Mapping of Seismic Horizons and Geological Implications of the Búzios Oil Field (Santos Basin)

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Abstract

This work investigates the geological implications of different seismic signals for the main horizons of the Pré-Salt Búzios Oil Field. Comparing seismic reflector amplitudes with sedimentary and structural geometries, well logs, as well as termination patterns, such as onlaps and downlaps, provided a more comprehensive understanding of subsurface unconformities. The seismic surface mapping process of the Búzios Field yielded several key results, including the identification of nonconformities in 43 wells, successful well-seismic ties, recognition of the basement unconformity, interpretation of faults, and the definition and tracking of Pre-Salt, Intra-Alagoas, Pre-Alagoas, Intra-Jiquiá, and Jiquiá-Buracica surfaces. The arrangement of internal reflectors and termination patterns played a vital role in addressing the absence of clear seismic reflector amplitude patterns in the transition of the presalt sequences, specifically between the Itapema and Barra Velha formations. This approach offers an enhanced seismic interpretation and creates a robust framework for Búzios Field exploration.

Introduction

Mapping key seismic horizons of Brazilian Pre-Salt petroleum fields is a common practice as the first steps either for its reservoir characterization and stratigraphic studies. Typically, presalt unconformities are featured by highly reflective seismic horizons that correlate with prominent radioactive peaks from low-energy facies in gamma ray logs (Moreira et al., 2007; Carminatti et al., 2009; Oliveira et al., 2021). Nevertheless, the Búzios Field may display fluctuations in reflectance along specific unconformity seismic horizons (Figure 1).

Located in the northeastern Santos Basin, the Búzios Field is part of Brazilian Pre-salt Petroleum Province (Figure 2). It features reservoir rocks composed of Aptian lacustrine carbonates with diverse sedimentary facies and diagenetic processes. Therefore, mapping and characterizing carbonate reservoirs in this area might be difficult given the lateral variability and limited seismic expression of their internal boundaries (Oliveira et al., 2021; Brazil et al., 2022).

According to Almeida (1967), the formation of the Santos Basin is attributed to the breakup of Gondwana and the subsequent separation of South America and Africa, during the Late Jurassic to Early Cretaceous period. The region, located at the southeastern continental limit of Brazil, lies in the E-W sinistral Rio de Janeiro Transfer Zone, which regulates onshore tectonic activity, and is bordered to the north by the Cabo Frio High and the Campos Basin (Ojeda and Cesero, 1973; Moreira et al., 2007).

Three periods can be distinguished in the tectono-sedimentary history of the Santos Basin: Rift (Hauterivian to Lower Aptian), Post-rift (Upper Aptian), and Drift (Albian to Holocene) (Moreira et al., 2007). The K20-34 sequence of tholeiitic basaltic rocks (Camboriú Formation) is the oldest sequence and configures the Pré-Rift of Santos Basin (Valanginiano to Hauterivian). The Rift phase begins with the K36 sequence, which is composed of conglomerates, sandstones, shales and Mg-clays (Piçarras Formation) and is capped by the Pre-Jiquiá Unconformity (PJU).

The sequence K38 (Itapema Formation) is bounded at the base by the Pre-Jiquiá Unconformity and at the top by the Pre-Alagoas Unconformity (PAU). Itapema Formation comprises coquina deposits of the offshore pre-salt Buzios Field. In this context, PAU marks the transition from the Itapema Formation to the Barra Velha Formation during the Aptian period (Moreira et al., 2007).

Shrubs, spherulitites, laminites, and grainstones compose the Barra Velha Formation, configuring 3 mains sequences. The Intra-Alagoas Unconformity (IAU) defines the division of the K44 and K46–48 sequences, reflecting the rift to post-rift phase (Wright & Barnett 2015, Buckley et al. 2015, Neves et al. 2019). An informal unconformity denoting the onset of salt deposition defines the upper boundary of the Barra Velha Formation (Moreira et al., 2007, Wright and Barnett, 2017, Pedrinha et al., 2018; Pedrinha et al., 2024). At the lower part of the Albian, it is represented by anhydrites, halites, and chlorides of the K50 sequence (Ariri Formation).

