SEISMIC ATTRIBUTE ANALYSIS OF TURBIDITE SANDSTONES AND CARBONATE RESERVOIRS IN BRAZILIAN EQUATORIAL MARGIN BASINS: FOZ DO AMAZONAS, PARÁ-MARANHÃO AND BARREIRINHAS

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ABSTRACT. The Foz do Amazonas, Barreirinhas and Pará-Maranhão basins, located within the Brazilian Equatorial Margin, present significant hydrocarbon exploration potential. This study applies an integrated seismic attribute analysis to identify and characterize turbidite sandstones and carbonate reservoirs. Seismic attributes such as sweetness, trace envelope, and spectral decomposition were applied to 2D and 3D seismic datasets to enhance the interpretation of key geological features, including depositional systems and structural traps. The results reveal three leads in the Barreirinhas Basin and three leads in the Pará-Maranhão Basin, highlighting structural and stratigraphic traps associated with thrust fault systems and carbonate buildups. Spectral decomposition provided a detailed visualization of thin beds and depositional geometries, while sweetness attributes effectively identified hydrocarbon-bearing zones. These results contribute to a refined understanding of the petroleum systems in the Brazilian Equatorial Margin, offering a robust framework for future exploration and risk mitigation.

Keywords: geophysical interpretation; deep-water turbidites and carbonate; stratigraphic traps; petroleum systems; hydrocarbon exploration

INTRODUCTION

The Brazilian Equatorial Margin, encompassing the Foz do Amazonas (FZA), Pará-Maranhão (PAMA), Barreirinhas (BAR), Ceará (CE) and Potiguar (POT) basins, represents a region with a complex geological history and high exploratory interest due to its potential for hydrocarbon accumulation. These basins exhibit several depositional paleoenvironments and structural settings, influencing turbidite sandstones and carbonate reservoirs' presence, distribution and quality. Recent advances in seismic attribute analysis have improved detailed reservoirs identification, providing insights to interpret the geometry and the mechanisms of trapping in the subsurface. Therefore, this research focuses on applying integrated seismic attributes, specifically sweetness, trace envelope and spectral decomposition, seeking to interpret the potential petroleum reservoirs within these basins.

The sweetness attribute is particularly effective in enhancing the visibility of deep and ultra-deepwater turbidite sandstones and carbonate reservoirs layers, by highlighting the high-amplitude and the low-frequency zones, indicative of hydrocarbon-bearing formations (Chopra & Marfurt, 2007; Hart, 2008; Ogbu et al., 2024). The trace envelope attribute provides insights into reflectivity variations, enabling the mapping of lithological contrasts and the identification of potential hydrocarbon traps (Chopra & Marfurt, 2007; Sarhan, 2017). Meanwhile, spectral decomposition allows for frequency-based imaging, enhancing the visualization of thin-bed features and subtle stratigraphic variations, which are essential for delineating complex reservoir geometries (Marfurt, 2015; Wang et al., 2016; Wadas et al., 2023).

Integrated seismic attributes were applied to 2D and 3D seismic volumes from the Foz do Amazonas, Pará-Maranhão and Barreirinhas basins (Figure 1). A refined interpretation of the reservoirs' architecture and trapping styles was achieved by analyzing these seismic attributes, thereby improving the understanding of the exploratory leads and supporting future exploration efforts in these new frontier basins of the Brazilian Equatorial Margin (Conti & Oliva, 2021; Da Silva et al., 2021; Basilone et al., 2023; Da Silva et al., 2025).
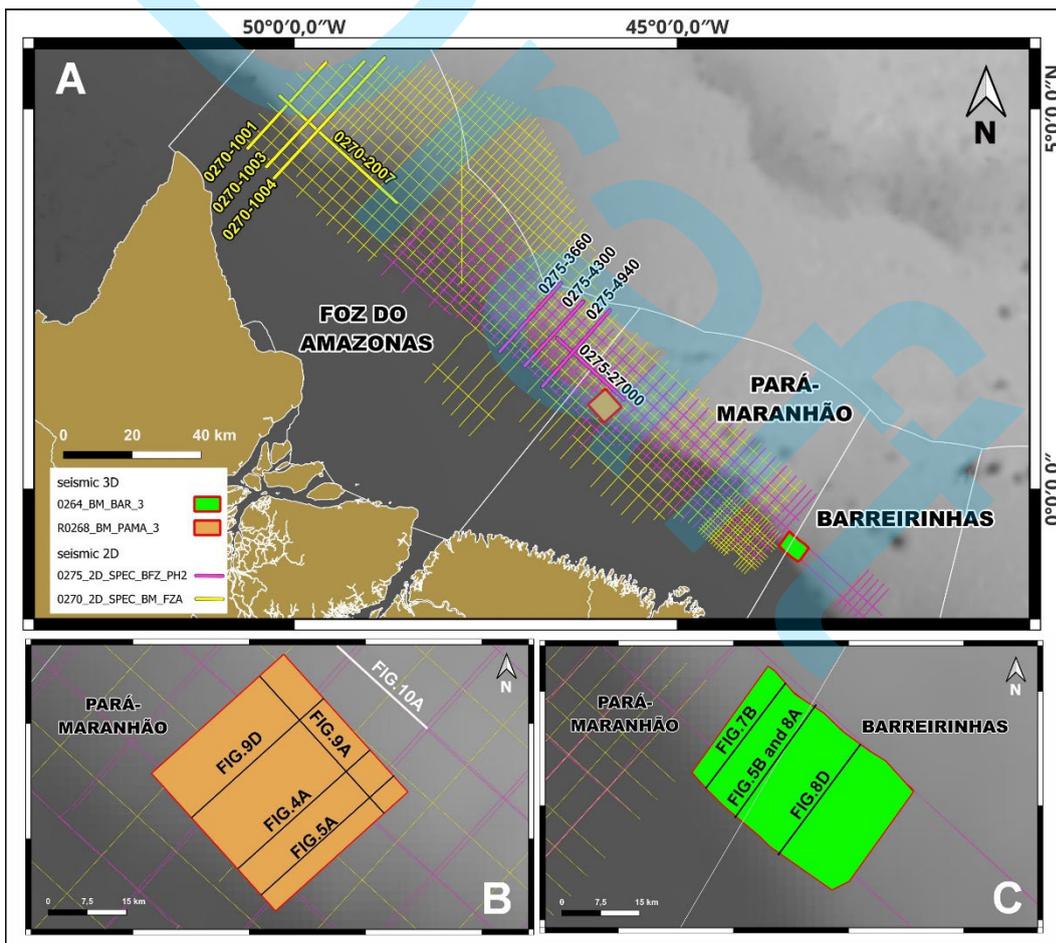

