Full Azimuth Nodes: rethinking seismic facies and sedimentary domains model in Buzios Field, Brazilian Pre-salt

Maria Taryn Relvas Campos, Victor Gustavo Mund da Rocha e Silva, Eliane Born da Silva, Júlia Campos Guerrero,
Leonardo Marcio Teixeira da Silva, Carlos Eduardo Borges de Salles Abreu, Petrobras

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

Located in the northeast part of the Santos Basin, the Buzios field is one of the largest oil fields in the Brazilian Pre-salt petroleum province. Its reservoirs are comprised of a variety of genetically different lacustrine carbonates from the Itapema and Barra Velha formations.

Buzios field recently acquired ocean bottom nodes dataset, which leading edge acquisition and processing technologies, lead to a leap in image quality, making this dataset the ultimate baseline for 3D interpretation and reservoir modeling, as well as a base survey for future 4D monitoring.

The OBN data revealed seismic features not previously identified and made possible to have new insights on geological distribution of sedimentary domains and helped shed light over the stratigraphic events from Itapema and Barra Velha formations. Seismic facies units were mapped using classic criteria widespread and consolidated in literature, allied with other geometrical characteristics, reflector stacking patterns and acoustic impedance attributes, as well as its correlation and integration with available well data and included in the geological model as different sedimentary domains.

Therefore, the identification, characterization and interpretation of seismic facies units are important inputs to the spatial distribution of the different depositional elements and their respective lithofacies in the geological reservoir model, reducing uncertainties in ambiguous areas where the signal strength (amplitude and/or impedance) alone cannot be directly linked to reservoir properties and therefore interfering directly on volume calculations and the optimization of the field exploitation strategy.

Introduction

Located about 180km off Rio de Janeiro coast, under a 1900m water column and with an area of approximately 850km², Buzios is by any metric, a supergiant field. Currently, it is one of the largest oil fields in the Brazilian Pre-salt petroleum province, both in terms of in place volume and productivity (ANP2023).

The reservoir rocks are lacustrine carbonates of different origins deposited in the Early Cretaceous during the Gondwana break-up and the development of the Atlantic Ocean. The lower reservoir is the Itapema Formation (ITP), composed mostly by grainstones and rudstones, whose particles are bivalve shells (Antunes, 2021; Brazil *et al*., 2022). These rocks are informally named coquinas. The pre-salt lake at this earlier rift stages was in tectonically active environment. Tectonic activity, together with coquinas prolific carbonate factory and important lake level variations caused the concentration and accumulation of enormous quantities of these types of sediments.

Overlying these deposits, occurs the pre-Alagoas Unconformity, which represents an environmental change to a shallow and hyperalkaline lacustrine environment (Wright and Rodriguez, 2018), that promotes a switch in the type of carbonate facies. Thus, the Barra Velha Formation (BVE) records the deposition of shrubs, spherulites and Mg-clay-rich rocks (Gomez *et al*., 2020; Brazil *et al.,* 2022). Towards the top of the BVE, the tectonics become less active, making climatic variations the most important control in the deposition of the rocks of this period. The field's final configuration is a result of structural tectonic highs combined with depositional geomorphologies (Figure 1).

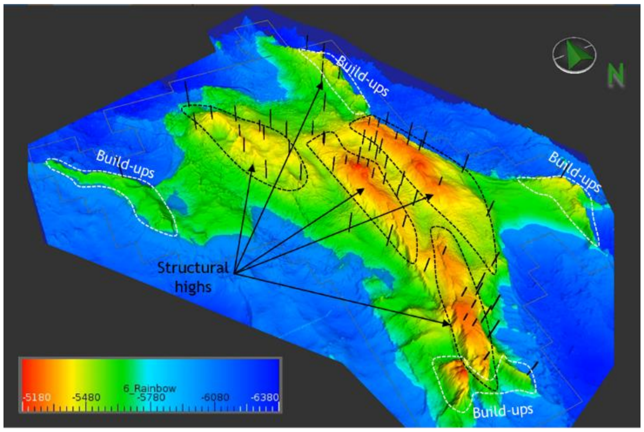

Figure 1 – Seismic reservoir top structural map showing the basement structural highs and build-ups highs.