Few studies have detailed the seismic mapping process and seismic-stratigraphic criteria for identifying unconformities in the Búzios Field. Consequently, this work investigates stratigraphic parameters, including seismic reflector amplitudes, geometries, termination patterns like onlap and downlap, and the spatial and temporal distribution of the presalt deposits.

Methods

This study employs geophysical research and analyses that leverage high-resolution seismic data (Nodes) given by Petrobras. Brazil et al. (2022) state that the OBN (Ocean Bottom Nodes) full-azimuth seismic data is the most recent technique used for data acquisition in the

Búzios Field. The data was collected between 2018 and 2019.

Geological and geophysical processing and interpretation were performed using Paradigm™ (by AspenTech) software, alongside Python. The interpretation involved creating horizons and their corresponding seismic grids, with an interval set at 16 x 16 inlines/crosslines.

Upon loading the seismic data, quality control was carried out by completing a comprehensive examination of the survey grid positioning, seismic reflectors, their connections with geology, and the phase and polarity of the seismic data.

For the well tie process, we used the concepts and methods described by Simm and Bacon (2014, Figure 1). According to the authors, any well tie approach involves translating depth measurements into corresponding time values. This typically involves the use of depth and time data from checkshots or VSP (vertical seismic profiles).

To determine a continuous time-depth function and generate synthetic seismograms, it is necessary to integrate checkshot data and some well logs. Due to velocity dispersion, which is frequency-dependent, it is important to integrate these data sets carefully. This means that the velocities measured in the logs must be adjusted to match the seismic scale before performing the well tie (Simm and Bacon, 2014).

In this work, the calculation of synthetic seismograms was based on the integration of Vp (P-wave velocity) and density logs, as well as checkshot data. We extracted wavelets from the full amplitude seismic volume near each well for further applications. Various logs, including gamma ray and resistivity, guided the annotation of geological markers in seismic amplitude interpretation. We applied adjustments like stretch and squeeze to the synthetic seismogram as needed. The logs' characteristics, such as density and velocity, were correlated with seismic signatures using the well-seismic tie technique across 43 wells (Figures 1 and 3).

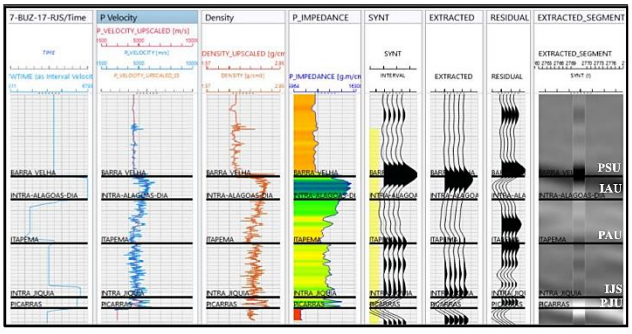

Figure 1 – Example of a well-seismic tie panel displaying the key seismic surfaces of the Búzios oil Field. From bottom to the top, the surfaces are as follow: Pré-Jiquiá Unconformity (PJU), Intra-Jiquiá Surface (IJS), Pré-Alagoas Surface (PAU), Intra-Alagoas Unconformity (IAU), and the Base of Salt or Pre-Salt Unconformity (PSU).

Some noteworthy points at this mapping stage in the seismic interpretation process are as follows:

In the initial phase of identifying stratigraphic units in the

After defining the well-seismic ties, we mapped geological unconformities. The criteria for selecting the reflectors were based on chronostratigraphic units of Santos Basin, using well markers tied to seismic reflectors near the wells. Figures 1 and 3 show the well-seismic correlation with the main horizons/unconformities interpreted in the study area along seismic lines intersecting wells. Notably, there was an excellent correlation between the well markers and seismic events in both wells and most of the wells analyzed.

We also determined the seismic interpretation of key unconformities in the presalt interval by analyzing the terminations of seismic reflectors, as shown in Figures 3-5.