Figure 1 – (A) Location map of the seismic surveys analyzed in this study, covering the Foz do Amazonas, Barreirinhas, and Pará-Maranhão basins along the Brazilian Equatorial Margin. Highlighted are the interpreted seismic lines, to which, the seismic attributes were, including 2D seismic surveys (0275_2D_SPEC_BFZ_PH2 and 0270_2D_SPEC_BM_FZA) and 3D seismic volumes. (B) 3D seismic volume R0268_BM_PAMA_3 (orange), located in the Pará-Maranhão Basin. (C) 3D seismic volume 0264_BM_BAR_3 (green), located between the Pará-Maranhão and Barreirinhas basins. Some seismic lines contained in these 3D volumes, will be presented in the mentioned figures.

GEOLOGICAL SETTINGS

The Brazilian Equatorial Margin (BEM) exhibits a geological evolution governed by strike-slip tectonics, distinct from the extensional regime of the Brazilian Eastern Margin. The BEM basins formed through transtensional and transpressional movements along transform fault zones during the Cretaceous (Szatmari et al., 1987; Matos, 2000; Basile et al., 2005). Structurally, the BEM is divided into two tectonic segments and five rift zones (Matos et al., 2021) (Figure 2). Segment 1, a short offset transform, includes the Demerara-Guyana-Liberia and Foz do Amazonas-Liberia rift zones, extending from the Doldrums to the St. Paul Fracture Zone. Segment 2, a long offset transform, comprises the Pará-Maranhão-Barreirinhas/Ivory Coast-Tano, Piauí-Camocim/Accra-Keta, and Mundaú-Togo/Offshore Potiguar-Benin rift zones, extending from St. Paul to the Chain Fracture Zone. The Romanche Fracture Zone (RFZ) is a key tectonic boundary influencing crustal deformation, sedimentation, and petroleum systems (Tavares et al., 2020).
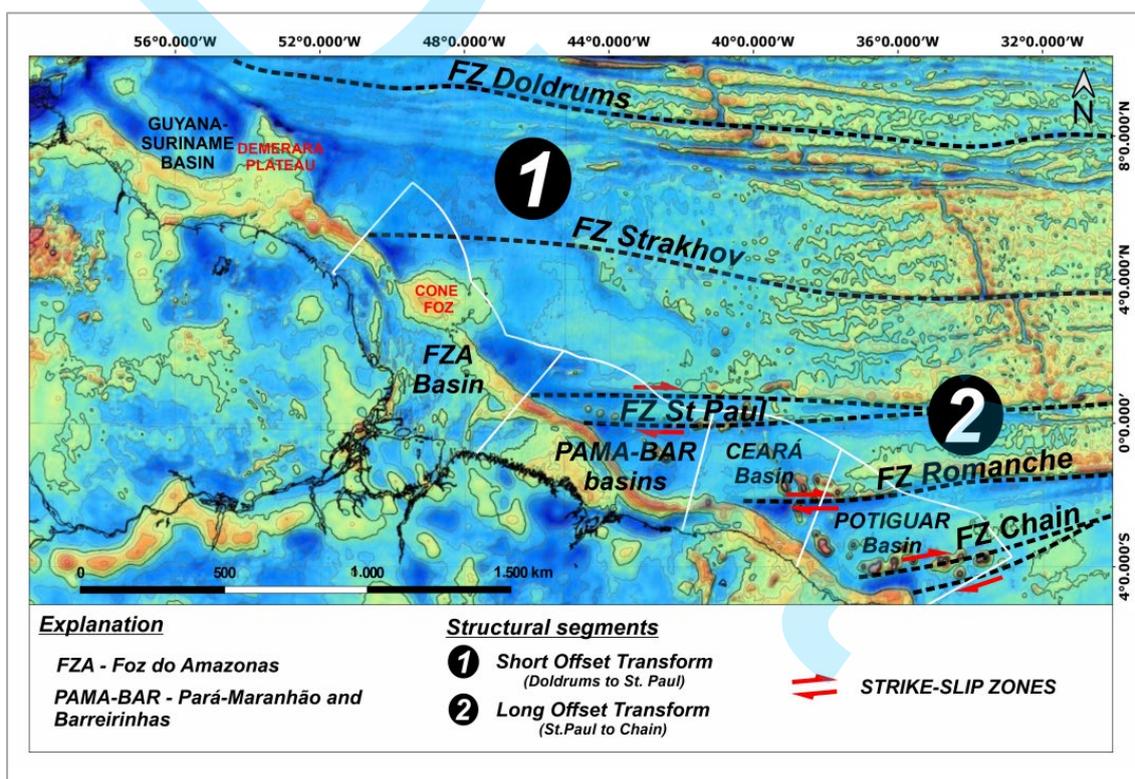

Figure 2 - Configuration of the Brazilian Equatorial Margin (BEM) basins, including the Foz do Amazonas (FZA), Pará-Maranhão (PAMA), Barreirinhas (BAR), Ceará and Potiguar basins. Together with the adjacent Guyana-Suriname Basin and Demerara Plateau, these basins illustrate the structural and geological linkage across the margin, reflecting a continuous tectonic evolution associated with transform fault systems. The map incorporates key structural features, such as major fracture zones (FZ Doldrums, FZ Strakhov, FZ St. Paul, FZ Romanche, and FZ Chain), which play a crucial role in the formation and evolution of these basins. The structural segments are categorized into short offset transforms (Doldrums to St. Paul) and long offset transforms (St. Paul to Chain). The data presented are based on gravimetric measurements (New Marine Gravity Anomaly, Sandwell et al., 2014) and the tectonic framework outlined by Matos et al (2021).

