretaceous time (e.g., Krueger, 2012; Pellegrini and Ribeiro, 2018). Thus, as shown in Figure 1, these basins were geographically close during the early drifting Atlantic stage, sharing a similar geological setting during the Cretaceous and the petroleum system associated with it.

The field size distribution graphs in Figure 1 display the significant discoveries found in Guyana and Tano basins. More than 45 discoveries have been reported in the Guyana basin after the Liza well successfully tested the prolific stratigraphic Cretaceous play in that basin with 2P recoverable resources of about 1.8 BBOE in 2015. For all these discoveries, the total 2P recoverable resources could be estimated in the order of 18 BBOE (IHS, 2023). For this group of discoveries, the exploratory success initially occurred on the Guyana side; it was in 2020, five years after the giant Liza discovery in neighboring Guyana, that the first commercial success happened in offshore Suriname with the Maka Central well. Moving into the African side, it is also remarkable to see the discoveries in the Cote d'Ivoire and Tano basins; the most recent are Baleine and Eban in 2021 and Aprokuma in 2022. Most of these African discoveries occurred after the Jubilee field, which was found in 2007 with about 900 MMBOE of 2P recoverable resources. It is worth mentioning that the Jubilee well is considered the Late Cretaceous stratigraphic play opener in the Atlantic margin. The occurrence of these hydrocarbon fields indicates how prolific Guyana and West African basins are and suggests that similar hydrocarbon potential should be expected in the Brazil equatorial basins.

The BEM is composed by five sedimentary basins, from northwest to southeast: Foz do Amazonas (Amazon mouth), Para Maranhao, Barreirinhas, Ceara, and Potiguar basins (Figure 1). There have been exploration efforts on the BEM, but mainly focused on the shallow water. For the deepwater, the region can be considered a frontier exploration, as only four wells have been drilled at water depth greater than 2000 m. Results of the shallow water exploration campaign, mainly targeting syn-rift plays, are some producing fields on the continental shelf of Ceara and Potiguar basins such as Atum, Curima, Xareu, Ubarana and Dentao fields. There has been a break in the drilling activity after the last well drilled in the Potiguar basin in 2015. However, the Brazil exploration focus can pivot to this region as most of the latest presalt wildcat wells drilled in the outboard of Santos and Campos basin have not been favorable, coming up dry or subcommercial. In addition, the Brazilian National Agency of Petroleum, Natural Gas & Biofuels (ANP) regulator intends to generate more interest in the Brazil equatorial basins making more acreage available for the permanent offer programs. At present, the number of blocks included