Results and Discussion

The seismic surface mapping process of the Búzios Field yielded several key results. These include the identification of nonconformities in 43 wells, successful well-seismic ties, recognition of the basement unconformity, interpretation of faults, and the definition and tracking of Pre-Salt, Intra-Alagoas, Pre-Alagoas, Intra-Jiquiá and Jiquiá-Buracica surfaces.

The recognition of the Base of Salt or Pre-Salt Unconformity (PSU) marked the distinction between the pre-salt section and the evaporites of the Ariri Formation. After that, we found a continuous positive peak surface at the base of the pre-salt sedimentary sequence. This enabled to locate the Pre-Jiquiá Unconformity (PJU) and identify the boundaries between the Jiquiá and Buracica sequences. We referred to this surface as the Intra-Jiquiá Surface (IJS). After this, we mapped other regional-scale seismic unconformities, including the Intra-Alagoas Unconformity (IAU) and the Pre-Alagoas Unconformity (PAU).

In this context, it is worth noting that the PJU, PAU, IAU, and PSU unconformities, in addition to having chronostratigraphic and/or tectonostratigraphic significance, generally correspond to the lithostratigraphic boundaries, from base to top, between the Piçarras, Itapema, Barra Velha and Ariri formations, as reported in the literature by Moreira et al. (2007), and Carminatti et al. (2009).

The lower segment of the rift, corresponding to the Piçarras Formation in the Santos Basin, is primarily composed of alluvial fan conglomerates and polymictic sandstones. Deepward deposits comprise sandstones, siltstones, and shales (Moreira et al., 2007). Towards structural highs, sediments of the Piçarras Formation display onlap terminations covering the underlying basement. In certain areas, its upper boundary is clearly delineated by an erosional truncation, where seismic reflectors exhibit a divergent to subparallel configuration, marking the Pré-Jiquiá Unconformity (PJU) (Figures 3 and 4). This unit generally exhibits low to medium amplitude reflectors, while certain sections may lack internal reflections.

