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SEISMIC INTERPRETATION AND 3D STRUCTURAL MODELING IN THE BARREIRINHAS BASIN (MARANHÃO, BRAZIL)

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Abstract

Discoveries of hydrocarbons in the basins of the African Equatorial Margin and Guinea Gulf stimulated the exploratory interest in the basins of the Brazilian Equatorial Margin, for being together before the Continental Drift. This interest emerges because both African and South American equatorial margin are considered analogous. The Barreirinhas Basin is a member of the Brazilian Equatorial Margin. This work presents the results of the seismic interpretation and structural 3D modeling, in the gravitational tectonics context, in an area covered by 3D seismic data, in the Barreirinhas Basin. The compressional domain of an extensive-compressive system was mapped were identified reverse faults, thrust faults and fault-related folding like fault-bend and fault-propagation fold that can be accompanied by backthrust features. These structures are connected by a single basal displacement surface covering deep to ultra-deep waters of the basin. The 3D structural modeling provided a more robust visualization of the structural framework. The information can form the basis of the 3D structural model for integration with the 3D stratigraphic and petrophysical models, with the representation of the lateral and vertical distribution that are important for the decreased exploratory risk, contributing to the knowledge of the Equatorial Margin, especially in the Barreirinhas Basin.

Keywords: Brazilian Equatorial Margin; Gravitational Tectonics; Extensive-Compressive Systems.

INTERPRETAÇÃO SÍSMICA E MODELAGEM 3D ESTRUTURAL NA BACIA DE BARREIRINHAS (MARANHÃO, BRASIL)

Resumo

Descobertas de hidrocarbonetos nas bacias da Margem Equatorial Africana e no Golfo da Guiné impulsionaram o interesse exploratório nas bacias da Margem Equatorial Brasileira, por terem estado juntas antes da Deriva Continental. Este interesse surgiu pois ambas margens equatoriais da América do Sul e a Africana são consideradas análogas. A Bacia de Barreirinhas pertence a Margem Equatorial Brasileira. Esse trabalho apresenta os resultados da interpretação sísmica e da modelagem 3D estrutural, no contexto da tectônica gravitacional, em uma área com cobertura sísmica 3D na Bacia de Barreirinhas. Mapeou-se o domínio compressional de um sistema extensivo-compressivo. Identificaram-se falhas inversas e falhas de empurrão, dobras relacionadas a falhas, como dobra de inflexão de falha (fault bend fold) e dobra de propagação de falha (fault propagation fold), por vezes acompanhadas de feições de retro-empurrão (backthrust). Estruturas conectadas por uma única superfície de deslocamento basal. O modelo 3D estrutural proporcionou uma visualização mais robusta do arcabouço estrutural. As informações podem formar a base do modelo 3D para integração com os modelos estratigráficos e petrofísicos, com representação da distribuição lateral e vertical os quais são importantes para diminuição do risco exploratório, contribuindo para o conhecimento da Margem Equatorial, principalmente da Bacia de Barreirinhas.

Palavras-Chave: Margem Equatorial Brasileira; Tectônica Gravitacional; Sistemas Extensivo-Compressivo.

INTERPRETACIÓN SÍSMICA Y MODELADO ESTRUCTURAL 3D EN LA CUENCA DE BARREIRINHAS (MARANHÃO, BRASIL)

Resumen

Los descubrimientos de hidrocarburos en las cuencas del Margen Equatorial Africano y el Golfo de Guinea despertaron el interés exploratorio en las cuencas de la Margen Ecuatorial Brasileña, ya que estaban juntas antes de la Deriva Continental. Este interés surgió porque ambos márgenes en América del Sur y África son

considerados análogos. La Cuenca de Barreirinhas pertenece al Margen Ecuatorial Brasileño. Este trabajo presenta los resultados de la interpretación sísmica y el modelado estructural 3D, en el contexto de la tectónica gravitacional, en un área con cobertura sísmica 3D en la cuenca de Barreirinhas. Se cartografió el dominio compresivo de un sistema extensivo-compresivo con la identificación de fallas inversas, fallas de empuje y pliegues relacionados con fallas como pliegues de fallas y de propagación de fallas que pueden ir acompañados de características de retroceso. Estas estructuras están conectadas por una única superficie de desplazamiento basal que cubre las aguas profundas a ultraprofundas. La información puede formar la base del modelo estructural 3D para su integración con los modelos estratigráficos y petrofísicos, con la representación de la distribución lateral y vertical que son importantes para la disminución del riesgo exploratorio, contribuyendo al conocimiento del Margen Ecuatorial y la Cuenca de Barreirinhas.

Palabras-clave: Margen Ecuatorial Brasileño; Tectónica Gravitacional; Sistemas Extensivos de Compresión.

1. INTRODUCTION

The knowledge of the structural framework and the tectonic context are essential for understanding the performance of the petroleum system in a sedimentary basin and for the construction of 3D structural models allows a simultaneous visualization and an integrated interpretation of different geological elements (PAVLOVSKI, 2009).

The Brazilian Equatorial Margin includes Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará and Potiguar basins. These basins are structurally complex, with few published studies and few areas with 3D seismic data. On the continental margins, especially in regions with a large amount of sedimentary input, gravitational flows and associated deposits are identified, which are extremely important for the sedimentary construction of these places (ARAÚJO et al, 2009, p. 486).

The study of gravity tectonics has received special attention from the scientific community in recent decades, since important potential and/or oil-producing areas are structurally affected by deformations induced by a mobile basal level, such as the Gulf of Mexico, basins of East Brazilian margin, West African margin, basins around the Mediterranean (PEROVANO et al, 2009, p. 490).

Notable examples of structures related to gravitational tectonics and for the gravitational fold-and-thrust belts in the Equatorial Margin Basins (Brazilian and African) were presented by Zalán (1998; 2001, 2011), Oliveira et al. (2012); Da Cruz et al. (2009), Krueger et al., (2012), Perovano et al., (2009), Pellegrini and Ribeiro (2018); Corredor et al., (2005); Yang et al. (2020). However, despite being known, there are still many studies that can be carried out to contribute to a more complete interpretation of different geological elements.