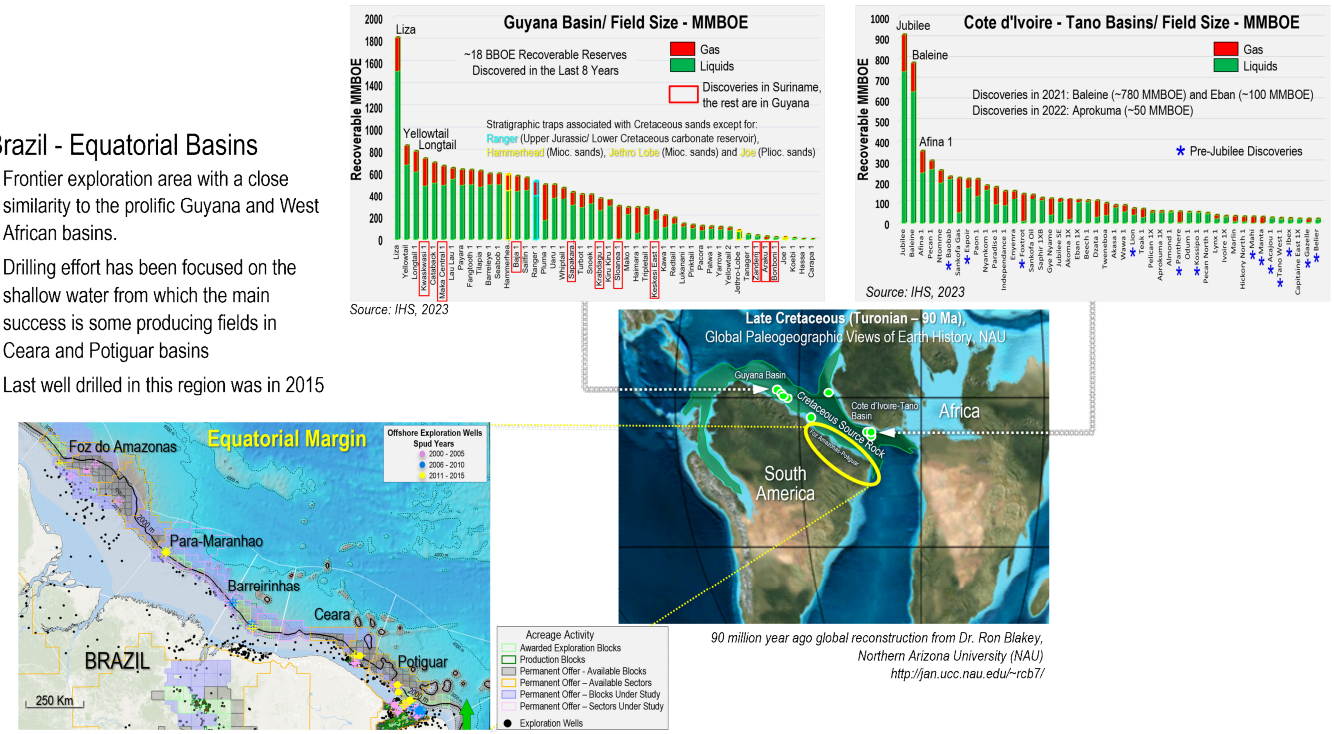

Figure 1- *Exploration overview of the Atlantic equatorial segment. Plate reconstruction map shows the proximity of the South America and Africa equatorial basins during the Late Cretaceous.*

in this permanent offer initiative is very significant; there are 83 blocks already available covering a total area of approximately 59,435 Km^2 and 289 blocks under study, waiting for environmental instructions, covering an additional total area of approximately 143,700 Km^2. As shown in the BEM map in Figure 1, these blocks spread across the deepwater and ultra-deepwater areas of Brazil's five equatorial basins.

With the available seismic data, the challenge is to make a thorough prospectivity assessment over this extensive region. BEM seismic coverage is mainly provided by 2D data, especially over the deepwater and ultra-deepwater provinces since the existing 3D seismic data are located in some sectors in the upper part of the slope of these Brazilian basins. Improvement of the seismic image of the 2D datasets is crucial in the exploration approach, as about 80% of 2D seismic acquisitions in BEM were completed more than 20 years ago and the last 2D regional reprocessing programs, prior to those discussed in this paper, were carried out five or eight years ago.

Here, we show the seismic imaging improvement achieved in the initial 2D reprocessing pilot projects in the Foz do Amazonas and Para Maranhao basins, as well as in the full reprocessing project already completed in Ceara basin. Current results of the ongoing regional seismic interpretation using this 2D new reprocessing data and the available information from the shallow water wells are also presented in this work. The 2D reprocessed data enables a more confident stratigraphic correlation across the basins and provides a better understanding of their geological evolution compared to the 2D legacy data. The better image of the 2D reprocessed data also helps document the diversity of hydrocarbon play types in the region and is key to unraveling attractive exploration opportunities.

Geological Setting Overview

The equatorial basins located in northern Brazil offshore are limited by the Sierra Leone Fracture Zone (FZ) to the north and the Chain FZ to the south (Figure 2). The evolution of these basins began during the Early Cretaceous as a series of several continental rift basins that were subsequently affected by the transcurrent movements along the fracture zones that exist between Brazil and Africa in the equatorial segment.

The tectonic evolution of the BEM can be divided into three major phases (Figure 2):

- An intracontinental rifting that began in the Potiguar and Foz Do Amazonas basins during the Valanginian time (~140 Ma) and then extended into the Para Maranhao, Barreirinhas and Ceara basins during the Barremian and Aptian time (Ávila, 2018). The rift sequences in these basins are mainly characterized by siliclastic rocks deposited in continental lakes and fluvial systems.
- A post-rift or transitional phase initiated in the Mid Aptian in the Potiguar basin and then developed toward the Ceara, Barreirinhas, Para Maranhao and Foz do Amazonas basins, during Late Aptian up to Cenomanian. This phase represents the period from the generation of the first oceanic accretion centers until the end of a tectonic deformation controlled by

