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# APPLICATION OF SEISMIC ARCHITECTURE INTERPRETATION IN PRE-SALT CARBONATE RESERVOIRS OF THE BUZIOS FIELD, SANTOS BASIN, OFFSHORE BRAZIL

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**ABSTRACT.** The Brazilian pre-salt carbonate reservoirs, in deep water, are examples of interesting places for oil and gas industry exploration due to their high production capacity. Oil and gas companies are often collecting information about the geology and the reservoir's characteristics to improve its understanding and consequently optimize the production results. Seismic interpretation is mandatory for the understanding of geology, always pondering reducing the risks during exploration. Seismic and well data are commonly used together as a useful approach to comprehend the geological history and provide a good reservoir characterization. In this paper, we performed the seismic interpretation of the pre-salt carbonate reservoirs of the Buzios Field, Santos Basin, and used seismic attributes to obtain a better comprehension, as the TecVA attribute. Also, we generated isopach maps for a better understanding of reservoir intervals. As a result, we achieved a better definition of fault distribution and tectonic behavior, as well as determined the main interval thickness and the possibility of build-up and coquina bank occurrence.

**Keywords:** seismic interpretation, reservoir characterization, pre-salt.

**RESUMO.** Os reservatórios carbonáticos do pré-sal brasileiro, em águas profundas, consistem em um dos locais mais procurados pela indústria de energia devido à sua capacidade de produção. Empresas de óleo e gás estão frequentemente adquirindo novas informações sobre a geologia e a caracterização de reservatórios, para melhorar seu entendimento e, consequentemente, otimizar os resultados da produção. Dados sísmicos e de poços são comumente usados juntos como uma abordagem útil para compreender a história geológica e fornecer uma boa caracterização do reservatório. A interpretação sísmica é obrigatória para o entendimento da geologia, sempre pensando em reduzir os riscos durante a exploração e a produção, auxiliando na compreensão da história geológica, além de fornecer informações necessárias para a caracterização do reservatório. Neste trabalho, realizamos a interpretação sísmica das principais discordâncias da seção do pré-sal do Campo de Búzios, Bacia de Santos, com o auxílio do atributo TecVA. Mapas de isópacas também foram gerados para um melhor entendimento das seções dos reservatórios. Como resultados, obtivemos uma melhor definição da distribuição de falhas e comportamento tectônico, bem como determinamos a espessura do intervalo principal e a localização de possíveis *build-ups* e bancos de coquinas.

**Palavras-chave:** interpretação sísmica, caracterização de reservatórios, pré-sal.

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## INTRODUCTION

The Santos Basin represents the largest pre-salt exploration and production area in Brazil. Currently, it accounts for more than 70% of the country's oil and gas production (ANP, 2021). In this context, the Buzios Field is considered a super-giant field with an estimated volume in place of 3,058 million barrels of oil equivalent. In January 2021, the outstanding result of 146,524 Bbl/d was achieved by the platform with the highest oil production in the country. In this Basin, the main reservoirs are the inner coquinas (a type of sedimentary rock composed mainly by shells and their fragments) of the Itapema Formation and the spherulitic, laminated deposits, shrubs, and reworked facies of the Barra Velha Formation (Gomes et al., 2020). The carbonate sedimentation processes are extremely sensitive to climatic factors, hydrodynamics, basin tectonics and morphology. These differences might cause vertical and lateral heterogeneity effects in seismic facies (Porta, 2015).

Castro (2019) showed that the Itapema Formation in the Buzios Field is less influenced by the presence of fine grain sediments and has better permeabilities than the Barra Velha Formation. Both formations are important pre-salt exploration targets and have quite different sedimentary-tectonic contexts.

The objective of this work is to understand the evolution of the rift and sag phases in the Buzios Field area from seismic data analysis. Furthermore, this paper intends to collaborate for a better understanding of the paleoenvironments and tectonic settings of the Itapema and Barra Velha formations, Barremian-Aptian succession of the Santos Basin.

### Geological Setting

The Santos Basin is located in the southeastern Brazilian margin, bounded by the Campos Basin at the North, and the Pelotas Basin at the South. Santos Basin is one of the most extensive offshore Brazilian basins, with an area of 352,000 km², and a current water depth of up to 3,000 m. The main structural features are the Cabo Frio High to the Northeast and the Florianópolis Platform to the Southwest, the Santos hinge line to the West, which marks the external (western) limit of the salt (Ariri Formation), and the São Paulo plateau to the East (Moreira et al., 2007). The Buzios Field is located in the Santos Basin (Fig. 1).

According to Moreira et al. (2007), the geological history of the Santos Basin can be divided into three phases: Rift, Post-rift and Drift. The Rift phase displays extension efforts of separation between the South American and African plates, which started from the Lower Cretaceous. Muniz and Bosence (2015) describe that the sequence of tectonic events that caused the fragmentation of Gondwana would have started from the stretching and thinning process of the continental crust, triggering a rifting process. This fragmentation consisted of a mixed process controlled by lithospheric stretching and thermal anomalies.

The breakup of Gondwana occurred over a complex and heterogeneous basement, composed of Paleoproterozoic–Archaean age cratonic blocks and Neoproterozoic orogenic rocks (Heilbron et al., 2008), in addition to presenting a Paleozoic sedimentary coating covered by Eocretaceous volcanic rocks. As stated by Moreira et al. (2007), the crystalline basement of the Santos Basin, generated in the context of Gondwana's amalgamation, is characterized by granites and gneisses from Precambrian age of the Coastal Complex and metasediments of the Ribeira Belt (Moreira et al., 2007). During the main rifting process, around 145 Ma, the northwestern portion remained closed while a wedge was extended to the South, along the east of South America (Szatmari and Milani, 2016). According to the authors, volcanism would have been absent where the lithosphere was thick.