According to Gilbert (2011) because deformation rates can control the generation of mass flows (i.e., turbidites) and displace large masses of water, understanding the mechanisms and kinematics of deformation in these systems can be critical to several fields, notably reservoir presence for hydrocarbon exploration and local sequence stratigraphy.

The present work aims to interpret 2-D seismic profiles and describe the subsurface structures associated with mass movements that resulted in the formation of gravitational fold-and-thrust belts, which constitute the compressive domain of an extensive-compressive system in the Barreirinhas sedimentary basin. The 3D structural modeling increases the knowledge of the structural framework in the region of gravitational fold-and-thrust belts that are present from the breaking of the continental slope to continental rise in deep to ultra-deep waters of the Barreirinhas Basin.

1.1. Study Area

The Barreirinhas sedimentary basin covers part of the coast and continental shelf of the Brazilian state of Maranhão, occupying an area of approximately 46,000 km², of which 8,500 km² are immersed (FEIJÓ, 1994, p. 103; TROSDTORF et al., 2007, p. 331, Figure 1).

The Brazilian Equatorial Margin was formed in a geological context of transforming tectonics resulting from the opening of the Atlantic Ocean in the Cretaceous (PELLEGRINI AND RIBEIRO, 2018, p. 486).

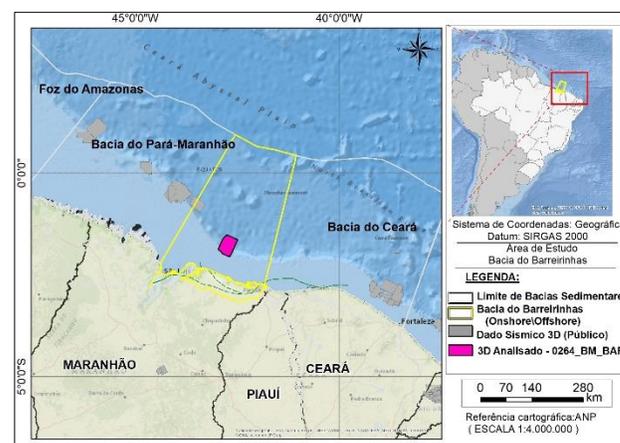


Figure 1 - Location map of the Barreirinhas Basin.

1.2. Geological Setting

Structural styles characteristic of transtensive rifting along this plate boundary led to a segmented evolution of the Equatorial Margin, with sub-basins that present contrasting histories in terms of thermal flow, subsidence, sedimentary facies distribution, magmatism, uplift events and episodes of deformation (MILANI, 2000, p. 362).

In these areas it is possible to identify structures with compressive components, transcurrent (SZATMARI et al., 1987, p. 180) and, especially in regions of significant sedimentary input, structures related to the gravitational tectonics induced by the movement of sedimentary sequences over one or many detachment levels (PEROVANO et al., 2009, p. 1; DA CRUZ et al., 2009, p. 1). It is the target of the present study (Figure 2).

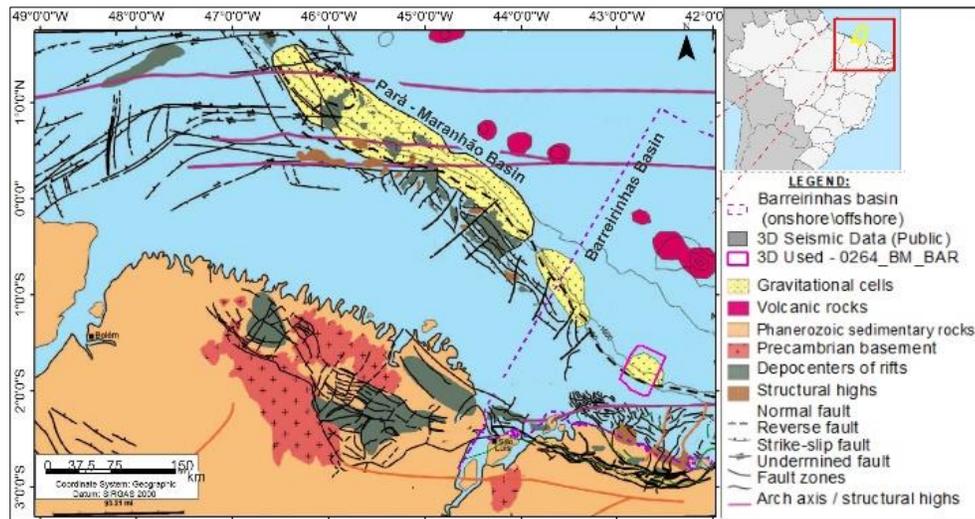


Figure 2 - Structural framework of the Brazilian equatorial margin with representation of the gravitational and structural systems present in the Pará-Maranhão and Barreirinhas Basins and the location of the 3D survey area used in the study. Source: Modified de Oliveira, et al., (2012).

The dynamics of the African and South American plates during the rift and continental drift phases are divided into three distinct domains considering the nature and orientation of the regional tension fields: A predominantly extensive region, between southern Argentina and the extreme northeast of the Brazilian coast; a segment of transforming nature, which corresponds to the Equatorial Atlantic; and the region to the north of Foz do Amazonas, where again extensive processes operate (MILANI, 2000, p. 358).

In the Equatorial Atlantic region, the E-W direction stretches are directly related to the nucleation of oceanic fracture zones in areas of continental crust, while the NW-SE stretches reflect the oblique rupture of the old Precambrian cratons during the continental drift (ZALÁN, 2004, p. 1) (Figure 3).