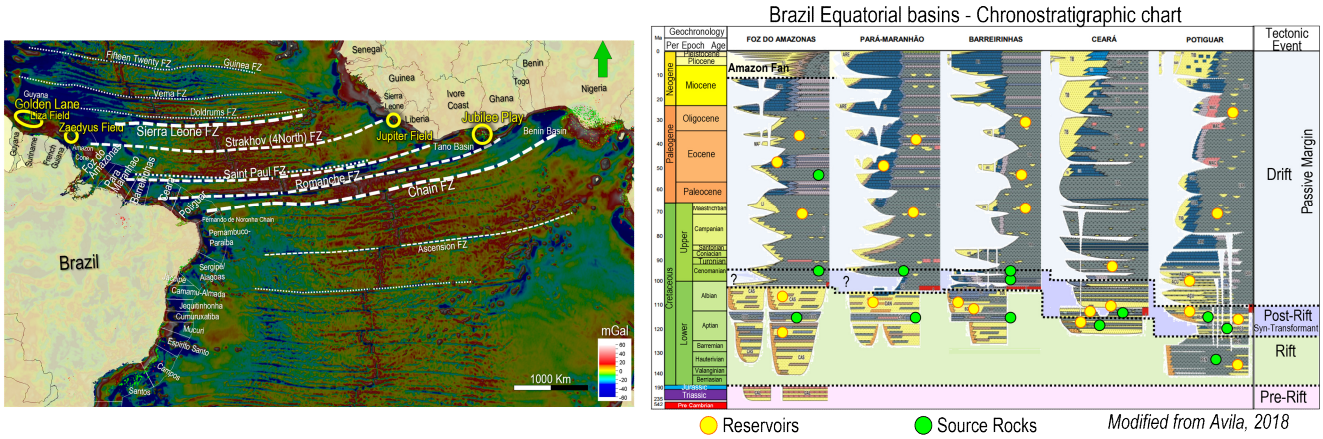

Figure 2- *Free-air gravity map of the Equatorial Atlantic region and chronostratigraphic chart of the Brazil equatorial basins. On the map, white dashed lines are the major fractures zones and gravity data is from GeoMapApp (www.geomapapp.org).*

transforming faults (Pellegrini and Ribeiro, 2018). Transtensive and transpressive processes occurred simultaneously during this stage, producing subsidence and uplift events in different basins (e.g., Matos 2000). With the evolution of the strike-slip motions between South America and Africa, these two continents were totally disconnected during the Late Albian (~100 Ma), thus creating the conditions for open marine sedimentation (Rupke et al., 2010).

- A drift phase that began in the Potiguar basin in the Early Albian (Wittstrom et al., 2013) and in the rest of the Brazil equatorial basin in the Cenomanian. This drift tectonic phase initially occurred in a context of a transforming passive margin until the Santonian and later from the Upper Santonian to Recent in divergent conditions (Basile et al., 2005). Gravity gliding systems were also produced during this drift period in Barreirinhas, Para Maranhao and Foz Do Amazonas basins. They occurred in these basins when slope instability generated listric normal faults on the shelf and upper slope and thrust faults on the toe of slope.

Based on the geochemical data collected in several exploration wells, four major source rock systems have been confirmed in the Brazil equatorial basins: (1) An Aptian/Barremian calcareous black shale related to lacustrine freshwater in Potiguar, Ceara and Barreirinhas; (2) A Late Aptian calcareous shale associated with fluvial-deltaic to marine environment in all basins; (3) An Albian to Turonian anoxic marine shale in all basins; and (4) Paleocene-Eocene marine-deltaic shales in Foz do Amazonas and Para Maranhao (Mello et al., 2013; Ávila, 2018).

The main reservoirs in the BEM (Figure 2) are represented by: (1) Lower Cretaceous fluvial - deltaic sandstones in all basins; (2) Late Cretaceous - Paleogene shelf and turbiditic sandstones in all basins; (3) Paleogene porous and fractured calcarenites in Foz do Amazonas and Para Maranhao basins; and (4) Neogene shelf and turbiditic sandstones in the Foz do Amazonas basin.

Database and Methodology

About 65,000 linear kilometers of 2D seismic data are included in a large reimaging project in the BEM covering Foz do Amazonas, Para-Maranhao, Barreirinhas and Ceara basins (Figure 3). This 2D reprocessing mega program started with a proof-of-concept approach by designing pilot tests in the Ceara, Para Maranhao and Foz do Amazonas basins over 11 selected regional sections.

Based on the intensive testing carried out during the pilot projects, the workflow to be applied on the 2D full reprocessing was defined. This workflow includes an optimized broadband technique with significant noise and multiple attenuation, as well as five tomographic iterations to produce a geologically conformable velocity model calibrated by available public wells. It leads to a KPSDM (Kirchhoff Pre-Stack Depth Migration) product with further enhancements carefully given by post-migration tasks. The workflow derived from the already completed pilot projects was implemented in the Ceara 2D full reprocessing. Similarly, it is also used in the Foz do Amazonas, Para-Maranhao and Barreirinhas 2D full reprocessing projects that are currently underway (Figure 3).