An important consequence during the rift phase was the space-forming mechanism for sedimentary accommodation in an extensional tectonic setting, and widespread normal fault generation due to the mechanical subsidence process, causing reactivation of faults in the Precambrian basement (Mohriak et al., 2008).

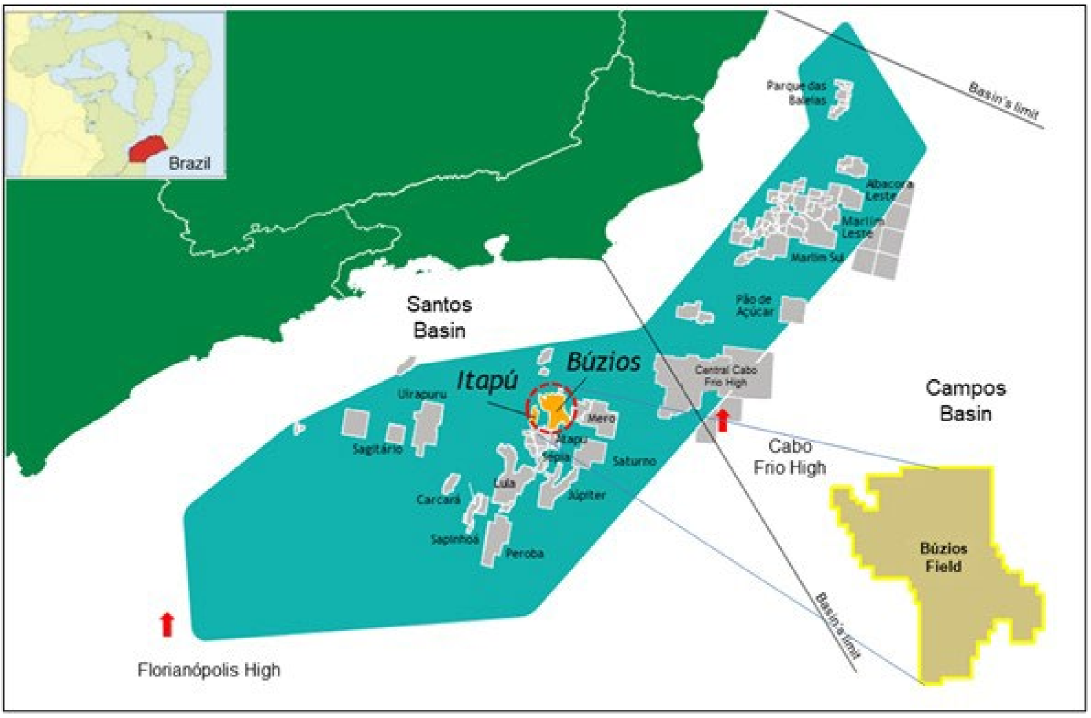


**Figure 1 -** Location map of the Buzios Field.

Strugale et al. (2021) point out that the different basement compositions represent another determining factor for the way the rifting process takes place. Where the basement is heterogeneous, the pre-existing fabric was reactivated whenever its orientation was favorable, producing faults as the extension direction rotates, whereas low to very low angle basement fabric were cross-cut by rift faults. Where the basement was homogeneous and more stable, only the previous formed faults remained active throughout the rifting. Another effect observed was the contribution and influence of thermal anomalies in the region of the Santos Basin, which would have been responsible for inducing the strain softening process since the beginning of the rift, leading to the development of uplifted areas (ANP/LEBAC, 2003). The importance of understanding the different processes related to the rifting phase relies on comprehending its influence during the deposition of the overlying sedimentary layers.

The rift super-sequence is composed of continental siliciclastic, talc-stevensite ooids with interbedded lacustrine coquinas and organic-rich shales of the Piçarras and Itapema formations, consisting of essentially continental sediments (Szatmari and Milani, 2016). As opposed to what was proposed by Moreira et al. (2007), Wright & Barnett (2015) state that the lower part of the Barra Velha Formation belongs to the rift phase. During the rift phase, the sediments from the bottom of the Barra Velha Formation were deposited. These deposits show a prominent wedge geometry, which may represent differences in the fault movement rate that consequently created space for accommodation (Buckley et al., 2015). Thus, they state that this may represent an increase in the sedimentation rate at the base of the Barra Velha Formation when compared to the Piçarras and Itapema formations.

The post-rift sequence, also known as the sag phase, is represented by the Upper Barra Velha Formation, which is characterized by shrubs, spherulite, laminated deposits and reworked facies (Gomes et al., 2020) precipitated in non-marine carbonate successions (Wright & Barnett 2015). The absence of unambiguous palaeoecologically significant fossils, together with the presence of the mineral stevensite rather than marine-derived evaporates (sulphates and chlorides), indicates an alkaline lacustrine setting with a volcanic source area (Wright & Barnett 2015).

In short, the pre-salt reservoir rocks are mainly in the Itapema and Barra Velha formations.

The Itapema Formation is represented by grainstones to bivalves (coquinas), wackestones and bioclastic packstones, carbonate shales, and dark shales rich in organic matter, which sometimes also work as source rocks. The Barra Velha Formation is composed of carbonates deposited in a lacustrine environment with a multiplicity of facies from boundstones and grainstones to mudstones. The Itapema Formation is limited at the bottom by the Jiquiá/Buracica unconformity (126.4 M.y.) and at the top by the Pré-Alagoas unconformity, while the Barra Velha Formation is limited at the bottom by the Pré-Alagoas unconformity and at the top by the Base of Salt (Moreira et al. 2007).