The stratigraphic evolution of the BEM basins is divided into four major supersequences: Intracratonic, Pre-Rift, Rift, and Drift (Figueiredo et al., 2007; Soares et al., 2007). However, stratigraphic characteristics vary significantly between the Foz do Amazonas Basin and the Pará-Maranhão and Barreirinhas basins (Figure 3).

In the Foz do Amazonas Basin, the Intracratonic Supersequence is poorly defined due to limited Paleozoic records. The Pre-Rift Supersequence includes the Calçoene Formation, composed of sandstones interbedded with basaltic lava flows, representing continental environments. The Rift Supersequence is divided into three stages: Rift I and III, represented by the Cassiporé Formation, comprising dark-gray shales interbedded with fine- to medium-grained sandstones; and Rift II, marked by the Codó Formation, consisting of shales and calcilutites deposited in anoxic lacustrine environments. This supersequence is defined based on well profiles (e.g., wells 1-APS-18-AP and 1-APS-49-AP) and seismic data, from the identification of high-amplitude continuous reflectors. The Drift Supersequence includes the Limoeiro, Travosas, Amapá, and Marajó formations, characterized by turbidite sandstones and slope deposits in deep-waters. In the Amazon Cone, the Orange, Pirarucu and Tucunaré formations are noteworthy.

The Intracratonic Supersequence in the Pará-Maranhão and Barreirinhas basins comprises Paleozoic deposits, including the Itaim (sandstones), Pimenteiras (shales) and Cabeças (sandstones) formations, which represent typical intracratonic basin deposits. The Pre-Rift Supersequence is represented by the Codó Formation, composed of lagoonal shales and calcilutites, indicative of anoxic evaporitic events. The Rift Supersequence is characterized by the Canárias Group, with continental siliciclastic rocks transitioning to paralic sediments, including lithic sandstones, reddish siltstones and greenish shales deposited in lacustrine, fluvial, and deltaic environments. In the Barreirinhas Basin, the Caju Group comprises the Bonfim (bioclastic calcarenites) and Preguiças (calcilutites) formations, deposited in shallow marine environments with variable energy. The Drift Supersequence in the Pará-Maranhão and Barreirinhas basins comprises equivalent carbonate-siliciclastic units, represented by the Caju and Humberto de Campos groups. In the Barreirinhas Basin, the Pirabas Formation represents shallow marine transgressive deposits, while deep-water turbidites are associated with the Travosas Formation (Feijó, 1994; Figueiredo et al., 2007).

The Foz do Amazonas Basin features source rocks in the Cassiporé/Codó formations are made up of marine shales and anoxic evaporite shales. They have total organic carbon (TOC) values ranging from 1.14 to 10.3 wt%, S2 between 2.50 and 62.5 mg HC/g rock, and hydrogen index (HI) values exceeding 890 mg HC/g TOC. The source rocks in the late Albian-early Cenomanian Limoeiro Formation have a TOC between 1.76 and 4.4 wt%, S2 ranging from 3.52 to 20.01 mg HC/g rock, and an HI of about 530 mg HC/g TOC. In the Cenomanian-Turonian interval of the Limoeiro Formation, the marine shales exhibit TOC values ranging from 1.14 to 3.48 wt%, S2 ranging from 3.09 to 19.09 mg HC/g rock, and an HI between 164.40 and 548.56

mg HC/g TOC. In the Pará-Maranhão and Barreirinhas basins, the Caju Group (late Albian-early Cenomanian) is represented by calcilutites and marine shales with TOC values between 1.00% and 1.56%, predominantly composed of kerogen type II (Table 1) (Da Silva et al., 2024).

Table 1 - Displays the minimum (Min.) and maximum (Max.) values of the geochemical parameters (TOC, S1, S2, S3, Tmax, HI, and OI) obtained from shallow waters wells of the Foz do Amazonas and Pará-Maranhão/Barreirinhas basins.

	BASINS	CHRONOSTRATIGRAPHY INTERVAL	LITHOSTRATIGRAPHY		TOC	S1	S2	S3	Tmax	HI	OI
SHALLOW WATERS WELLS	Foz do Amazonas	Paleocene-Middle Miocene	Amapá/Travosas	Min.	1.34	-	2.93	0.48	418.00	212.15	35.80
				Max.	1.81	-	3.84	1.16	431.00	218.65	64.08
		Cenomanian-Turonian	Limoeiro	Min.	1.14	0.10	3.09	0.43	420.00	164.40	25.86
				Max.	3.48	0.90	19.09	1.61	432.00	548.56	121.96
		late Albian-early Cenomanian	Limoeiro	Min.	1.76	0.26	3.52	0.92	426.00	177.77	37.60
				Max.	4.40	1.70	20.01	1.72	440.00	531.06	110.79
		late Aptian-early Albian	Cassiporé/Codó	Min.	1.14	0.01	2.50	0.12	426.00	65.01	6.79
				Max.	10.30	1.98	62.50	2.93	450.00	898.01	151.63
	Pará-Maranhão /Barreirinhas	late Albian-early Cenomanian	Caju Group	Min.	1.00	0.05	3.22	0.45	430.00	287.50	43.96
				Max.	1.56	0.44	6.03	2.10	440.00	463.80	136.44

Total organic carbon (TOC) (wt%), S1 (mg HC/g rock), S2 (mg HC/g rock), S3 (mg CO_2/g rock), Tmax (°C), HI (mg HC/g TOC) and OI (mg CO_2/g TOC).