These different geological settings make sedimentary facies and reservoir permoporous distribution modelling very challenging. The wells provide vertically dense information but are very sparse laterally. Therefore, the comprehension of how seismic features are related to depositional environments and well data is of great importance to the spatial distribution of the different depositional elements that constitute the carbonate system, as well as their lithofacies to build the geological reservoir model. This model is essential to support the oil field's production development projects, as well as production forecasts and reserves.

Dataset

In addition to geological complexity of the field and the great reservoir depth, Buzios is located bellow a complex overburden, including very irregular topography of the overlying evaporitic sequence, abrupt lateral velocity variations and anisotropy of stratified layers, imposing challenging environment to adequate image the reservoir. The dataset used during major Buzios projects decision-making and approval processes was a towed streamer narrow azimuth seismic (NAZ). Despite its importance this dataset presented significant technological limitations, showing serious image issues and imposing relevant uncertainties to reservoir geophysical and geological modeling (Silva et. al, 2021). Furthermore, this dataset was not suitable as a base survey for the Life-of-the-Field seismic monitoring projects in Buzios. Therefore, Petrobras has taken the early decision to shoot an ocean bottom nodes (OBN) acquisition in 2018/2019 over the entire field, acquired by Seabed Geosolutions and processed by CGG. This new full azimuth (FAZ) seismic data was available in 2021 and provided a leap in image quality as well as velocity and amplitude estimates when compared to vintage streamer dataset (Figure 2).

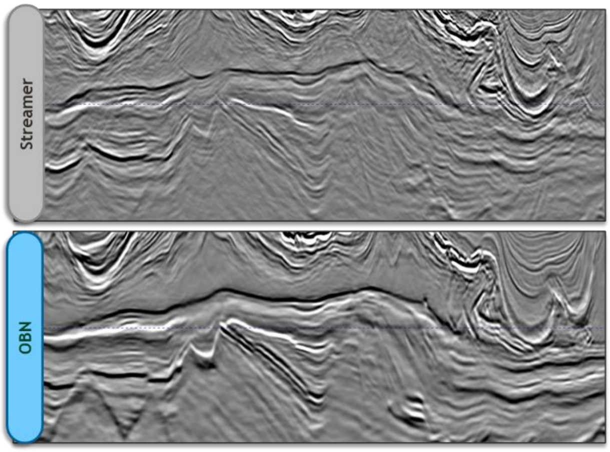

Figure 2 – Seismic section comparing the streamer vintage data (upper) with the full azimuth OBN data.

This image upgrade was possible due to full azimuth illumination, with long offsets and low frequency content, all of which are distinctive characteristics of the OBN. These allow full waveform inversion (FWI) algorithms to perform better in updating the velocity model and include heterogeneities in it. Imaging is also improved by increased fold and low ambient noise levels, since the nodes are placed on the seafloor (Cypriano et al. 2019). The migration method used was Least-square Reverse Time Migration (LSRTM) which is better suitable to deal with detailed velocity models.

Method

Identification of seismic facies was based on classical concepts such as used by Brown & Fischer (1977), Prather *et al*. (1998), and Posamentier *et al*. (1988), as well as other geometrical elements, reflectors stacking patterns and acoustic impedance attributes and their relationship with lithofacies. Each seismic facies were individualized as a 3D unit and were used: 1) directly as a sedimentary domain or 2) conceptually to improve the stratigraphic comprehension of the interval.

In this paper, the term "Sedimentary domain" is used to describe a geological unit that combines features in multiple scales including depositional regions and architectural elements. Thus, the sedimentary domain model is applied as a constraint for facies modelling and this one, in turn, for porosity and permeability three-dimensional distributions.

Seismic facies characterized in Itapema Formation

Platform Edge Clinoforms: The thick intervals of clinoforms observed in Buzios field can be described as an oblique sigmoidal complex pattern, previously defined by Mitchum *et al.* (1977). In this pattern, reflector terminations such as toplap, offlap, onlap, downlap and concordant were observed (Figure 3A). These intervals are predominantly formed by coquina facies deposited during rift phase in lacustrine littoral and sublittoral environments. The dynamics of transportation and deposition is similar of that of siliciclastic sediments and, therefore, in situ sediments are poorly preserved, with a predominance of reworked sediments. The characterization of this seismic facies was essential to enumerate the main stratigraphic events for the ITP, as well as define an important forced regression surface. Figure 3B shows OBN data compared to vintage data where the reflector terminations and internal reflection were hardly visible.