## METHODOLOGY

The seismic data provide information about the regional context, depositional systems, tectonic history and allow inferring geological features and heterogeneities, favoring better understanding of sedimentary basins. The interpretation of seismic reflection terminations (onlap, downlap, toplap and erosive truncations) is the main criteria for the recognition of stratigraphic units . They are essential to better understand the resulting processes, allowing foreseeing the current geological behavior (Mitchum et al., 1977). We performed the identification of seismic parameters to recognize information about the depositional environment, source of sediments and the geological context, in which the seismic facies were deposited.

In carbonate rocks, due to the high heterogeneity of these rocks, the integration of well and seismic data is essential for the reservoir characterization. The steps used to develop this work are summarized in Figure 2. The seismic data used consist of a PSDM volume (prestacked depth migration), on which we apply a structural smoothing filter to remove part of migration smile noises. The parameterization was a median filter, with a vertical window (5mx5m) not to lose the vertical resolution and a lateral window of (7.5m x 7.5) (x,y). Then, we interpreted four important unconformities in the pre-salt zone: (i) Economic basement; (ii) Jiquiá-Buracica unconformity (Piçarras and Itapema Formations); (iii) Pré-Alagoas unconformity (top of coquina deposits and the boundary between Itapema and Lower Barra Velha Formations); (iv) Intra-Alagoas unconformity, which separates the Lower Barra Velha from Upper Barra Velha; and (v) the Base of the Salt. Data from 15 wells (Fig. 3) helped in the seismic interpretation based on the identification of the boundaries between the lithostratigraphic units. We selected well 9-BUZ-4-RJS through section BB' to represent the identification of the main unconformities (and formation boundaries) and for analysis of depositional environment (Fig. 3). Previous works were also fundamental for a better understanding of the sedimentary-tectonic history of the study area (Castro, 2019; Ferreira et al., 2021a, 2021b).

The seismic attribute TecVA (Bulhões and Amorim, 2005) was applied to highlight reflection events, which is calculated from the absolute amplitude or RMS (Fig. 4). After calculating the absolute value of the trace (RMS amplitude) and its estimation of the seismic trace envelope, the debias filter is applied, and finally a phase rotation at -90º (Hilbert transform).

## RESULTS AND DISCUSSION

The pre-salt succession of the Santos Basin was described in this work based mainly on the (i) identification of seismic reflection terminations and the (ii) interpretation of regional unconformities and faults (Figs. 5, 6, 7 and 8). We recognize in Figure 5 the erosional truncations as reflectors that end on the base of the salt, as a result of possible erosion, especially in the region at the east of the F1 fault, which caused a strong tilt in the strata. We also visualized the amount of onlap markings, present mainly in the region of a build-up, to the East (Fig. 6). It is noted that the