The petroleum systems of the BEM basins are primarily related to the Lower and Upper Cretaceous source rocks, including lacustrine and marine shales in the Foz do Amazonas Basin, the hypothetical Cassiporé/Codó-Limoeiro and Limoeiro-Limoeiro petroleum systems are characterized by turbidite sandstone reservoirs confined by stratigraphic traps (Da Cruz et al., 2021). Mass Transport Deposits (MTDs) overlying these systems act as regional barriers to vertical migration (Reis et al., 2016). In the Pará-Maranhão and Barreirinhas basins, the petroleum systems include Codó-Travosas, Caju-Travosas and Travosas-Travosas, with reservoirs found in the Canárias Group (fluvio-deltaic sandstones), Caju Group (fractured carbonates and shallow marine sandstones) and Travosas Formation (turbidite sandstones). Migration pathways involve direct contact between source and reservoir, as well as conduits through faults, while marine shales from the Travosas Formation serve as effective seals (Pellegrini & Severiano Ribeiro, 2018).

The main reservoirs analyzed in this study are the Late Cretaceous turbidite sandstones of the Limoeiro and Travosas formations, located respectively in the Foz do Amazonas, Pará-

Maranhão and Barreirinhas basins. Additionally, Paleogene carbonate reservoirs were also investigated. The interpretation focused on these key stratigraphic units, aiming to refine the understanding of their depositional architecture, trapping styles and hydrocarbon potential.
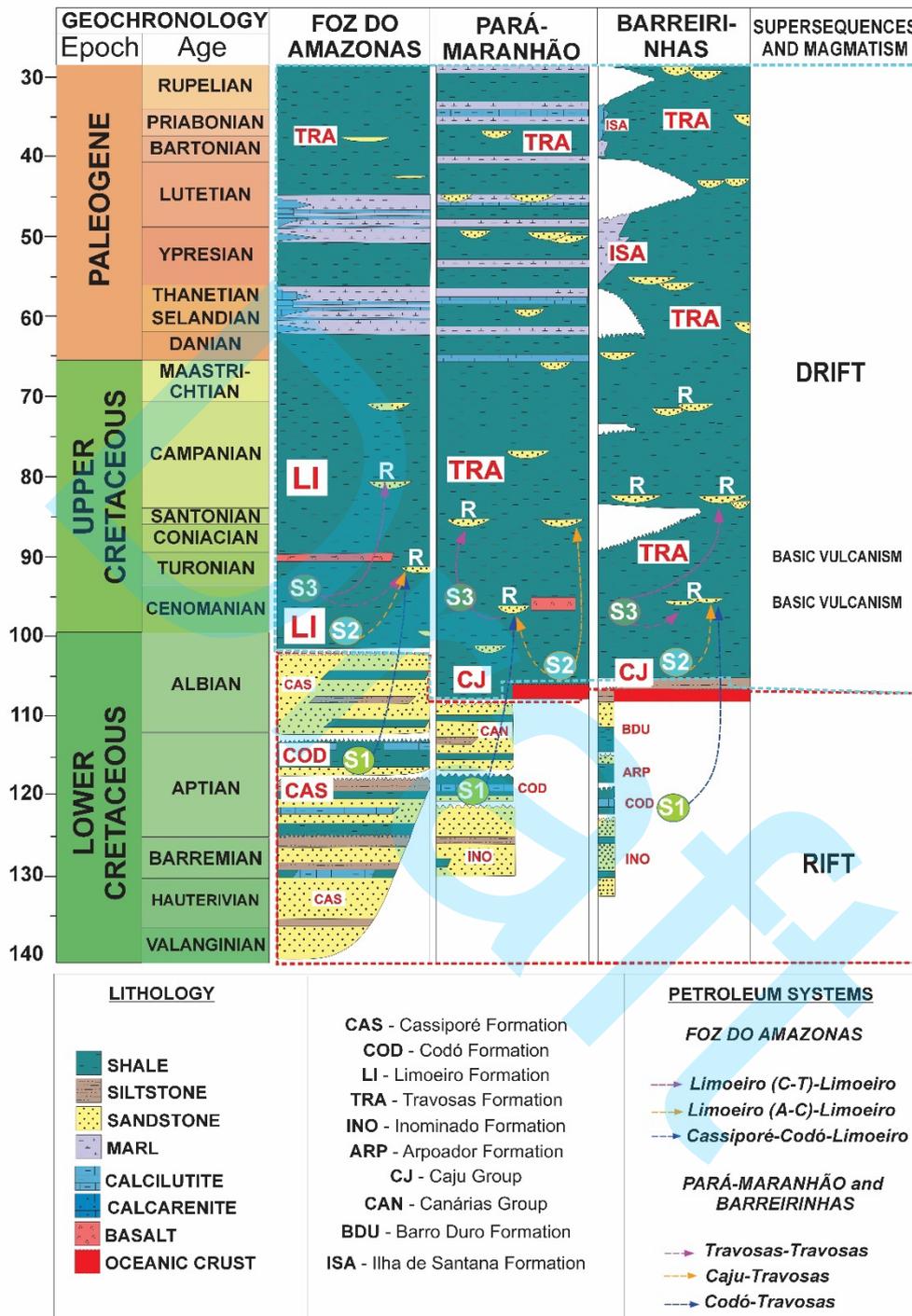

Figure 3 - Simplified stratigraphic charts for the deepwater slope regions of the Brazilian Equatorial Margin (BEM), encompassing the Foz do Amazonas, Pará-Maranhão and Barreirinhas basins. The chart identifies petroleum systems and supersequences related to distinct tectonic phases, including the Rift and Drift stages, and volcanic activity. Adapted from Milani et al. (2007).