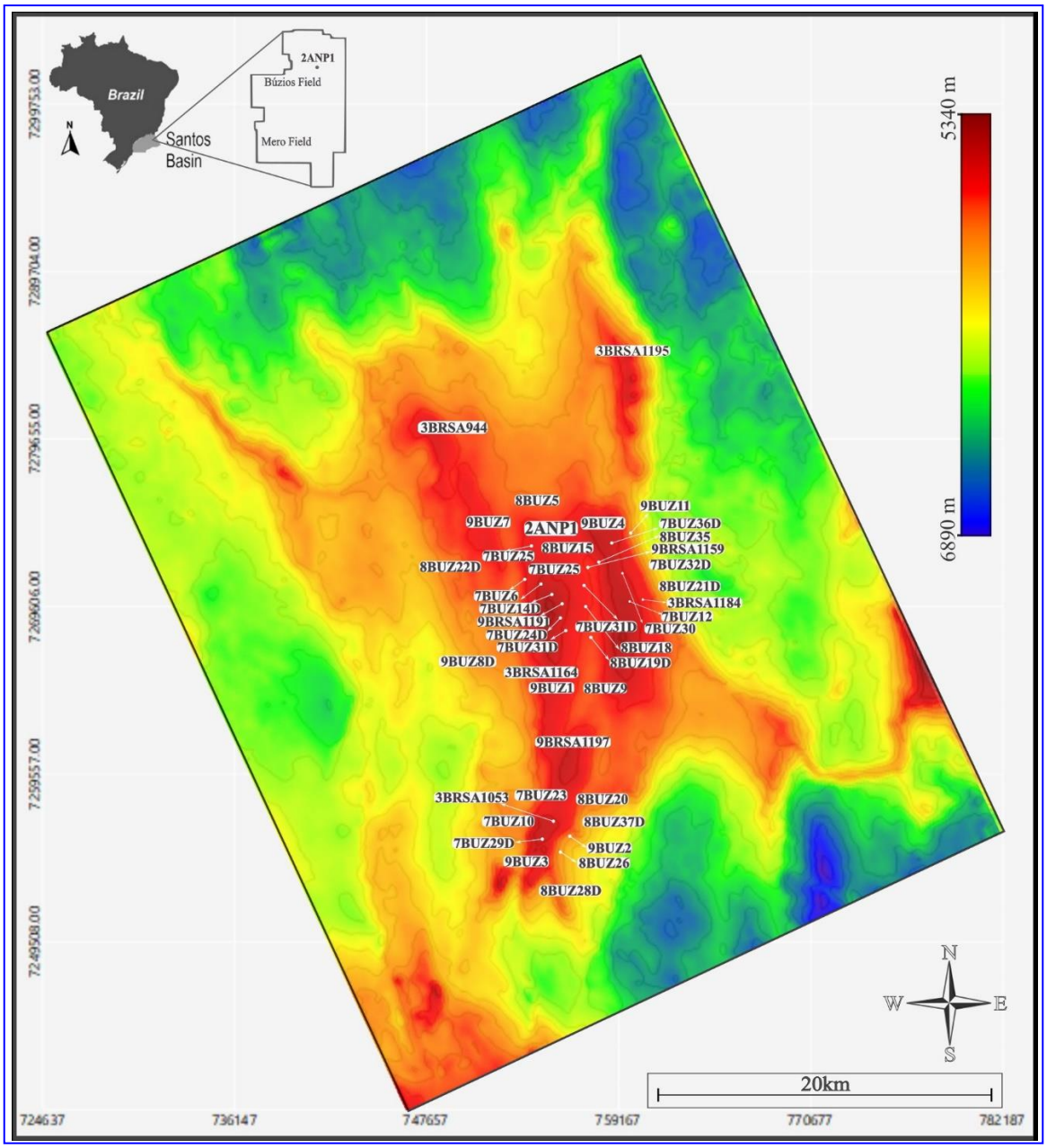

Figure 2 – Location map of the Búzios Field featuring well locations overlaid on a contour map of the salt base layer.