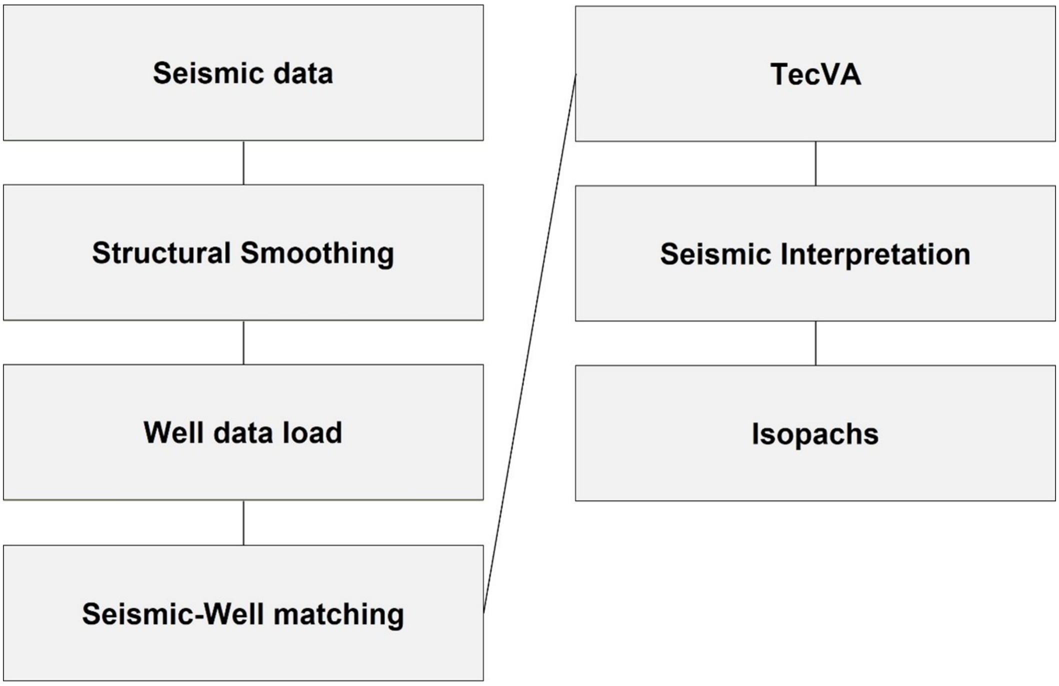


**Figure 2** - Location map of the Buzios Field.

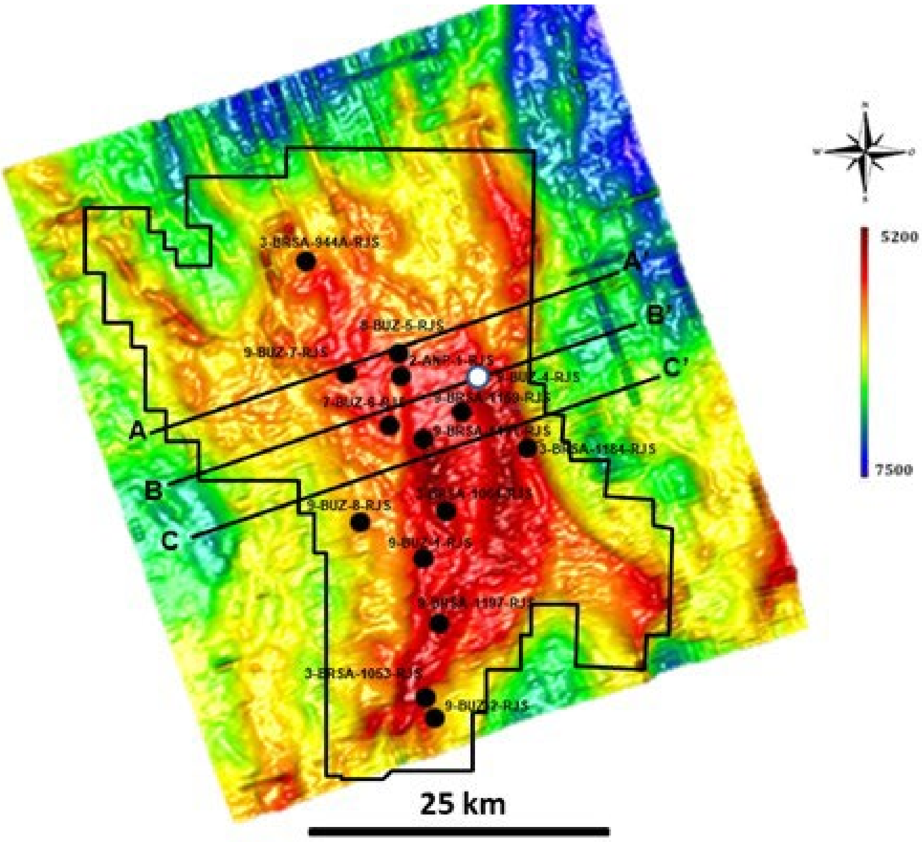


**Figure 3** - Location map of the Buzios Field.

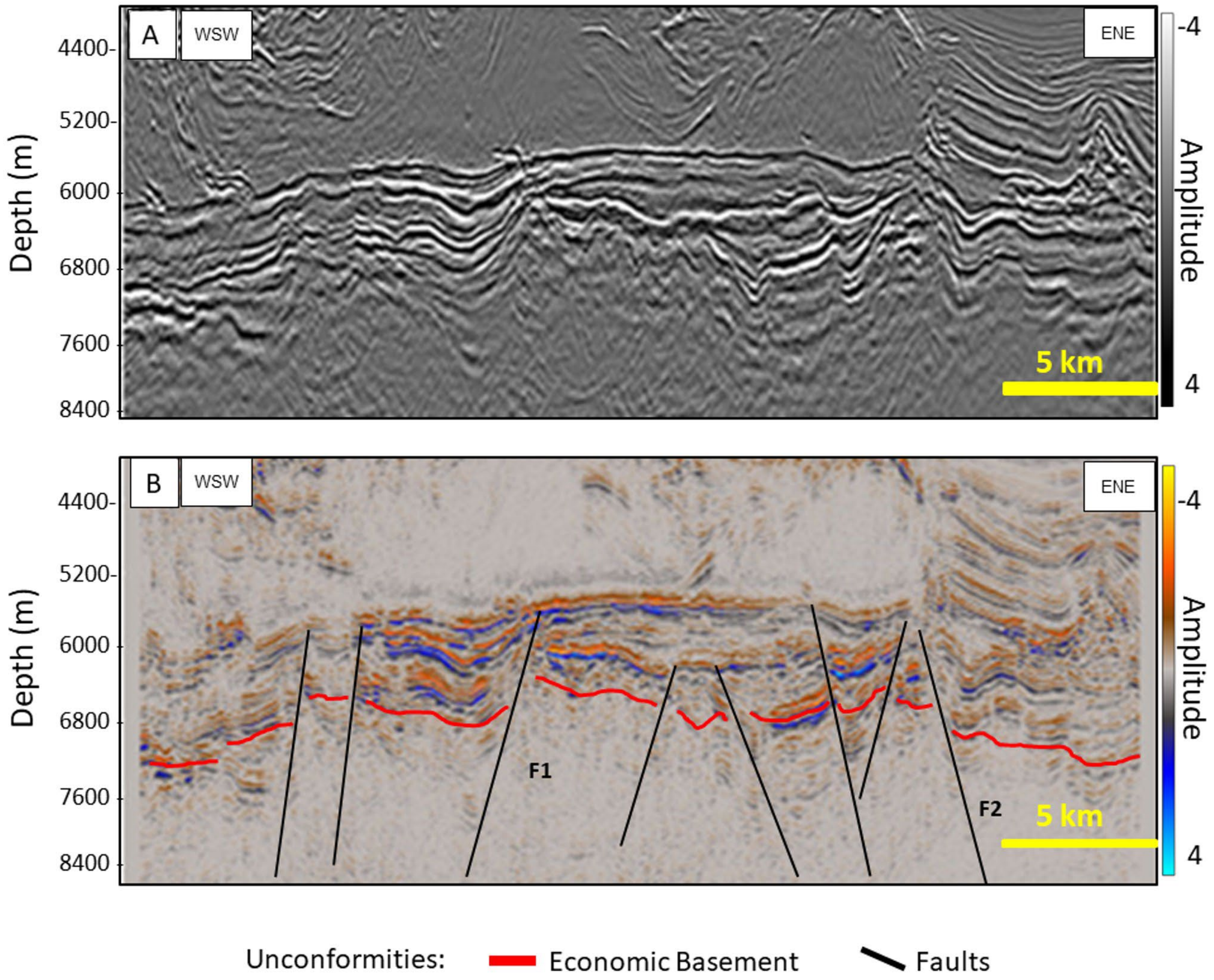


**Figure 4** - Section AA'. Original Seismic (A) and TecVA attribute (B) with Economic basement (red) and main faults (black) highlighted.