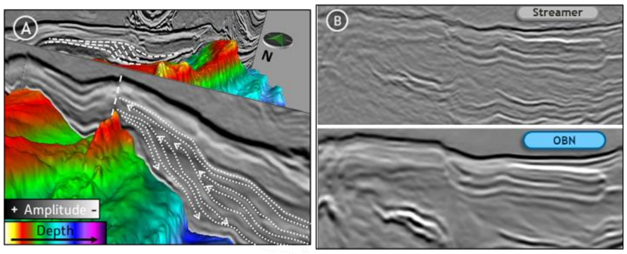

Figure 3 -A) *Seismic sections A-A' e B-B' show examples of platform edge clinoforms, where the interpreted reflectors terminations are the white dotted arrows.* ***B)*** *Seismic section comparing streamer (upper) with OBN (lower).*

Deep Lake Siltstones: Set of parallel and sub horizontal seismic reflectors with high amplitudes, predominantly negatives (anomalous amplitudes due to tuning effect). Well observations from these intervals show thick packages of intercalated layers of siliciclastic siltstones and mudstones (Figure 3) with bioclastic grainstones.This seismic facies is associated with lacustrine profundal sedimentary domain.

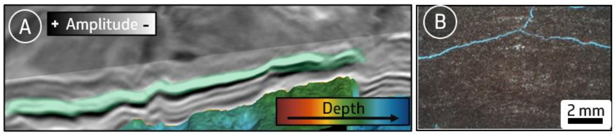

Figure 4 - *A) Seismic cube in amplitude, highlighting the seismofacies in the green shaded area (frontal face). B) Photomicrography described as siltstone composed by red argilous minerals and high silica content.*

Onlaps filling relative low structures: It is a set of plane-parallel seismic reflectors, which form a termination pattern in onlap (Mitchum *et al*., 1977) against the reservoir base, occurring in the relative structural lows. In the higher portion of the reservoir, well results evidence depositional lack of the lower interval of this seismofacies, corroborated by the isotopic data of carbon and oxygen in whole rock (Figure 4).

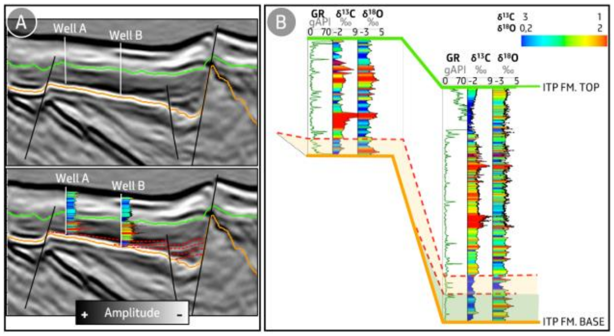

Figure 5 - *A) Amplitude seismic sections in depth, without interpretation (above) and with interpretation (below); the onlaps constitute the red dotted lines and logs show whole rock carbon isotopes. B) Correlation between the two wells of A, with logs of gamma ray (GR), δ13C and δ18O. Note the absence of the green shaded interval in upper well.*

Seismic facies characterized in Barra Velha Formation

Carbonate Platform Backstepping: Seismic facies observed as a stacking of reflectors with low angle developed above a surface of smooth inclination, resulting in a retrogradational stacking pattern, with thicker sequences deposited in the higher structural portions. Thus, the top of the carbonate backstepping marks a surface of maximum expansion of the lake, corresponding to a maximum flooding of the system in a classic sequence stratigraphy. Wells drilled in the lower portions of these sets of reflectors show lithofacies indicative of deeper water depths increasing upwards. Wells drilled in the higher portions, in turn, indicate shallower conditions, while also showing depeer water depth facies increasing upwards (Figure 6).