MATERIALS AND METHODOLOGY

The seismic data analyzed in this study were provided by the National Petroleum, Natural Gas, and Biofuels Agency (ANP) and consist of two 2D post-stack seismic surveys lines (0275_2D_SPEC_BFZ_PH2 and 0270_2D_SPEC_BM_FZA) and two 3D post-stack seismic surveys (R0268_BM_PAMA_3 and 0264_BM_BAR_3), covering the Foz do Amazonas, Pará-Maranhão and Barreirinhas basins (Figure 1). The 2D seismic data, processed in the two-way travel time (TWT), provided a structural framework for interpreting the fault systems and the major geological horizons, while the 3D surveys, characterized by higher spatial resolution, enabled the identification of stratigraphic and structural features, such as sedimentary facies and hydrocarbon traps.

The identification of the reservoirs in this study was based on the qualitative interpretation of advanced seismic attributes, specifically selected for their effectiveness in delineating subsurface features such as turbidite sandstones and carbonate reservoirs. By analyzing variations in amplitude, frequency, and phase, these attributes enhanced the recognition of key stratigraphic and structural elements, supporting a more refined geological interpretation (Taner, 2001; Chopra & Marfurt, 2007; Veeken, 2007).

Sweetness, a composite seismic attribute first introduced by Radovich & Oliveros (1998) and later expanded upon by Hart (2008), is calculated as the ratio of the trace envelope to the square root of instantaneous frequency. This attribute has proven particularly effective for identifying clean, thick and porous reservoirs, as it enhances the visibility of high-amplitude, low-frequency anomalies commonly associated with hydrocarbon accumulations. It is especially useful in clastic systems, where it highlights coarse-grained, sand-rich reservoirs. In this study, Sweetness was critical for mapping channel bodies and depositional features with potential as hydrocarbon traps.

According to Chopra & Marfurt (2007), the trace envelope, also referred to as reflection strength, represents the total instantaneous energy of the seismic signal and was used to detect amplitude variations related to acoustic impedance contrasts. This attribute provides reliable indicators of sequence boundaries, thin-bed tuning effects, and possible gas accumulations, as evidenced by "bright spots".

Spectral decomposition, a technique that breaks down seismic signals into their constituent frequency components (Partyka et al.,1999), was applied to reveal subtle structural and stratigraphic details not discernible in conventional seismic data (Marfurt & Kirlin, 2001; Wang et al., 2016). By examining frequency responses, this method facilitated the mapping of thin beds, channels and depositional geometries. The use of RGB color-blending to combine low, medium and high-frequency bands further enhanced the identification of tuning effects and depositional environments, significantly contributing to seismic geomorphology studies (Henderson et al., 2008).

The interpretation workflow was conducted using OpendTect® V7.0, encompassing horizon selection, fault mapping and attribute analysis. This integrated approach combined structural, stratigraphic and attribute-based interpretations to construct a geological model of the study area, providing insights into key reservoir characteristics and hydrocarbon potential.

RESULTS AND DISCUSSIONS

The chronostratigraphic interpretation emphasized the identification of depositional intervals conducive to reservoir development and the structural analysis of both thrust and extensional fault systems. Key horizons were interpreted, including the Albian top, Cretaceous top, middle Eocene, middle Oligocene, middle Miocene, and the Seabed (Figures 4A and 4B). These horizons provided a framework for understanding the stratigraphic evolution and tectonic dynamics of the study area, which are critical for delineating potential hydrocarbon-bearing intervals and assessing structural traps.
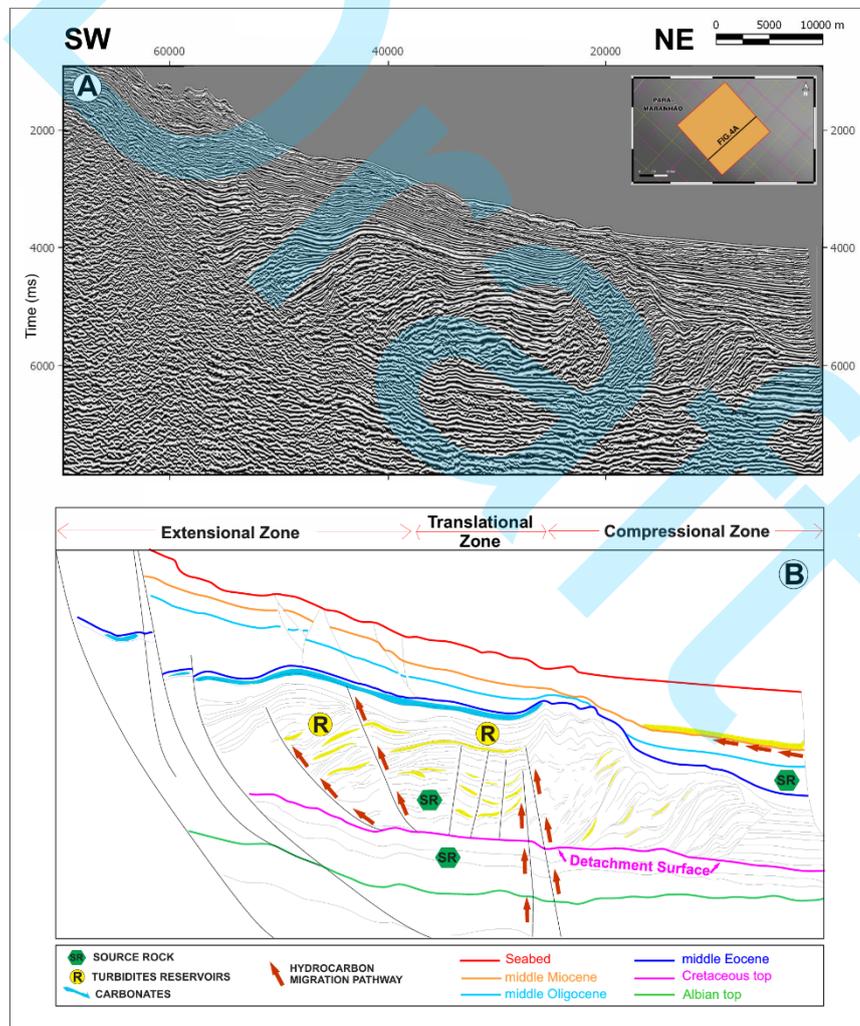