In the particular case of Ceara 2D reprocessing, this project was completed in September 2022 and comprised 6,200 linear km of 2D data spread across 70 seismic sections (Figure 3).

Regional seismic interpretation was conducted on the newly reprocessed 2D seismic data from the pilot tests and Ceara full reimaging project. Stratigraphic information from wells drilled mainly in shallow water was used to calibrate the horizon interpretation. This enabled the documentation of the main tectono-stratigraphic events and hydrocarbon play types in the region.

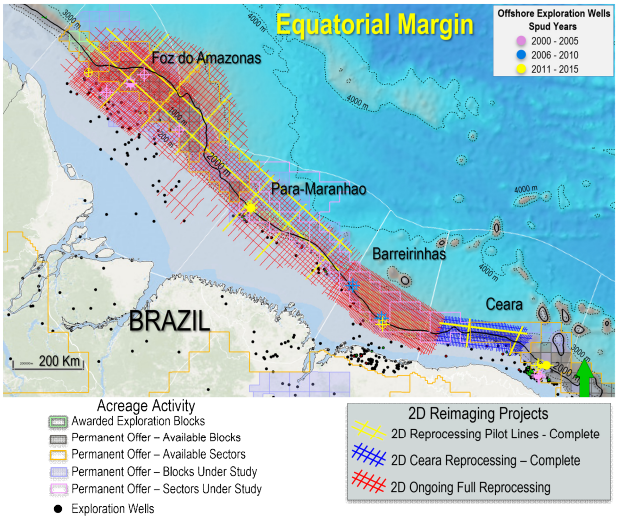

Figure 3- *2D seismic reprocessing projects in Foz do Amazonas, Para-Maranhao, Barreirinhas and Ceara basins.*

Seismic Reimaging Results and Exploration Play Identification

A significant seismic image uplift was achieved both during the 2D reprocessing pilot projects and in the Ceara 2D full processing. Together with the application of advanced noise attenuation, deghosting and demultiple techniques in the signal processing, the construction of a robust velocity model based on multiple tomography iterations and calibration with well data was key to obtaining these results.

Figure 4 shows an example of the final velocity model done in the pilot project for one of the regional sections worked in the Para-Maranhao basin. Observed in this figure are important velocity variations in both the lateral and vertical directions, which can be associated with the geology of the area. As indicated by the nearby wells, the high velocity on the left side of the section (Figure 4) corresponds to mostly carbonate units developed in the shelf portion of the basin. On the central and right side of the section, the seismic velocity decreases as the lithofacies become more clastic along the slope.

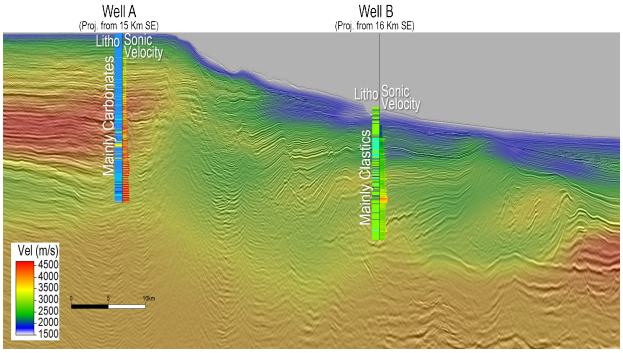

Figure 4- *Example of final velocity model achieved in 2D reprocessing pilot projects.*

The resulting seismic images from these 2D reprocessing projects show a remarkable enhancement in terms of definition and resolution at both deep and shallow intervals (Figure 5). For the deeper interval related to the syn-rift sequence, seismic events in the new reprocessed 2D data are clearer and fault planes are better defined compared to the legacy data. For the shallower intervals associated with post-rift and passive margin sequences, the new 2D reimaging data show better stratigraphic definition and variability, thus allowing better identification of seismic discontinuities and helping to carry out seismic facies analysis, which was very ambiguous in legacy seismic data.