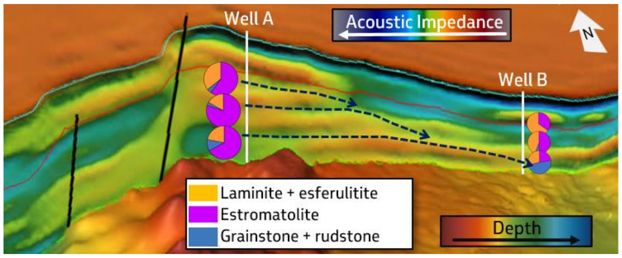

Figure 6 *Acoustic impedance section in 3D perspective. Dark blue dotted arrows highlight the backstepping reflectors and pizza graphs show lithofacies proportions for each stratigraphic interval. Wells A and B increase proportions of laminate (deeper water depth) upwards.*

Coastal Ridges: Set of plane parallel reflectors, inclined, that are laterally very continuous, forming elongated narrow bodies that dip towards structurally lower regions. In wells, main lithofacies consists of well selected grainstones, with ripple marks and low angle cross-bedded lamination, interpreted as formed by substract reworking from wave activity in a high energy environment (Figure 7).

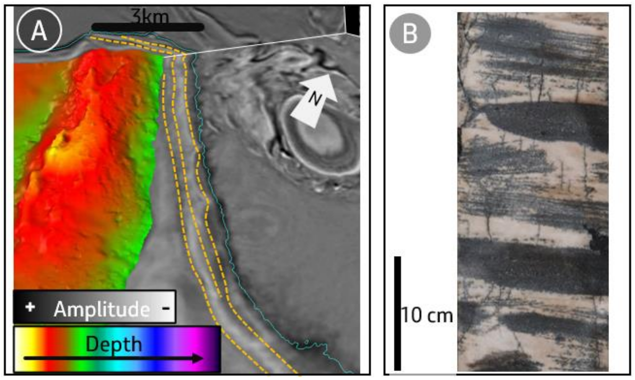

Figure 7 - *A) Seismic section and depth slice, with reflectors interpreted as coastal ridges (yellow dotted lines). B) Grainstone with cross-bedded lamination found in a core sample.*

Shelf Edge Collapse Deposits: This seismic facies shows chaotic internal reflections, subordinately plane-parallel, and external geometry in wedge-like shape. It occurs positioned in steep structural high flanks, and their top surfaces form jagged reliefs (Figure 8), showing scars from landslides, debris flow and falling blocks into the slope.

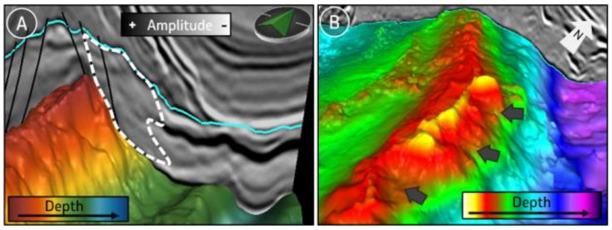

***Figure 8** - A) Dip section showing chaotic feature of internal reflections (inside white dotted lines). B) 3D view of depth structural top with arrows pointing at scars from landslides of the platform collapse.*

Clay-rich Minibasins: They are concave and wide features, with the external geometry of a plate, usually associated with a structural low. Typically, these bodies present low acoustic impedance, therefore the top reflector has negative amplitude and base reflector positive amplitude, as show in Figure 9. Representative lithotypes deposited in these seismic facies are Mg-clays deposits with spherulite and shrubs carbonate facies associated.

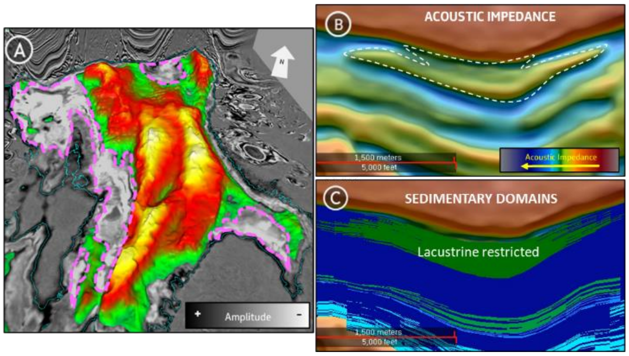

***Figure 9** - A) 3D view base of the clays sectioned by the amplitude depth slice. Mg-clay deposits correspond to the negative (throughs) lower amplitude signal delimited by pink lines. B) Acoustic impedance section (dip) in the relative structural low. Mg-clay minibasins show low acoustic impedance index. C) Section in the sedimentary domains model where the mg-clay minibasins correspond to lacustrine restricted environment.*