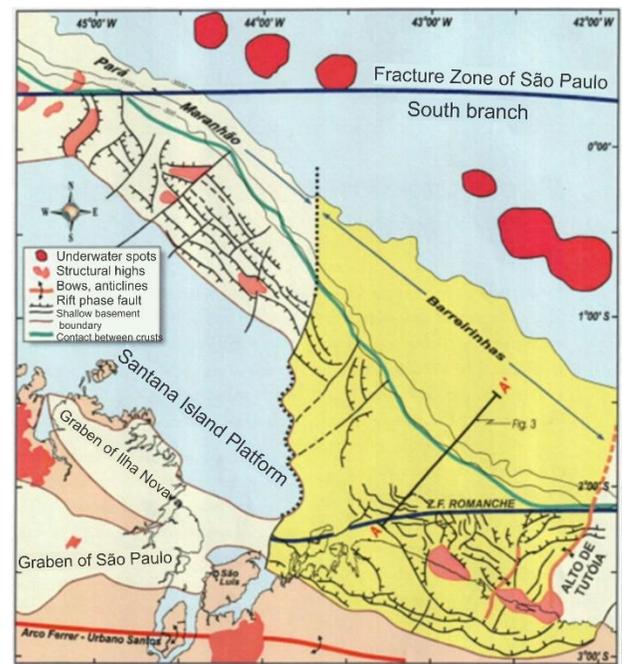


Figure 3 - Location, limits and structural framework, at the level of the rift section, of the Barreirinhas Basin. Source: Zalán et al., (2004).

According to Brandão & Feijó (1994) the Barreirinhas Basin is composed of three tectono-stratigraphic sequences: Rift sequence (Pre Aptiana), Post-Rift sequence and Passive Margin sequence (drift).

The rift sequence is represented by the Canary Group, of Mesozoic age, composed of a section of immature lithic sandstones, siltstones and greenish shales. These strata are interpreted as deposits of delta fans responsible for the early filling of the basin (MILANI, 2000, p. 362).

The post-rift stage in the margin evolution is represented by the Caju and Humberto de Campos Groups. The first of Neozoic age is composed mainly of carbonates from high and low energy neritic environments. The second group consists of a classic sedimentary complex platform-slope-basin, the Travosas Formation being composed of deep-water facies associated with sandstones of turbiditic flows (BRANDÃO & FEIJÓ, 1994, p. 104; MILANE, 2000 p. 362).

In the drift stage, in the region of the basin platform/slope, gravitational extensive-compression systems predominate, these induced by the movement of sedimentary sequences over the detachment of one or more levels of depressurized shales (DA CRUZ et al., 2009, p. 1) and forming true gravitational-folding-and-thrust belts frequently observed in ultra-deep waters (ZALÁN, 2001 p.1; ZALÁN et al., 2004, p. 6).

The extensive-compressive system associated with the detachment surface can be divided into three tectonic domains: extensional, translational and compressional (Fig. 4). The extensional domain is characterized by normal listric faults associated with rollover anticline and synthetic sedimentary wedges tectonics, with often antithetic faults to the main fault (ZALÁN, 2001, p.1).

The translational domain is predominantly undeformed, and there may be a slight arching of the rocks. In the compressional domain, generally called gravitational fold-and-thrust belts, is possible to observe many types of reverse and thrust faults, as well as several types of fault-related folding: detachment folds, fault-propagation-folds, and fault-bending folds. Described by Zalán (1998, 2001, 2005).

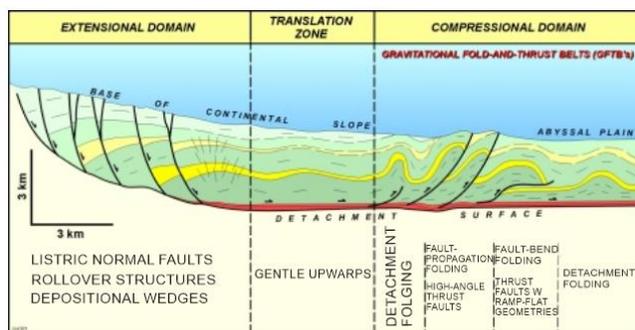


Figure 4 - Illustration of the Extensive-Compressive System with its domains and main structures present in each one. Source: Zalán (2011).

Gravitational mass movements and the structures associated with them can be generated due to the sliding of unstable

sediments that were quickly deposited through the basal level of detachment, induced by the inclination of the seabed (PEROVANO et al., 2009, p. 460; OLIVEIRA et al., 2012, p. 1). The movements occur when fine sediments or fractured rocks are subjected to the effects of hurricanes, storms or high pore pressures (OLIVEIRA et al, 2012, p. 1).

2. MATERIALS AND METHODS

For the execution of the present work, a workflow was used that considers everything from the choice and loading of data in interpretation software to the construction of the structural framework by 3D modeling (Fig. 5).

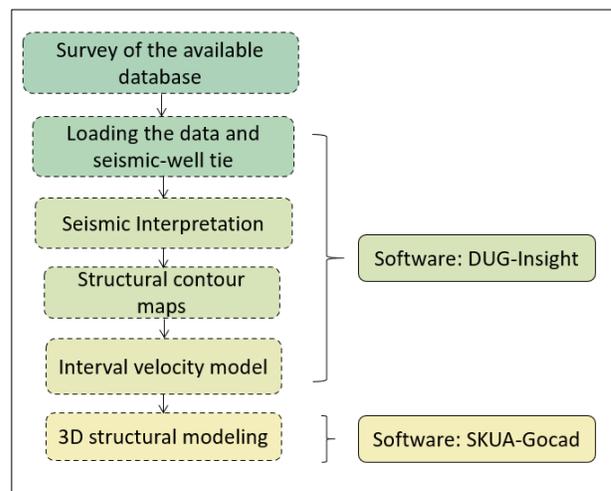


Figure 5 - Workflow used for interpretation and 3D structural modeling in the Barreirinhas Basin.

The data used in this work belong to the 3D pre-stack seismic survey 0264_BM_BAR_1, which covers part of the center-south area of the Barreirinhas Basin. Well data from 2 wells within the study area were also used: 1-BRSA-729-MAS (MAS-35) and 1-BRSA-1015-MAS (MAS-36) (Figure 6). This data set was provided by the Petroleum, Natural Gas and Biofuels Database - National Petroleum Agency (BDEP-ANP).