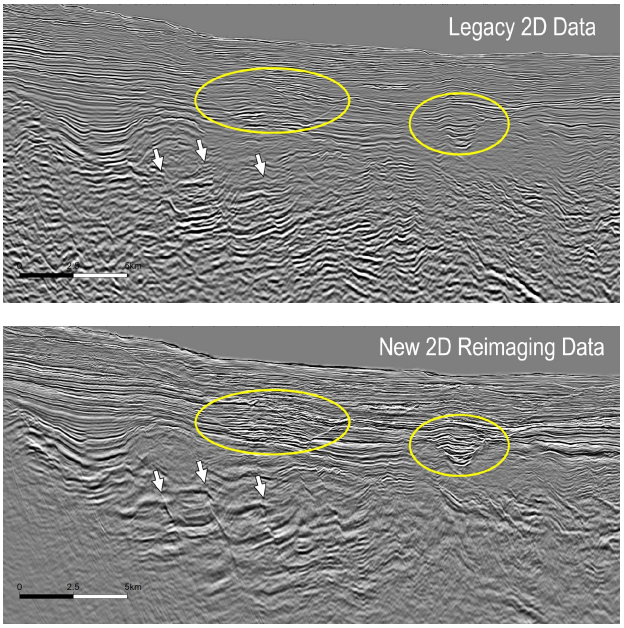

Figure 5- *Comparison between legacy and newly reprocessed 2D data. Reprocessing resulted in a greatly improved image showing better stratigraphic definition and variability (e.g., yellow polygons) and better fault delineation (see white arrows)*

A more confident seismic interpretation was performed using the recent 2D reprocessed data. The enhanced seismic image in depth of this dataset enables a better mapping of trap geometries, unlocking new leads and prospects even in untested plays. Therefore, it can provide new insights into the prospectivity assessment of the BEM, which would be useful in defining priority areas for the initial exploration phases of this extensive region.

As an example of the different trapping mechanisms that occur in the Brazil equatorial basins, the regional seismic sections in Figure 6 illustrate some of the play types identified in the Para-Maranhao and Ceara basins. Stratigraphic plays involving Upper Cretaceous and Tertiary deep-water sands (e.g., onlapping terminations, channel systems, buried hills) are attractive targets in the post-rift and passive margin sequences. Structural plays can be identified both in the passive margin and syn-rift intervals. In the passive margin sequence, the structural plays are mainly related to gravitational tectonics, which produced listric and toe-thrust faults in some of the Brazil

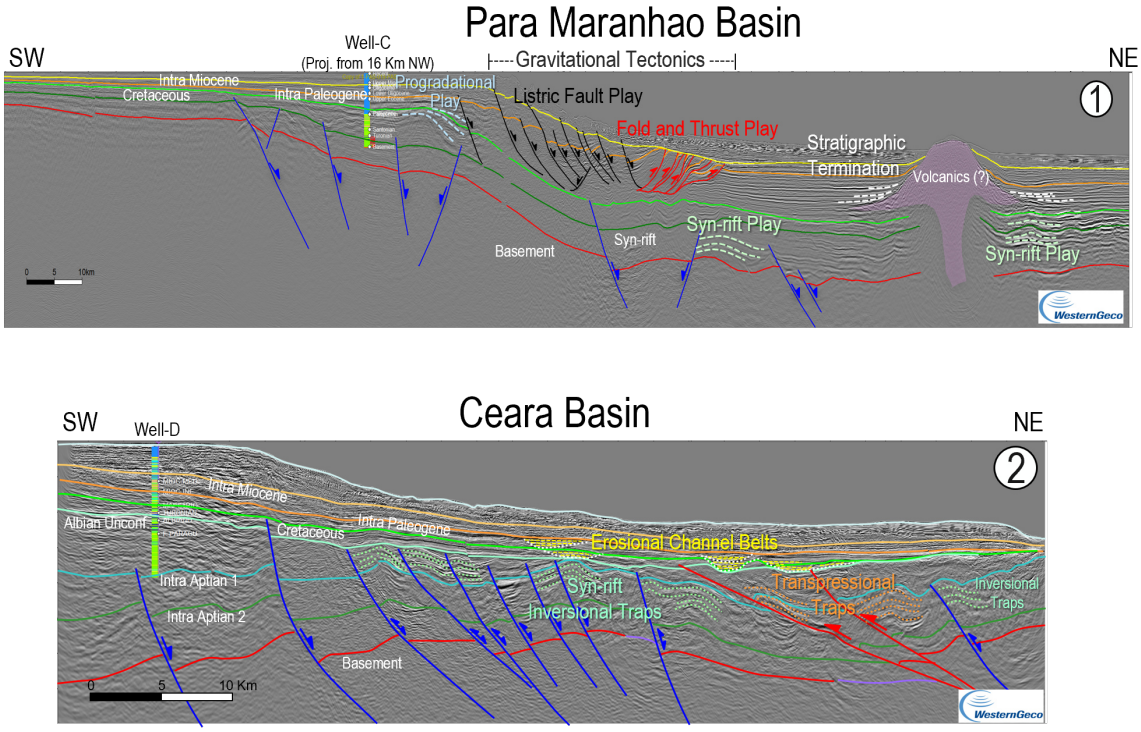

Figure 6- *Regional seismic interpretation in depth showing examples of some of the play types identified in the BEM.*