Figure 4 - Interpretation of seismic in-line 2352 from the 3D seismic volume R0268_BM_PAMA_3, Pará–Maranhão Basin. (A) Cosine of phase seismic attribute highlighting extensional, translational, and compressional deformation zones, as well as associated fault systems. (B) Interpretation of key seismic horizons and faults, emphasizing turbidite reservoirs and carbonate layers. Fault systems are interpreted as the main hydrocarbon migration pathways feeding these structurally controlled reservoirs.

Pará-Maranhão and Barreirinhas basins

Application of the sweetness attribute facilitated the identification of the main reservoir intervals, including turbidite sandstones and carbonate horizons, in the Pará-Maranhão and Barreirinhas basins. High sweetness values, highlighted in yellow in the seismic sections, correspond to hydrocarbon-prone zones, such as structured turbidites sandstones and carbonate accumulations. Carbonate horizons in the Pará-Maranhão Basin (Figure 5A) present moderate to high sweetness values, indicating favorable porosity and potential hydrocarbon accumulation intervals. Likewise, in the Barreirinhas Basin (Figure 5B), sandstone turbidite deposits associated with thrust fault systems exhibit distinct high sweetness anomalies, suggesting potential reservoir zones within structural traps.
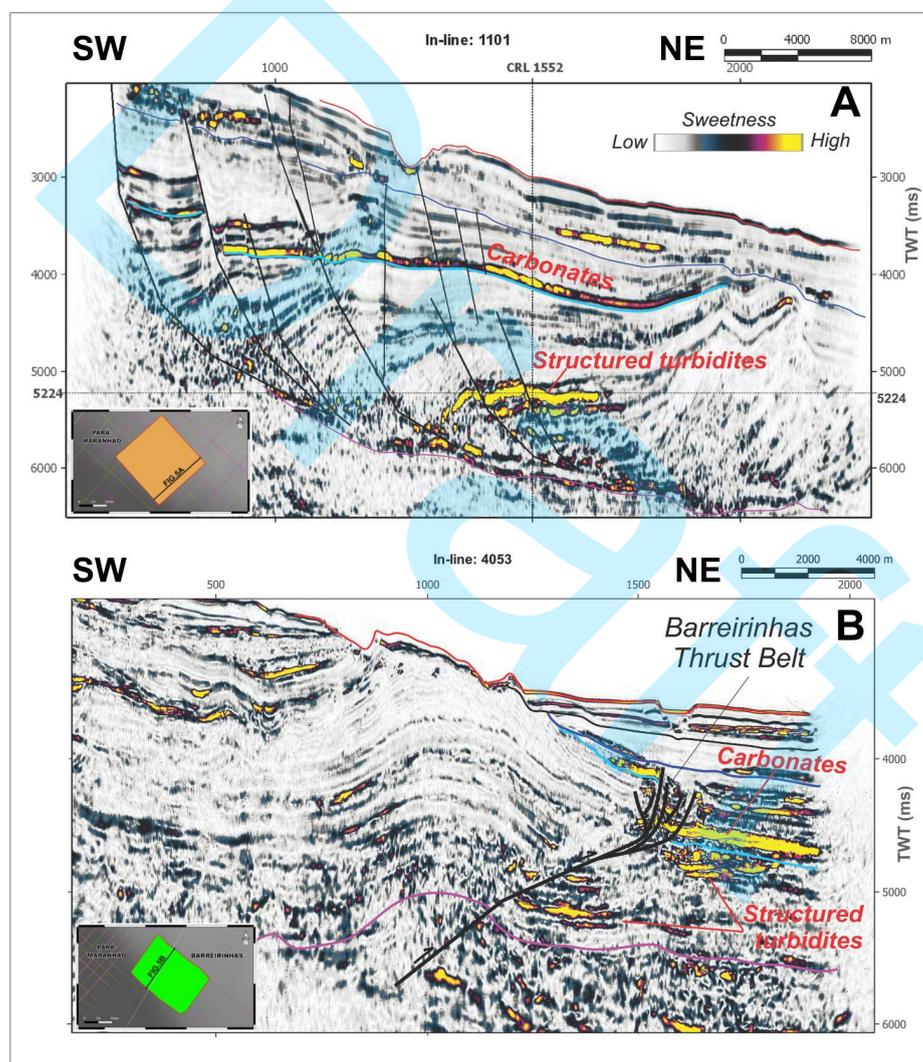

Figure 5 - Application of the sweetness attribute. (A) In-line 1101 from the 3D seismic volume R0268_BM_PAMA_3, highlighting high sweetness values that help distinguish and identify structured turbidite reservoirs. The carbonate horizon is also clearly delineated. (B) In-line 4053 from the 3D seismic volume 0264_BM_BAR_3, identifying the thrust belt zone of Barreirinhas, where thrust faults predominate and confine carbonate reservoirs with very high sweetness values. Additionally, the occurrence of structured turbidite sandstone reservoirs is identified. Interpretation of the key horizons and faults highlights turbidite sandstone reservoirs and carbonate layers. Faults are identified as the main migration pathways for hydrocarbons into these structured reservoirs.