The 3D seismic survey was acquired according to the structural features dip and strike (inline and crossline), respectively, in NW-SE and SW-NE, contemplating the continental slope to continental rise in deep to ultra-deep waters, where the combination of a thick sediment pile, steep basinward surface slope, and a gentle landward basal slope commonly generates shear stress to promote basinward sliding up the basal slope (DAVIS et al., 1983; DAHLEN, 1984).

Figure 6 shows the survey grid of the seismic survey with the lines (inline and crossline), the study area and the location of the sections that will be presented throughout this work (il 4139, il 3589, il 3579 and Arblin).

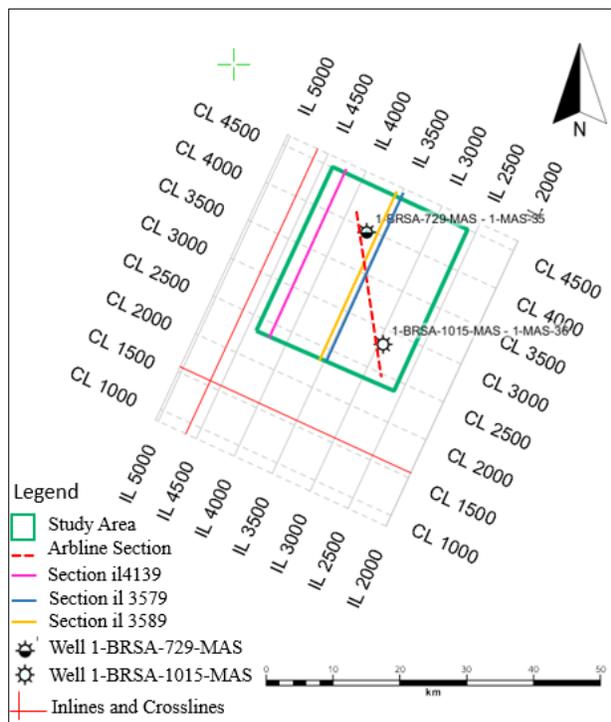


Figure 6 - 3D pre-stack seismic survey 0264_BM_BAR_1 in the study area. Note the NW-SE and SW-NE orientation of the inlines and crosslines.

The data set (seismic and well) were subsequently loaded into the DUG-Insight software, where the traditional interpretation flow was carried out with the mapping of reflectors of interest that showed characteristics that helped in the description and identification of the types of subsurface structures related to movements and mass flow and associated with the formation of gravitational- folding-and-thrust belts.

The mapped surfaces were defined based on the integration of information from the composite profiles of the available wells and the correlation with the reflectors present in the reflection seismic, according to the variations in the behavior of the electrical profiles and contrast of the seismic reflectors.

The seismic information and the well data were also used for the well-seismic tie. The seismic horizons were interpreted and the data were converted from the time domain to the depth domain using an interval velocity model obtained in well 1-BRSA-729-MAS (MAS-35) and also of checkshot information.

Finally, the structural contour maps of the tops of the surfaces and the faults associated with them, exported and loaded on the SKUA-GOCAD platform where the 3D structural modeling was developed.

3. RESULTS AND DISCUSSION

The structural features mapped in this work were related to gravitational tectonics (ZALÁN, 1998 p.362; TROSDTORF et al, 2007, p.335; ZALÁN, 2001 p.2; 2005) in which the formation mechanism is associated with gravitational collapse processes on

the platform and compressions in the oceanic crust region, particularly in regions affected by fracture zones (AZEVEDO et al, 2012 p.2).

According to Zalán (2011) the activity of faults and related deformation and their influence on the sedimentation of growth strata in the compressional domain point to a single long-term event (Eocene to Oligocene) of slip and contraction.

In addition to the seismic mapping of the faults, six seismic horizons were mapped, thus enabling the elaboration of the structural framework consistent with the appropriate geological time.

3.1. Compressional domain of the extensive-compressive system in the Barreirinhas Basin

From the interpretation of the seismic data, it was possible to identify and map reverse and thrust fault surfaces, fault propagation folds and fault bend folds, in the region that extends from the continental slope to continental rise, and are connected via basal level of detachment. These structures are associated with the gravitational collapse of the marine sequences of the basin, which consequently compress in the region of the oceanic crust, in a deep marine environment (deep and ultra-deep waters with bathymetry between 1400 to 2200 m). The deformation of the sediments indicates the presence of compressive stress due to the accommodation of the gravitational collapse, and characterizes the distal compressive domain of an extensional-compressional system. Conceptually these features are called gravitational fold-and-thrust belts - GFTB's (ZALÁN, 2001, p.3).

The deformed region by the thrust front has an NW-SE orientation, and is about 16 km long in parallel to the coastline (strike section) and 21 km in the continental slope- continental rise direction (dip section), resulting in a total deformed area of approximately 336 km². These structures are approximately 5500 m deep below the ocean floor, which can reach more than 2000 m of water depth, with a seismic traveltime of 5800 milliseconds. The thrust fault surfaces are about 20 km long and the distance between them is approximately 6.5 km.

The seismic interpretation carried out shows that the slide of the marine section of the basin occurred along a single detachment surface (basal level). The overlapping of the thrust faults branched upwards from the detachment surface, where there is presence of fault-related folds, which reflect the shortening of the upper crust. Correlating with existing studies, the detachment surface is formed by shales and/or overpressurized marshes from the Upper Cretaceous/Paleogenic (DA CRUZ et al, 2009, p.1; KRUEGER et al, 2012, p.12; OLIVEIRA et al, 2012, p.174).