Carbonate Mounds: This seismic facies unit was identified in Buzios field as features of convex external geometry usually with high angle flanks, forming positive structures that may have pyramidal or rounded tops (Figure 10A), corroborating the classification of Mitchum *et al*. (1977). Internal seismic reflections in general show disorderly and discontinuous patterns, and in a few cases may also present parallel reflectors. Mounds commonly shows steep flanks that area harder to illuminate with narrow azimuth data, in the OBN some of the mounds mapped were poorly observed in the vintage data (Figure 10B). The Buzios mounds genesis is interpreted as associated with deep faults and hydrothermal activity in the latest stages of Pre-salt reservoir deposition and the main sedimentary facies that occurs in this seismic unit is shrubstones (Figure 10C).

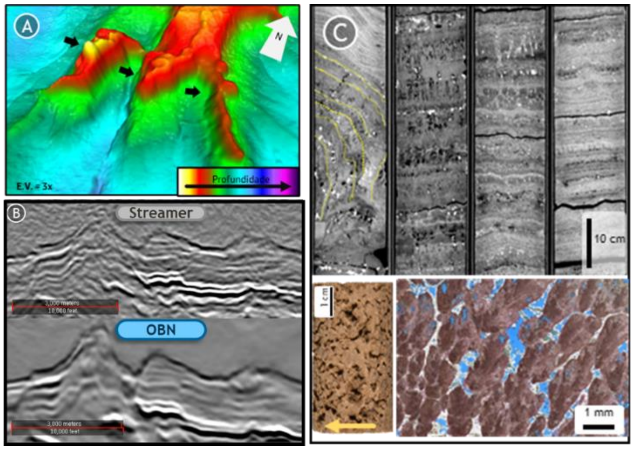

***Figure 10**: A) 3D view of Buzios reservoir top showing some of the carbonate mounds that form structural highs along the field. B) Seismic section comparing streamer and OBN data. C) Cores (upper), plug (lower left) and petrographic thin section (lower right) showing shrubstones found in the carbonate mounds.*

Conclusions and Future Work

The characterization and detailed mapping of the seismic facies described in the present work was only made possible by the significant improvements achieved by the FAZ OBN 3D seismic data made available for Búzios field in 2021. The proposed denominations for each seismic facies unit, along with its interpretative character, were all defined alongside and supported by well data. In Itapema formation, this new seismic data enables the distinction of reflectors terminations of large platform edge clinoforms, as well as onlaps patterns in the relative structure low of the Buzios Field, giving important insights for the stratigraphical model and the forward modelling process in this interval. In Barra Velha formation, were possible to delimitate domains such as costal ridges, mounds and shelf edge collapse deposits, and more important, it was possible to establish the boundaries of the deep lake siltstones and clay-rich minibasins which was essential to separate reservoir from non-reservoir facies (Figure 11). Distinguish them is key to the identification of good and poor reservoirs zones, mitigating uncertainties in areas where remaining ambiguities in the seismic signal alone (amplitude and impedance) cannot be used to directly derive reservoir quality maps. Low acoustic impedance intervals may represent both good reservoir facies with high porosity and clay-rich non-reservoir facies, demonstrating the importance of assessing reliable rock-physics elastic model to have a better spatial distribution. Therefore, better estimates of oil volumes are obtained, and an optimal field exploitation strategy can be achieved.

Evaluating seismic anisotropy through the interpretation of angle/offset & azimuthal prestack gathers is an ongoing work in Buzios asset team, aiming at improving the representation of a whole suite of both stratigraphic and structural elements in the geological models that impacts the fluid flow distribution in reservoir models. These features includes both density and direction of natural and induced fractures, subseismic faults, damage zones, karsts, and other features. The potential of inspecting both seismic travel-time or velocity variations with azimuth (VVAZ) from seismic off-set gathers and seismic amplitude variations from seismic azimuth-gathers (AVAZ) will bring news insights on the description and characterization of Pre-salt carbonates, imposing at the same time, new technological challenges to simultaneously handle huge amount of prestack seismic volumes. The use of Machine Learning (ML) and Artificial Intelligence (AI) algorithms will also provide tools to optimize and accelerate the use of azimuthally rich data, improving seismic characterization of complex geological features, and reducing drilling risks due to geohazards.