The application of spectral decomposition to the seismic volume of the Barreirinhas Basin provided a detailed visualization of the geological features through the analysis of the seismic signal in different frequency bands. The frequency slices (10 Hz, 20 Hz, and 30 Hz) allowed the identification of critical stratigraphic and depositional patterns for reservoir characterization. The RGB blending technique combined these frequencies into a single composite image, highlighting variations in thickness, lithology and fluid content across reservoir zones. Low-frequency anomalies in the RGB mixture were particularly effective in delineating potential hydrocarbon-bearing sandstone turbidite reservoirs (Figures 6A and 6B).

Figure 6C presents a spectral decomposition time slice at 4688 ms, using a 10 Hz frequency in a flipped view. The image highlights amplitude anomalies that may be associated with features of geological significance. In this representation, red tones indicate higher amplitude responses, which can suggest variations in lithology, fluid content, or stratigraphic features. Such anomalies are valuable for interpreting potential hydrocarbon accumulations, mapping stratigraphic traps, or delineating sequence boundaries.

Figure 6D presents an interpreted block diagram of the Barreirinhas Basin, highlighting Leads 1, 2, and 3 associated with a thrust fault system, indicating structural traps with hydrocarbon potential.

An integrated attribute analysis of seismic data from the Barreirinhas Basin identified three exploratory leads composed of turbidite sandstones and carbonate reservoirs. These leads were mapped using spectral decomposition (Figure 7A) and sweetness attributes, which highlight amplitude contrasts and thrust faults (Figure 7B). In seismic in-line 4724, high sweetness values correlate with potential reservoir zones. The geological interpretation (Figure 7C) emphasizes a compressional setting characterized by faults and folds, which are critical for trap formation. The significant areal extent and thickness of these leads support the need for more detailed exploration.