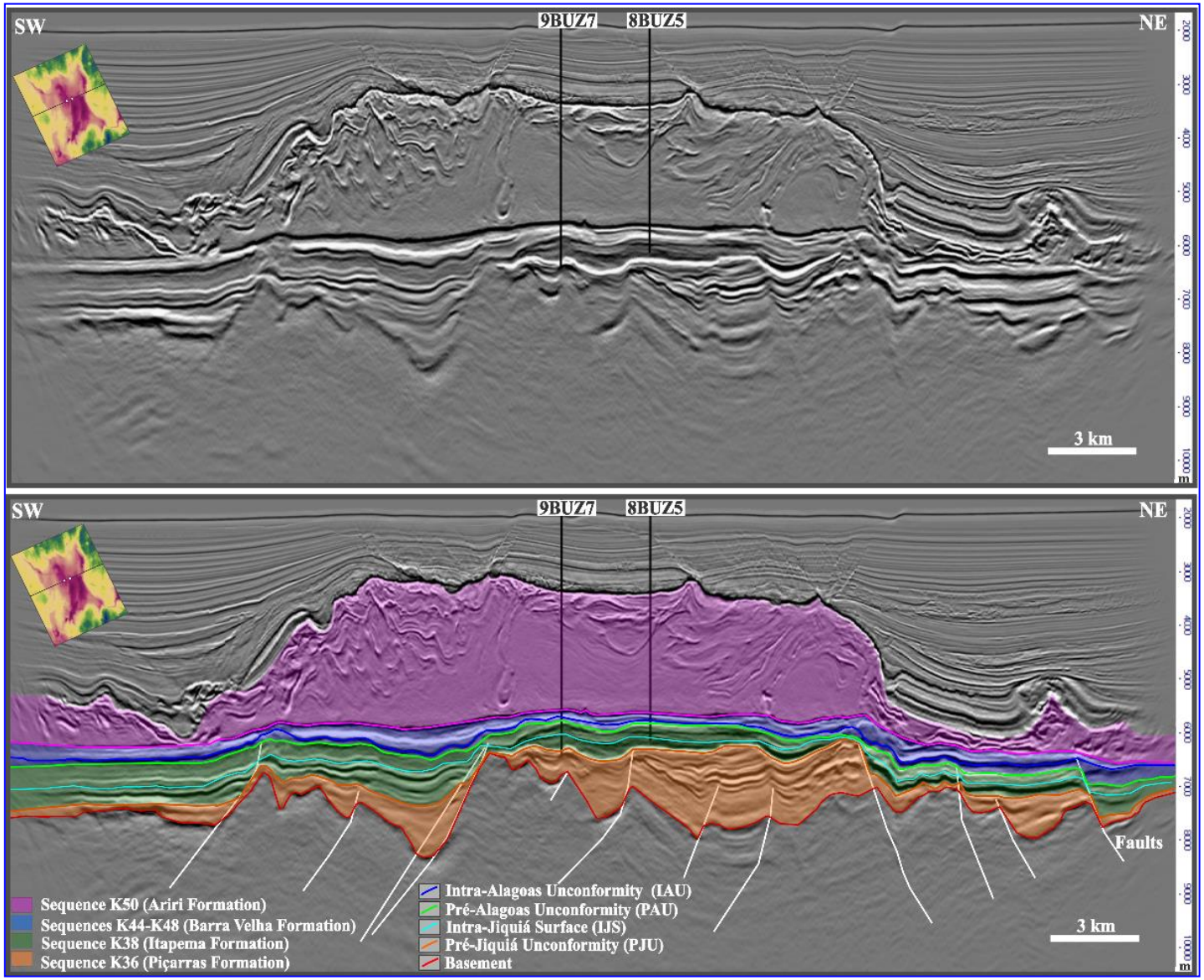

Figure 3 – Mapped Unconformities and Surfaces of the Búzios Oil Field (Santos Basin) and its sedimentary sequences and formations.

In the Búzios Field, the Itapema Formation is characterized by inclined seismic reflectors with onlap, downlap, and truncation terminations. This arrangement suggests a clinoform geometry, *sensu* Vial et al. (1977), which is particularly well-developed in the southern region of the field (Figure 4).

No distinct seismic pattern is evident in the transition from the Itapema Formation to the Barra Velha Formation (Figures 1, 3, and 4). This boundary exhibits different seismic responses, comprising low, medium, and high amplitude reflectors. In general, the prevailing reflections are primarily low and medium (zero-cross) reflections, making onlap and downlap terminations a key feature for PAU mapping.

Although the approach to this differentiation is not yet well established in the literature (Cruz, 2023) few indicators have proven useful (Moreira et al. 2007; Carminatti et al., 2009; Pietzsch et al. 2018; Barnett et al. 2020 and Oliveira et al., 2021). These include the entry of bioclastic carbonates, the presence of an angular or erosive unconformity and vertical succession thickening against normal faults, evidencing the tectonic activity (Figures 3 and 4).

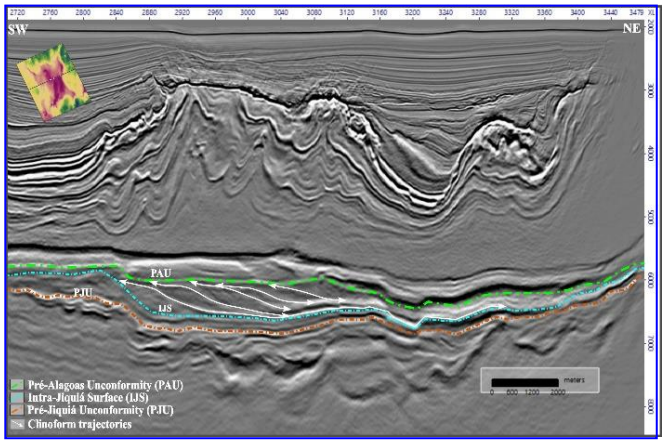

Figure 4 – The clinoform geometry characterizes the sedimentary geometries of the Itapema Formation in the Búzios Field (Sensu Vial et al., 1977).