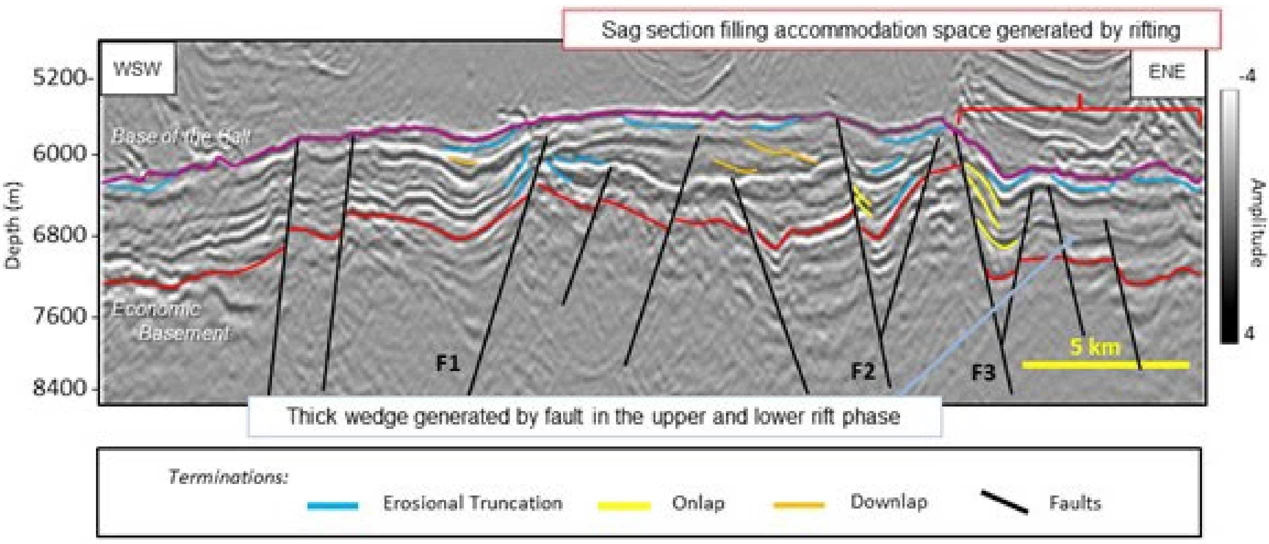


**Figure 5** - Section AA'. Schematic stratigraphic sequences and angular relationships defining the boundaries of the stratigraphic units.

horizontal strata ends against an inclined surface, being in this case a possible build-up (Figs. 5 and 6). This onlap configuration is very present in places with faults (F2-F3 in Fig. 6) that were generated during the rifting process, which has influence on the formation of accommodation space and generation of wedges in the synrift interval (Fig. 5). It is worth mentioning the possibility of apparent onlaps, terminations that previously presented downlap characteristics, but which underwent a change in geometry due to tectonic activity in half-graben systems, causing a new disposition of the lateral layers as a consequence (Hart, 2000).

The Economic Basement was interpreted as a high amplitude reflector due to the high impedance contrast of the basalts with the siliciclastic deposits of the Piçarras Formation. The TecVA attribute helped during the interpretation of this surface (unconformity). This attribute allowed improving the characterization of the seismic facies below the basement, which is characterized as chaotic of low amplitude. In addition, TecVa also highlighted the faults of the pre-salt section (Fig. 4B). The typical pattern of the basement is the absence of internal reflections or the presence of chaotic reflections. The pre-salt interval in the Buzios Field has horst-graben systems, characteristic of extensional basins (Figs. 5, 6, 7 and 8). The faults are very consistent along the entire rift pre-salt rift succession. These two aspects have influence on geological sedimentation, and the faults might act as fluid conductors (Moreira et al., 2007; Szatmari & Milani, 2016) throughout the studied sections. In these seismic sections, the fault's orientation is N-S and can reach up to 2 km of displacement. In the syn-rift segment (below Intra-Alagoas unconformity), we observed medium to low amplitude reflectors, with subparallel and wavy configurations of medium continuity and low frequency, representing deposits of clastic sediments of the Piçarras Formation.

The next unconformity interpreted was Jiquiá-Buracica that delimits the lower Itapema Formation. The probable coquinas were interpreted as lacustrine deposits located at structural highs, deposited under shallow and high-energy conditions (Figs. 6 and 7) (Chinelatto et al., 2020). The Itapema Formation presented progradational to chaotic seismic facies during the seismic interpretation. Debris flows were also identified according to seismic reflection terminations added to the amplitude information, a possible result of the fragmented configuration due to the rifting process.

In the Pre-Alagoas unconformity interpretation, we observed higher amplitudes within plane-parallel seismic facies. The Barra Velha Formation is also subdivided into upper and lower Barra Velha, where the lower one is affected by a characteristic rifting tectonic regime and is described by reworked facies, with rudstones and grainstones being the prevailing facies (Arienti et al., 2018). The upper one, beneath the salt, shows a predominance of flat arrangement in situ facies, portraying a sag phase (tectonic quiescence) (Wright & Barnett, 2015; Neves et al., 2019; Silva, 2021). Because of this aspect, the layers are conformable.

We recognized the transition between lake bottom patterns of the upper rift phase passing upward to aggradational / progradational carbonate platform during the sag phase, indicating distal facies at the base of the sequence, which can be attributed to the fault development in the region during the Barra Velha Formation deposition. This fact helps to corroborate that the tectonic quiescence expected for the sag phase is not that much of a truth indicating that the upper section of the Barra Velha could be subdivided into upper rift and sag phases, which was proposed by Wright & Barnett (2015), Neves et al. (2019), and Silva (2021).