As a result of the affected compression zone, there is a set of fault-related folds, which are illustrated through seismic sections il 3589; il 3579, il 34139 and Arbline. Seismic section il 3589 (Fig. 7) shows a fault bend fold to the SSW and a fault propagation fold to the NNE. This section has a SW-NE orientation (Fig. 6), which is in the central part of the study area and there are other structures related to the deformation development. These folds are accompanied by features with SSW direction vergence, opposite to the main fault, and were interpreted as backthrust faults.

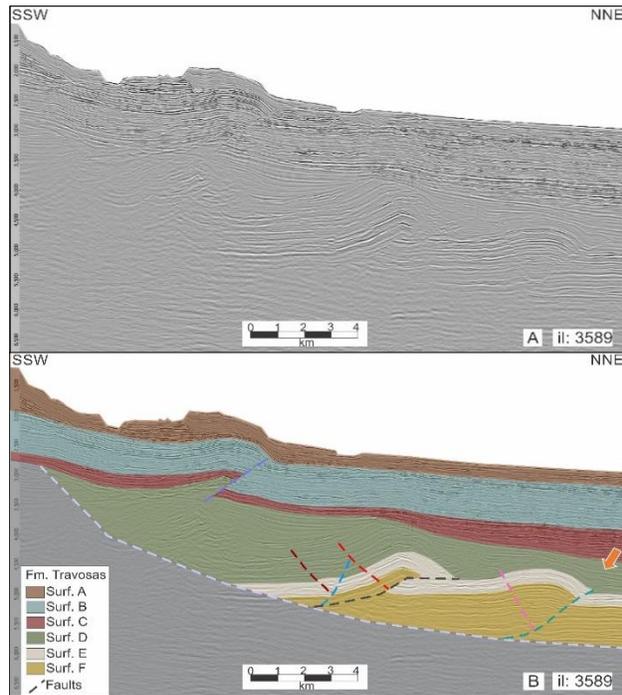


Figure 7 - Seismic section il 3589 in the time domain. (A) Not interpreted and (B) Interpreted. Note a fault bend fold to the SSW and a fault propagation fold to the NNE, accompanied by a backthrust fault. The orange arrow shows the thickening of the section along the compressive front and folding of the syntectonic layers.

The backthrust refers to a thrust fault with an opposite vergence to that of the main thrust system or thrust belt (McCLAY, 1992, p. 419). It was considered as a backthrust because a displacement of these reflectors is perceived, as illustrated by the dashed lines (white and black) in the seismic section il 3579 (Fig. 8). The resulting structure of the process is analogous to that of a pop-up.

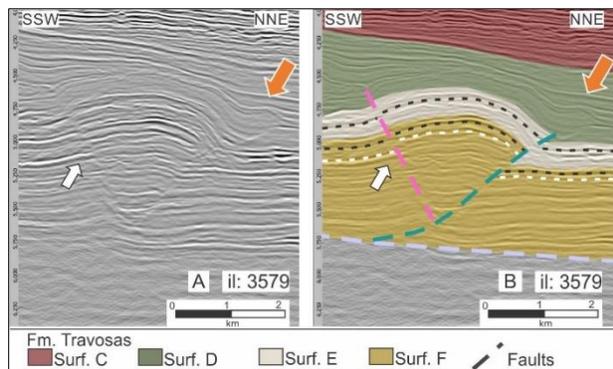


Figure 8 - Zoom on the il 3579 seismic section in the time domain. (A) Not interpreted and (B) Interpreted. Detail of the fault bend fold accompanied by a backthrust fault. The dashed lines, white and black, show the displacement of the reflectors.

The section il 4139 (Figure 9), is located to the northwest of the area (Fig. 6), marks one of the limits of the deformation area and consequently of the main structures found. In the southernmost area (SSW) of section il 4139, a fault propagation is a fold generated by propagation of thrust tip up a ramp into undeformed strata (McCLAY, 1992, p. 428).

In the central region of the previous section, heading north (NNE), the formation of a fault bend fold is observed, this is usually generated by movements of a thrust sheet over a ramp (McCLAY, 1992, p. 428). The last fault observed in this sequence, in the NNE direction of the seismic section il 4139, was also considered as a fault propagation fold.

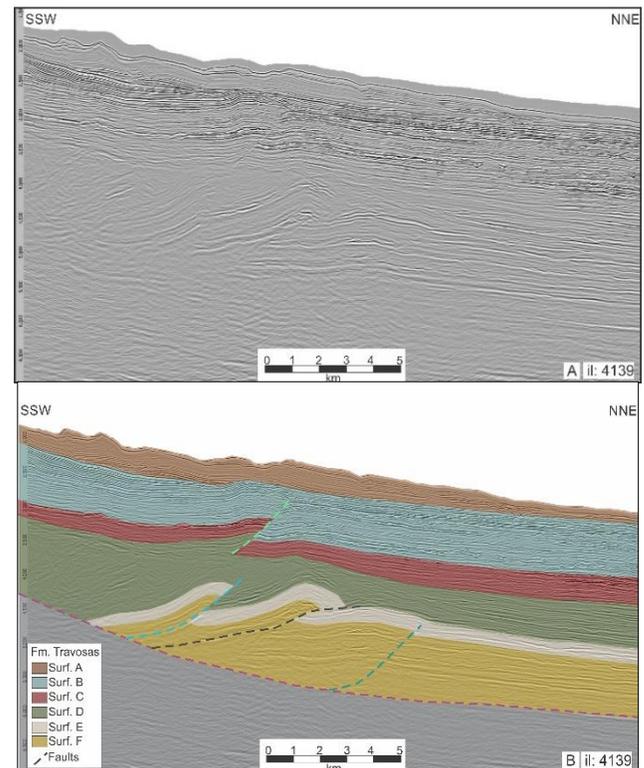


Figure 9 - Seismic section il 4139 in the time domain. (A) Not interpreted and (B) Interpreted. Fault propagation fold to section SSW. Fault bend fold, in the center of the seismic section and, at NNE, fault propagation fold.

The deformation is probably initiated with folds that give rise to overlapping of reverse faults and with the evolution of the deformation they form overlapping faults that can be accompanied by ramp-and-flat thrust and backthrust fault.