equatorial basins (e.g., in the Para-Maranhao basin, see section 1 in Figure 6). In the syn-rift sequence, structural plays are tilted blocks and structural highs associated with normal faults generated during the rifting phase. Structural plays related to the transpressional system of Romanche FZ have also been identified in the central portion of Ceara Basin. The seismic section 2 in Figure 6 displays the tectonic complexity of this area in the Ceara basin and shows some of the inversional and transpressional structures formed due to the effect of the Romanche FZ.

Conclusions

- 2D seismic reprocessing can significantly improve the subsurface imaging in the BEM as already demonstrated by the results of the Foz do Amazonas and Para-Maranhao pilot tests and the Ceara 2D full processing. Therefore, the reimaging of 2D legacy data with a modern processing workflow represents an effective way to uplift the seismic image. This will soon provide a good quality dataset to address the basin-scale prospectivity assessment required in this extensive frontier exploration region.
- In addition to the advanced signal processing techniques used in the 2D reimaging projects, building a geologically conformable velocity model was crucial to achieving the improvement observed in the seismic imaging.
- The enhancement in the image quality of the recent reprocessed 2D seismic data helps resolve some of the geological challenges that exist in the BEM. It not only enables a better understanding of the stratigraphic facies variations, but also of structural complexities such as the gravitational collapses involving the passive margin sequence and the transtensional and transpressional deformations affecting the syn-rift sequence.
- These 2D reimaged data reveal attractive exploration opportunities associated with a diversity of play types, showing their importance in unlocking the hydrocarbon potential on the open acreages of the BEM.

Acknowledgments

The authors thank SLB Multiclient for permission to use and publish the data sets included in this paper.

References

ÁVILA, R.M. 2018. Brazilian Equatorial Margin Prospectivity. ANP Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, Brazil Open Acreage Presentation, 23 p.

BASILE, C., MASCLE, J., AND GUIRAUD, R. 2005. Phanerozoic geological evolution of the Equatorial Atlantic domain. Journal of African Earth Sciences, 43: 275-282.

IHS. 2023. EDIN Data Search. IHS Energy Log Services, Inc; Copyright (2012) IHS Energy Log Services, Inc. https://edin.ihsenergy.com/portal/search.

KRUEGER, A. 2012. The Brazilian Equatorial Margin from Rift to Drift: Faulting, Deposition, and Deformation in the Offshore Barreirinhas Basin, Ph.D. dissertation, University of Houston, 182 p.

MATOS R.M.D. 2000. Tectonic evolution of the equatorial south Atlantic. In: Mohriak W., Talwani M. (Eds.). Atlantic rifts and continental margins, American Geophysical Union, Geophysical Monograph Series, 115: 331-354.

MELLO, M.R., FILHO, N.G.A., BENDER, A., BARBANTI, S.M., TAKAKI, T., FONTES, C.A., AND MOHRIAK, W. 2013. New Deepwater Frontiers an Ocean Apart. GEO ExPro, vol. 10, No.2-2013: 56-62.

PELLEGRINI, B.S. AND RIBEIRO, H.J.P.R. 2018. Exploratory plays of Pará-Maranhão and Barreirinhas basins in deep and ultra-deep waters, Brazilian Equatorial Margin. Brazilian Journal of Geology, 48(3): 485-502.

RUPKE, L.H., SCHMID, D.W., HARTZ, E.B., AND MARTINSEN, B. 2010. Basin modelling of a transform margin setting: structural, thermal and hydrocarbon evolution of the Tano Basin, Ghana. Petroleum Geoscience, Vol. 16: 283-298.

WITTSTROM, M.D., MIURA, K., ORANGE, D., BORGES, H.V., LEONEL, B.O., FAVERA, P.M.D., AND FAINSTEIN, R. 2013. New Exploration Frontiers of Brazil's Atlantic Equatorial Margin: From Theory to Reality. Offshore Technology Conference, OTC-24422, 11 p.