Acknowledgments

The authors would like to thank Petrobras S.A. for the data and partners CNOOC and CNDC for permission to publish this work.

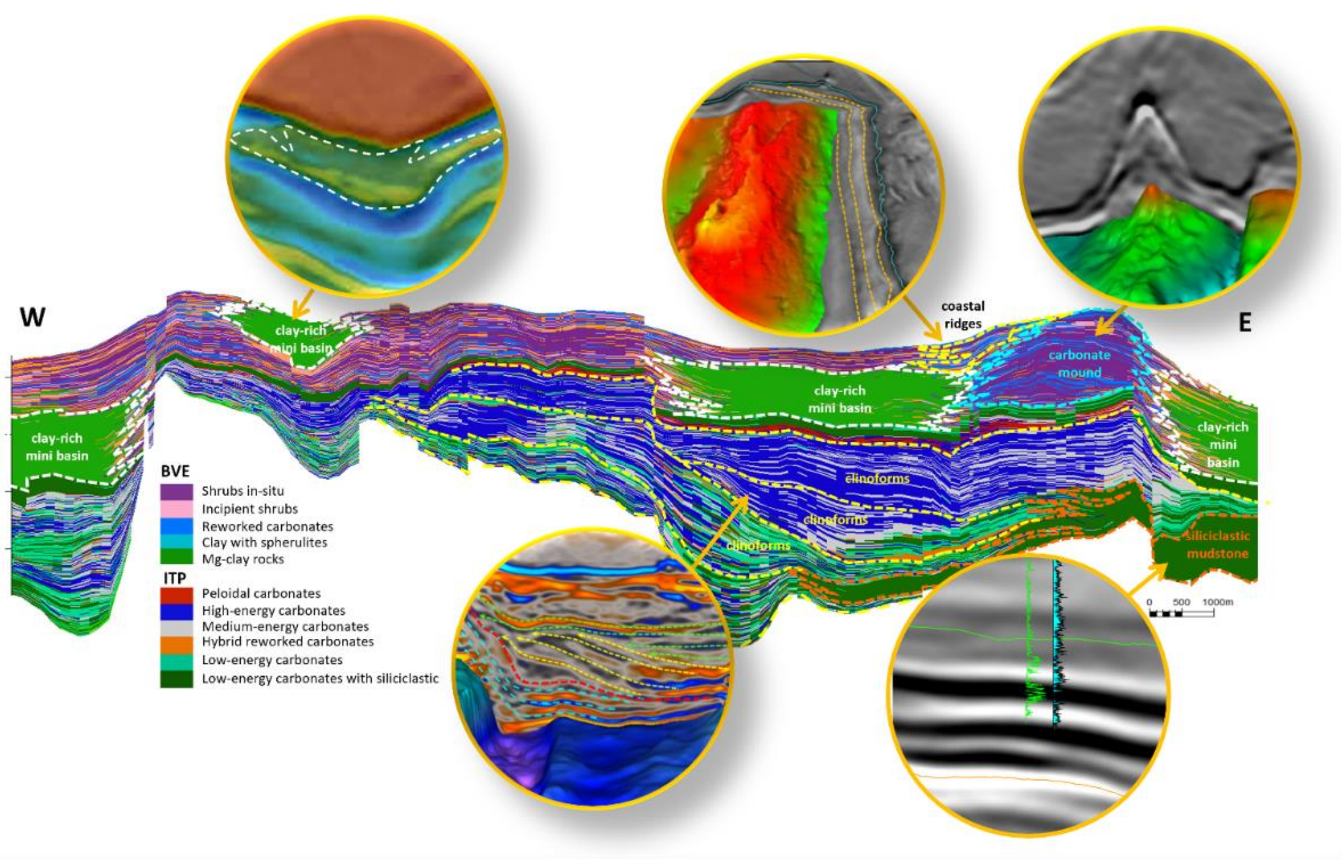

Figure 11 *- Cross-section of the sedimentary facies model. The seismic facies interpretated are highlighted in the dotted lines.*

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