The fault surfaces increase the dip angle, verticalize, and then move horizontally. The resistance to horizontal movement increases until the layers are unable to slide, bending and, consequently, forming anticlines (PEROVANO et al., 2009. p. 472).

According to the interpretation, the gravitational collapse compressed the pre-tectonic units, that's can be observed a sindepositional shortening. The final effect of the shortening is the thickening of the section along the compressive front and folding

of the syntectonic layers, represented by the orange arrow in Figures 7 and 8 above. There are syndepositional and postdepositional structures, which show reactivations after the formation of the folding and overlapping gravitational belts, such as the reverse fault interpreted in the upper strata seen in the presented sections, but which will not be detailed in this work.

Through the Arbline section (Fig. 10) that intercept the two exploratory wells existing in the region (1-BRSA-729-MAS and 1-BRSA-1015-MAS), and through the composite profile data, it is noted that well 1 -BRSA-729-MAS tested the turbiditic reservoirs at the apex of this structure, analogous to the pop-up, formed by the consequent deformation of the fault propagation fold and backthrust that accompanies it.

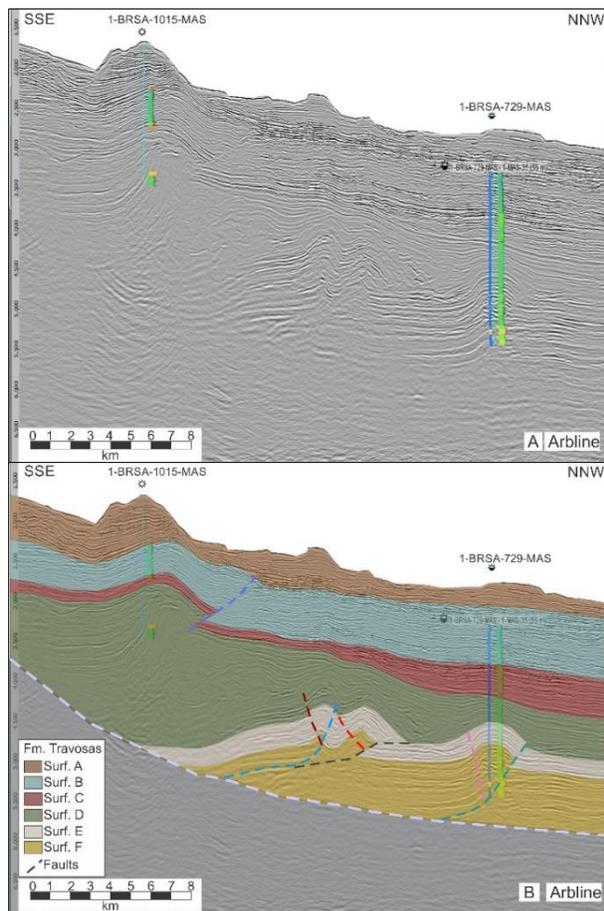


Figure 10 - Arbline seismic section, in the time domain. (A) Not interpreted and (B) Interpreted. Section that intercept the two exploratory wells existing in the region (1-BRSA-729-MAS and 1-BRSA-1015-MAS). Note that well 1-BRSA-729-MAS tested an anticline structure formed by the consequent deformation of fault propagation fold and backthrust that accompanies it.

Traces of gas were reported in these turbiditic reservoirs of the Travosas Formation, validating the petroleum system in the area. This well was classified as dry with gas shows and was abandoned. Well 1-BRSA-1015-MAS is less deep and tested younger reservoirs of the Travosas Formation in an anticline structure associated with structures that deform post tectonic sediments, formed by more recent reactivations than the main structures emphasized in this work. This well is a petroleum exploration well with gas shows.

For Oliveira et al, 2012 (p.165), the geometric analysis of faults, folds and growth strata seen in the seismic profiles that cover this region, allows to characterize the propagation of normal listric faults (in the extensional domain) and thrust faults as a backstep sequence. In this sequence, normal and reverse faults are younger towards the continent, with the consequent migration from depocenters to land during geological time, featuring out-of-sequence thrusts.

3.2. Structural Maps

To better understand the control mechanisms of gravitational tectonics in the Barreirinhas Basin, structural contour maps of the syntectonic sedimentary cover were made, where areas that were raised and areas that were depressed with the development of the structures that formed the gravitational fold-and-thrust belts can be observed. Characteristics that helped in the description and identification of the types of subsurface structures associated with the formation of gravitational-folding-and-thrust belts are shown through the contour surfaces named E and F, mapped close to the detachment surface, present in the time domain, are shown in Fig. 11.

Through the structural maps of the surfaces, it is possible to observe that the thrust fronts that form the gravitational fold-and-thrust belts and overlapping have a northwest-southeast orientation and form large folds and consequent anticline. The structural style of the gravitational fold belt is typical of a thin-skinned tectonic system as a deformation mechanism, in which tectonic efforts did not affect the basement, where there is deformation only in the sedimentary cover. The deformed region by the thrust front with NW-SE orientation is about 16 km long parallel to the coastline (strike section) and 21 km in the continental slope- continental rise direction (dip section), resulting in a total deformed area of approximately 336 km². These structures are approximately 5500 m deep below the ocean floor, which can reach more than 2000 m of water depth, with a seismic travelttime of 5800 milliseconds. The thrust fault surfaces are about 20 km long and the distance between them is approximately 6.5 km.

Most of the compressive deformation does not reach the current submarine bottom, demonstrating that the deformational process has ceased to form a paleo-fold-and-thrust belts under-riding in the continental slope.