It is visualized in Figure 6 that the coquina bank is limited by two normal faults, F1 and F2, sectioning the coquina bank in the central part of a structural high. Figure 7 displays a structural high controlled by faults F1 and F3 and represents a preferential zone of coquinas formation, observed in well 9-BUZ-4-RJS. As can be seen between faults F2 and F3 (Fig. 6),

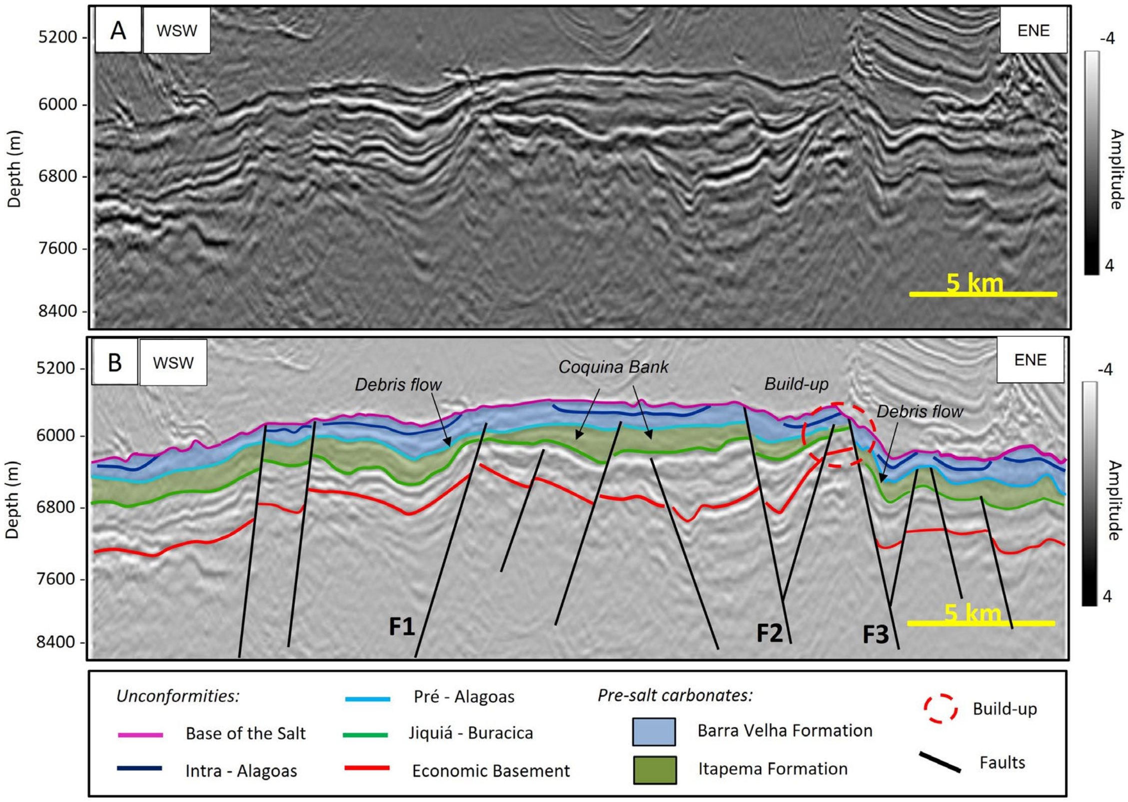


**Figure 6** - Seismic section AA' with unconformities and faults interpretation. F1, F2, F3 represent important faults. F1-F2 develop the compartmentalization of the inferred coquina bank. F1 and F3 show its extension to the base of the salt. It is also possible to recognize a build-up in the East (dashed red circle) and a Horst-Graben configuration.

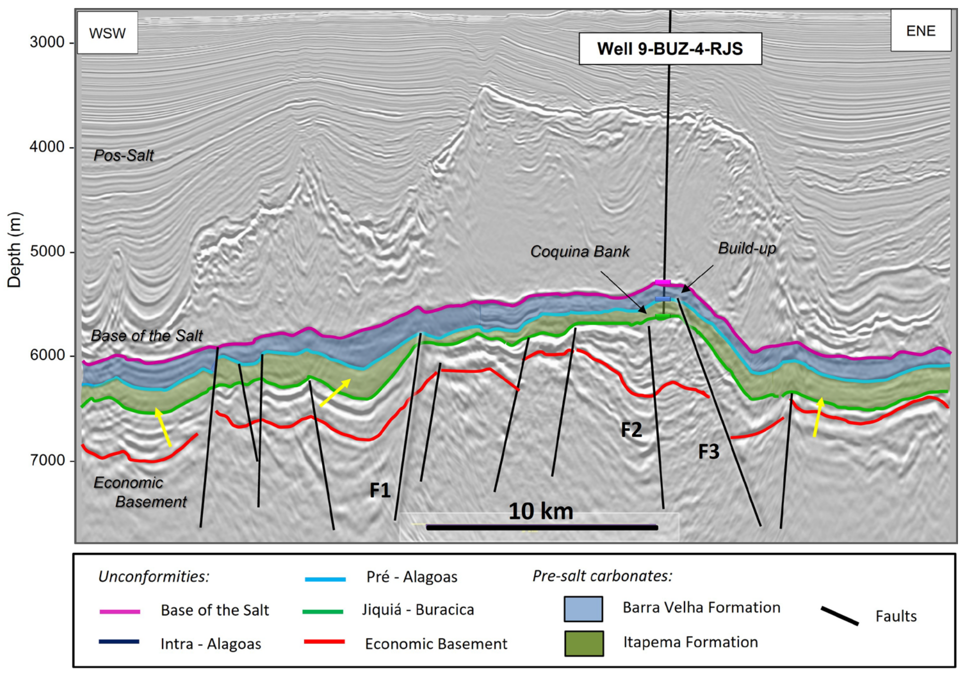


**Figure 7** - Seismic section BB' with unconformity and fault interpretation. The black vertical line shows well 9-BUZ-4-RJS, which provided information during the interpretation of the main unconformities. The yellow arrows indicate a thickness increase of the Itapema interval due to the tectonics.