Similarly, the Lower Barra Velha Formation (k44 sequence) displays onlap terminations towards structural highs and vertical succession thickening (Figure 5), aligning with the interpretation of the Upper Rift Phase for this sequence (e.g., Wright & Barnett 2015; Buckley et al. 2015; Castro 2019; Neves et al. 2019; Silva et al. 2021).

In the study area, Intra-Alagoas Unconformity (IAU) surface has been identified in most wells based on their petrophysical logs. Subsequently, depths of these surfaces in wells were plotted against the seismic volume, revealing a predominantly laterally mappable high-amplitude positive reflector. It covers the Lower Barra Velha Formation and indicates the end of the rift phase. Thus, this unconformity separates the K44 sequence (Lower Barra Velha; Upper Rift Phase) from the K46/K48 sequences (Upper Barra Velha; Sag Phase).

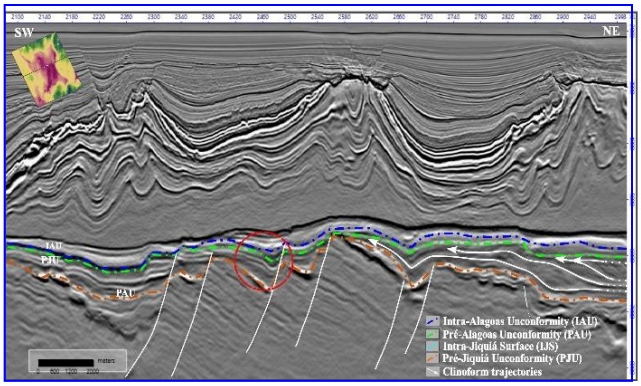

Figure 5 Intra-Alagoas Unconformity (IAU) covering the Lower Barra Velha Formation and indicating the end of the rift phase. In the Buzios Field, the IAU is featured as a laterally mappable, high-amplitude positive reflector.

The Base of Salt is identified in all wells as the top of the Barra Velha Formation. It marks the transition from a predominantly carbonate sedimentary environment to an evaporitic one during the Neoaptian, corresponding to the local Upper Alagoas stage (Moreira et al., 2007). In seismic sections, it is associated with a strong regional positive seismic reflector with high acoustic impedance contrast between the salt layer and the carbonates of the sag phase (Upper Barra Velha Formation). This surface configuration is commonly defined with good continuity and high amplitude. However, in areas with bioconstruction-type reservoirs the amplitude may decrease.

Despite the interpretation considering the positive peak for the seismic interpretation of the Base of Salt, when anhydrite is present, this event represents the base of this layer and not the top of the Barra Velha Formation (Figures 2 and 3). However, even from well analysis, it was decided to maintain the interpretation of the Base of Salt unconformity as the positive peak, as there is insufficient seismic resolution to map the top of the Barra Velha Formation. An alternative for analyzing the upper part of the Barra Velha Formation after mapping the Base of Salt, would be to perform a shift based on the anhydrite thicknesses from the wells, according to Cruz (2023).

Conclusions

The seismic surface mapping process of the Búzios Field has yielded significant outcomes. It encompassed the identification of nonconformities in 43 wells, successful well-seismic ties, recognition of the basement unconformity, interpretation of faults, and the delineation of key unconformities such as the Intra-Alagoas Unconformity (IAU), Pre-Alagoas Unconformity (PAU), Intra-Jiquiá Surface (IJS), and Jiquiá-Buracica unconformity (or the Pre-Jiquiá Unconformity). These findings provide a robust framework for understanding the geological evolution of the field.

Solving the lack of a distinct seismic pattern such as those in the transition between the Itapema Formation and the Barra Velha Formation requires a detailed analysis of stratigraphic parameters. A more comprehensive understanding of subsurface unconformities can be attained by comparing internal reflector configurations with sedimentary and structural geometries, as well as termination patterns. This stratigraphic insight offers more precise tools for seismic interpretation, allowing an enhanced exploration approach in the Búzios Field and other related geological environments.

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