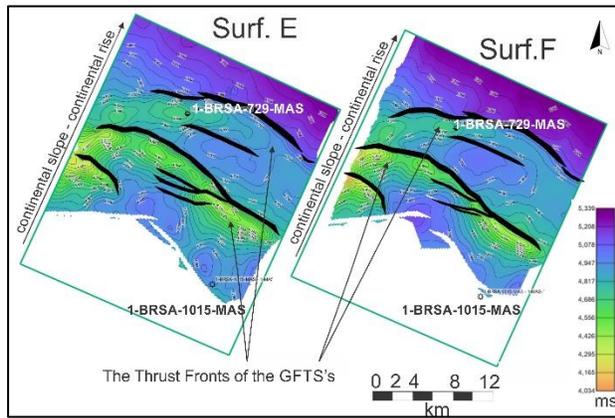


Figure 11 - Structural contour maps of the syntectonic sedimentary cover, in the time domain, of the top of the surfaces named E and F.

3.3. 3D Structural Modeling

The construction of the 3D structural model, performed using the Skua-Gocad software, was based on the surfaces of the horizons and faults mapped in the interpretation phase. Firstly, the conversion from the time domain to the depth domain was performed using an interval velocity model obtained in well 1-BRSA-729-MAS (MAS-35) and also from checkshot information so that for the 3D structural modeling developed in the domain of depth. The 3D visualization of the gravitational fold-and-thrust belts highlights the geometric variations that were found throughout the different profiles and strata interpreted.

Figures 12 and 13 represents the 3D visualization of the structural framework intercepted with the seismic sections il: 3589 and il: 4139 respectively, in the continental slope-slope direction (left to right) and the representation of the 6 reflector surfaces (Sup. A, Sup. B, Sup.C, Sup.D, Sup.E, Sup.F) and the faults that have been mapped.

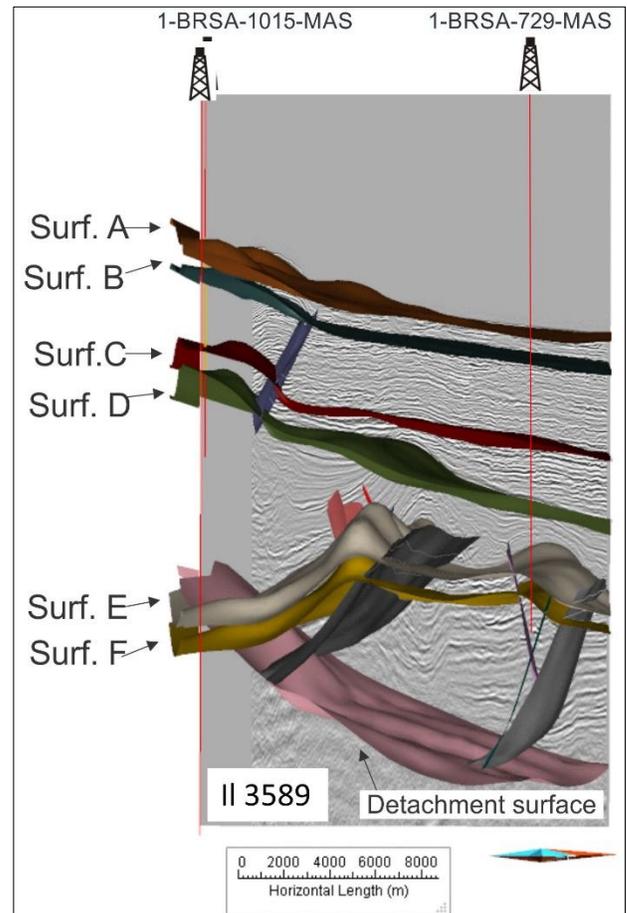


Figure 12 - 3D visualization of the structural framework intercepted with the seismic section il: 3589.

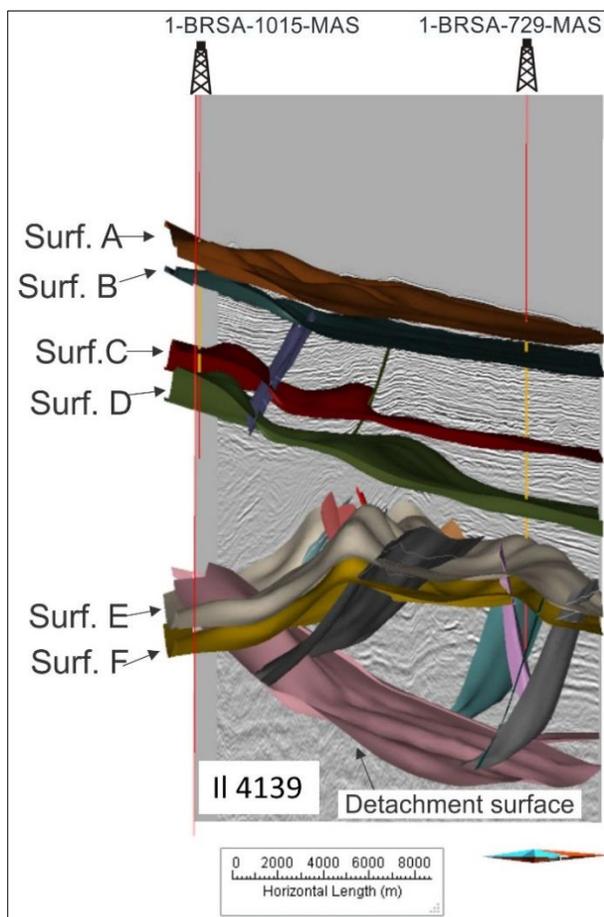


Figure 13 - 3D visualization of the structural framework intercepted with the seismic section il: 4139.

Figure 14 shows the surfaces E and F, which represent the deepest mapped reflectors and faults. These surfaces are related as the most relevant deformations and, consequently, it is more easily noticed as structures that comprise the thrust fronts of gravitational fold-and-thrust belts. In the lower part of the section, the detachment surface is shown, where the deformation is established through the overlapping of the thrust faults which branch upwards from these surfaces and cause the fault-related folds.