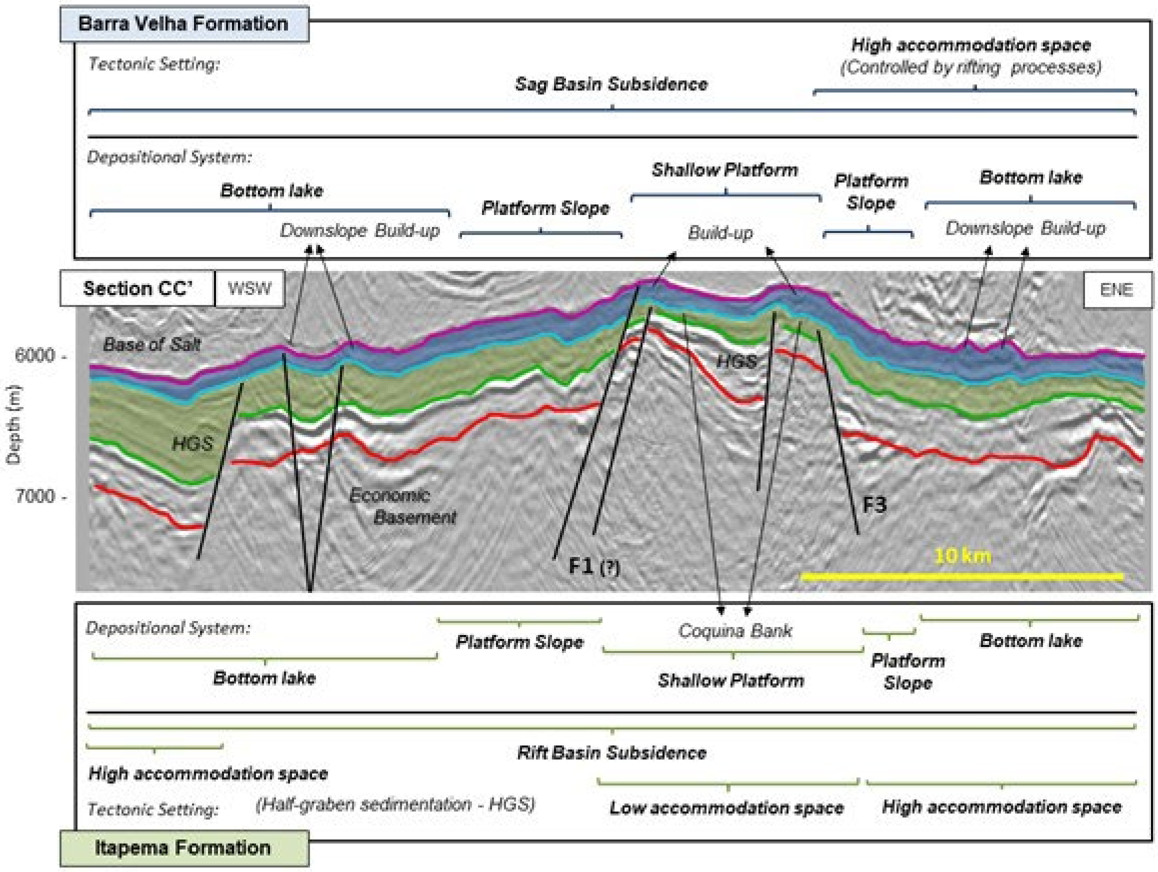


**Figure 8** - Architectural analysis of the seismic section CC', highlighting the depositional system distribution and tectonic settings of the Barra Velha and Itapema formations.

the thickness of the Barra Velha Formation was increased. We point out this effect as an accommodation space creation. The Sag phase is assigned as a period of tectonic quiescence. However, we can notice faults that reach the Base of the Salt (Figs. 6 and 7), leading to the discussion about the presence of some tectonic activity in this period.

Architectural differences between Barra Velha and Itapema formations, especially related to the thickness and strata geometry, can be observed in the Buzios Field (Fig. 8). The Itapema Formation exhibits fragmented asymmetric sections bounded by faults, internally presenting apparent onlap reflectors. All studied sections present this geometry and can be interpreted as half-graben structures formed during the rift phase (Figs. 6, 7, and 8). It is noted that the rifting configuration as horsts and grabens is mandatory for space creation in the structural lows and displays a huge space for sedimentation. In the central region of section CC' there is a structural high that controls the nearest sedimentation and allows the creation of a carbonate platform in a shallow zone. F3 marks another break caused by tectonics, which changes the sedimentation of the Itapema Formation to a bottom lake sedimentation.

Comparatively, Barra Velha Formation also displays facies controlled by tectonics, with F1 reaching the base of the salt. The sedimentation shows pathways modified due to tectonics, but the layers are more continuous than the ones in Itapema Formation. The space creation was more homogeneous than the one described in the Itapema succession. The Barra Velha platform was bounded by main faults and the development of build-ups (Fig. 8). The platform slope exhibits low inclination angles and the bottom lake areas are quite widespread. The shallow platform allowed a greater deposition of carbonate sediments. It is important to highlight that fault F1 reaches the base of the salt, which leads us to a discussion about the possibility of tectonics during the sag phase at upper Barra Velha.

We identified the following seismic patterns during interpretation:

1. Carbonate build-ups probably controlled by hydrothermal activity at the edge of faults;
2. Carbonate platform sedimentation controlled by topography and bathymetry, presenting aggradational or progradational character;
3. Extensive carbonate platforms with plane-parallel architecture present in the structural highs;
4. Debris flow (to the right of F3, Fig. 6), correlated to the tectonics.