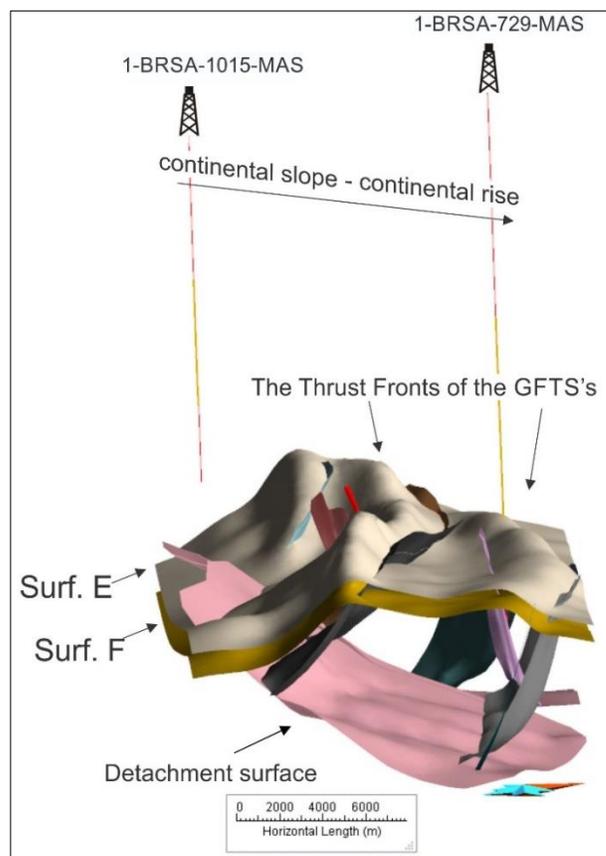


Figure 14 - Representation of the structural framework with emphasis on the Sup. E and Sup. F. On these surfaces, it is possible to see the thrust fronts of the gravitational fold-and-thrust belts. The detachment surface is also shown.

4. FINAL CONSIDERATIONS

The structures mapped in the study area are inserted within the compressional domain of an extensive-compressive system. They correspond to the thrust fronts of the gravitational fold-and-thrust belts (GFTB's) which are intrinsically associated with the gravitational collapse of the marine sequences of the basin and consequent compression in the oceanic crust region. The gravitational collapse compressed the pre-tectonic units and a syndepositional shortening. The final effect of the shortening is the thickening of the section along the compressive front and folding of the syntectonic layers.

Through the structural contour maps elaborated, it is noted that the thrust fronts present in the area have NW-SE orientation with 16 km long parallel to the coastline (strike section) and 21 km in the continental slope- continental rise direction (dip section) resulting in a total deformed area of approximately 336 km². These structures are approximately 5500 m deep below the ocean floor with more than 2000 m of water depth, with a seismic traveltimes of up to 5800 milliseconds. The thrust fault surfaces are about 20 km long and the distance between them is approximately 6.5 km.

The presence of reverse and thrust faults, fault-related folds, such as fault bend fold and fault propagation fold, as well as backthrust fault were verified. These geometries are more implied from a deformation of a true plastic shale. These structures are connected by a single basal detachment surface and reach the ultra-deep waters of the Barreirinhas Basin. The behavior of this surface is characteristic of a thin-skinned tectonic system, in which the tectonic efforts did not affect the basement.

In addition, most of the compressive deformation does not reach the current submarine bottom, demonstrating that the deformational process has ceased to form a paleo-fold-and-thrust belts buried in the continental slope.

Through the sections il 3589, il 3579, il 4139 and Arblin presented above, part of the development of the structures present in the area can be observed. A fault bend fold to the SSW and a fault propagation fold to the NNE of the seismic section il 3589. These folds are accompanied by faults with SSW direction opposite to the main fault, which are possibly backthrust faults, as seen in detail in il 3579.

The structures present in section il 4139 show, to the SSW, a fault propagation fold, the central region of the section, going north (NNE), a fault bend fold, and to the seismic section NNE il 4139 another fault propagation fold.

Through the Arblin section, that intercept the two exploratory wells existing in the region (1-BRSA-729-MAS and 1-BRSA-1015-MAS) and composite profile data, it is noted that well 1-BRSA-729-MAS tested the turbiditic reservoirs of an anticline structure formed by the consequent deformation of the fault bend fold mapped in the sections. These reservoirs also comprise a new play in ultra-deep waters in the Barreirinhas Basin.

The deformation is probably initiated with folds that give rise to overlapping of reverse faults and with the evolution of the deformation they form overlapping faults that can be accompanied by ramp-and-flat thrust and backthrust fault.

The seismic interpretation and consequent description of the types of structures present in the area, as well as the understanding the mechanisms and kinematics of the processes that are associated with the formation of gravitational fold-and-thrust belts was important to show that these areas have real oil potential when correlating them with models analogues which already have hydrocarbon production.

The mapping also contributed to dimensioning and highlighting these important structures.

The construction of the structural model allowed the 3D visualization of the Gravitational Belt for folding and overlapping, being important to represent the geometric variations that are present in the different profiles and strata interpreted throughout the study area which are important to evaluate the mechanisms that drive large-scale gravity glide systems.

According to Gilbert (2006), geometric differences implicit in the formation of true plastic shale masses versus coherent duplex fault blocks impact the hydrocarbon maturation and expulsion history, and migration pathways within structures. It is therefore important to discriminate between fault-cored structures and those produced by true plastic shale deformation.

In this work the seismic mapping of the subsurface structures and the 3D modeling of the structural-stratigraphic framework

brought new information that can be used in the identification and evaluation of structures with potential for hydrocarbon accumulations.

The availability of data in deep and ultra-deep waters in the Barreirinhas Basin is still very small, but the possibility of hydrocarbon production in the basin is quite relevant.

With the availability of data from more wells, it will be possible to integrate different geological elements. The information from this work can form the basis of the 3D structural model for integration with the 3D stratigraphic, lithological and petrophysical models, with the representation of the lateral and vertical distribution, through the modeling of properties such as facies, porosity and permeability, which are important for the decreased exploratory risk in these regions.

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