The carbonate mounds are often recognized presenting an internal low-amplitude reflector behavior, with great possibility to be an excellent reservoir (Jesus et al. 2019; Ferreira et al., 2019, 2021a). The build-ups display aggradational geometries that are onlapped and overlain by evaporates (Figs. 5 and 6). Above the Barra Velha Formation, during the Neoaptian, the evaporites of the Ariri Formation were deposited. The base of the salt has a high amplitude characteristic and acts as the hydrocarbon seal at the region.

An isopach map provides information on a geological horizon and, when combined with other geological information, it can help the geologist interpret the tectonic activity and the history of this layer and its time segment. The isopach map focuses on a special horizon and allows thickness analysis. Based on the isopach maps (Fig. 9), we analyzed the thickness of each reservoir interval, Itapema and Barra Velha strata, to better understand their deposition phases over time, which is characterized as an important step for future modeling.

To the Southeast, we see a thickness increase of the Barra Velha Formation (Fig. 9A), with probable mounds. At this location, the creation of accommodation space was very high. Figure 9B displays a thickness increase at the central part of Itapema Formation, at the same place where we observed a probable coquina bank restricted to the structural highs between the main faults. This configuration shows that the basic architecture and distribution of the shallow platforms and bottom lake areas remained similar (with some differences) during the deposition of these two lithostratigraphic units. However, the zones of high and low accommodation space vary with the tectonic context (Fig. 8): (i) heterogeneous in the Itapema Formation, due to development of half-graben structures; and (ii) very homogeneous in the Barra Velha Formation due to the dominance of sag basin dynamics (high accommodation regions controlled by rifting processes can be identified related to the lower Barra Velha sedimentation). Szatmari and Milani (2016) also point out that there is an increase in the occurrence of oil reserves at the south of the Santos Basin. According to the authors, there is an increase of thickness to the South with the widening and deepening of the rift. This pattern was also observed for the study area.

## CONCLUSIONS

Evidence of faults affecting the upper rift and sag sections in the location of the studied seismic sections indicates that the tectonic activity is at least locally controlling the sag phase sedimentation in some segments of the Buzios Field. We identified seismic patterns as carbonate build-ups, probably controlled by hydrothermal activity at the edge of faults, and carbonate platform sedimentation, controlled by topography and bathymetry, presenting aggradational or progradational character with plane-parallel architecture in the structural highs. Debris flows are correlated to the tectonics and there are platform slopes close to the main faults, indicating the horst-graben system. The coquinas found towards the top of the Itapema Formation are associated with structural highs, influenced by faults acting as depositional controllers. The thickness of the Barra Velha Formation increases along the section due to the geological behavior and tectonic activity. The thickness and geological structure of the Itapema Formation are more affected by the

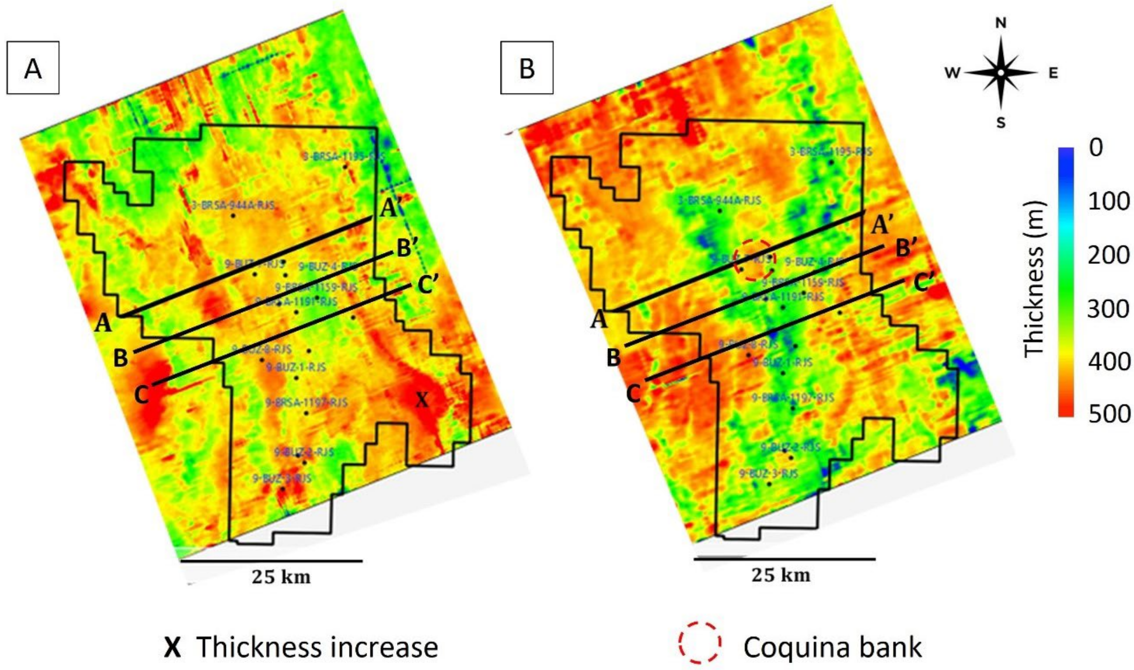


**Figure 9** - Isopachs showing the thickness variation of Barra Velha (A) and Itapema (B) formations. AA’, BB’, and CC’ are the seismic sections and the X point in the Barra Velha isopach map (A) displays a thickness increase, with a possibility of carbonate mounds. The red circle in (B) displays the interpreted coquina bank in the Itapema Formation.

faults than they are in Barra Velha Formation, which displays more plan-parallel facies. We observe an improvement of thickness of both formations from the North to the South, as can be seen at the isopach maps, and comparing sections AA’ and CC’. It might indicate more favorable environmental conditions for the development of carbonate facies due to development of shallow zones.

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