During the Eocene to Oligocene, gravitational collapse in the Barreirinhas Basin resulted in the deposition of significant turbidite sandstones and calciturbidites, confined within structural traps. Figures 8A and 8D show amplitude data that reveal stratigraphic variations within these deposits. Figures 8B and 8E incorporate sweetness attributes, which assist in identifying areas of high hydrocarbon potential, particularly associated with Leads 2 and 3 (Figure 7A). Finally, Figures 8C and 8F present interpreted cross-sections of the compressional zone, highlighting the Barreirinhas thrust belt as a key trapping mechanism. This integrated analysis improves reservoir characterization and supports the assessment of hydrocarbon prospectivity.
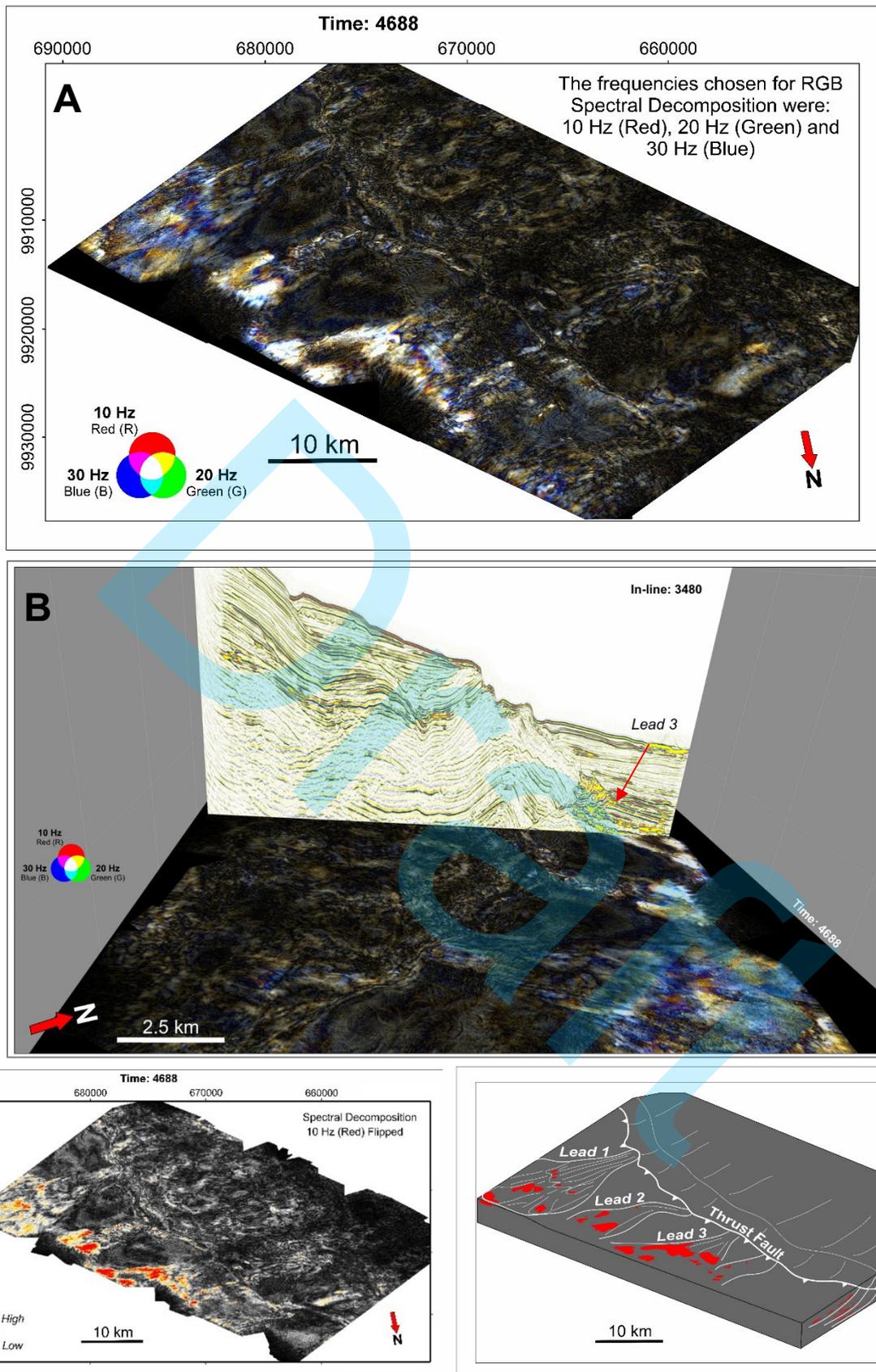
Figure 6 - (A) Spectral decomposition time slice at 4688 ms from the 0264_BM_BAR_3 dataset, combining 10 Hz (red), 20 Hz (green), and 30 Hz (blue) frequencies. White zones indicate similar amplitude across all bands, suggesting uniform geological or fluid properties. (B) In-line 3480 section showing the structural configuration and Lead 3, with the spectral decomposition time slice at 4688 ms highlighting geological features. (C) Spectral decomposition time slice at 4608 ms (10 Hz, flipped view), showing amplitude anomalies of potential geological interest; red indicates higher amplitudes. (D) Interpreted block diagram of the Barreirinhas Basin study area, showing the main leads (Lead 1, Lead 2, and Lead 3) associated with a thrust fault system.
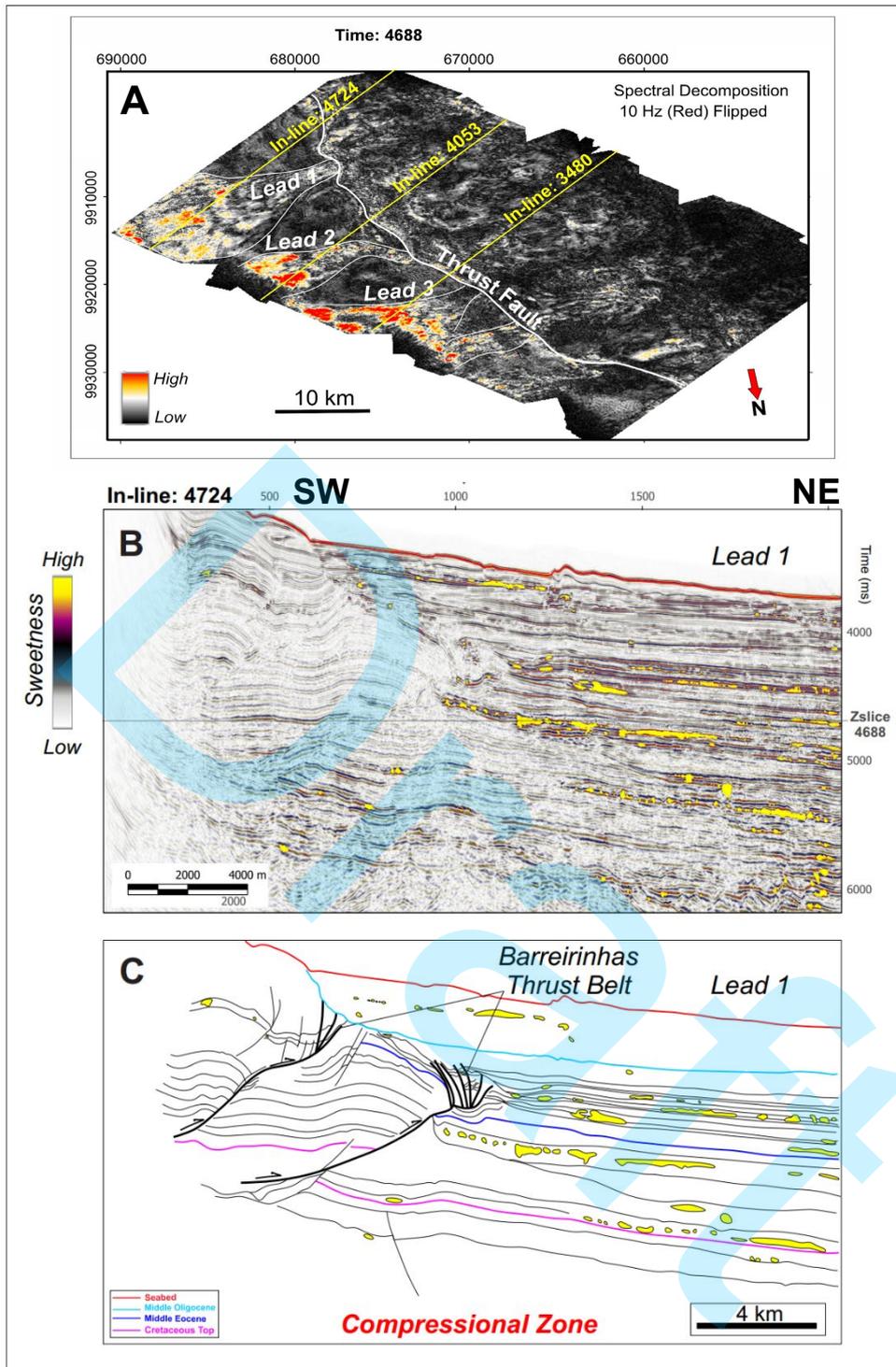
Figure 7 - The identification of the five exploratory leads in the Barreirinhas Basin, highlighting turbidite and carbonate reservoirs. (A) A spectral decomposition time slice at 4688 ms shows three prominent leads, with the high-amplitude areas (red) associated with carbonate horizons and turbidite sandstones. (B) A dip section (in-line 4724) utilizing the sweetness attribute underscores high-impedance contrasts related to Lead 1, indicating sandstone turbidites. (C) The geological interpretation detailing the structural and stratigraphic framework and the spatial arrangement and trapping mechanisms of the identified leads (seismic line location see Figure 1).
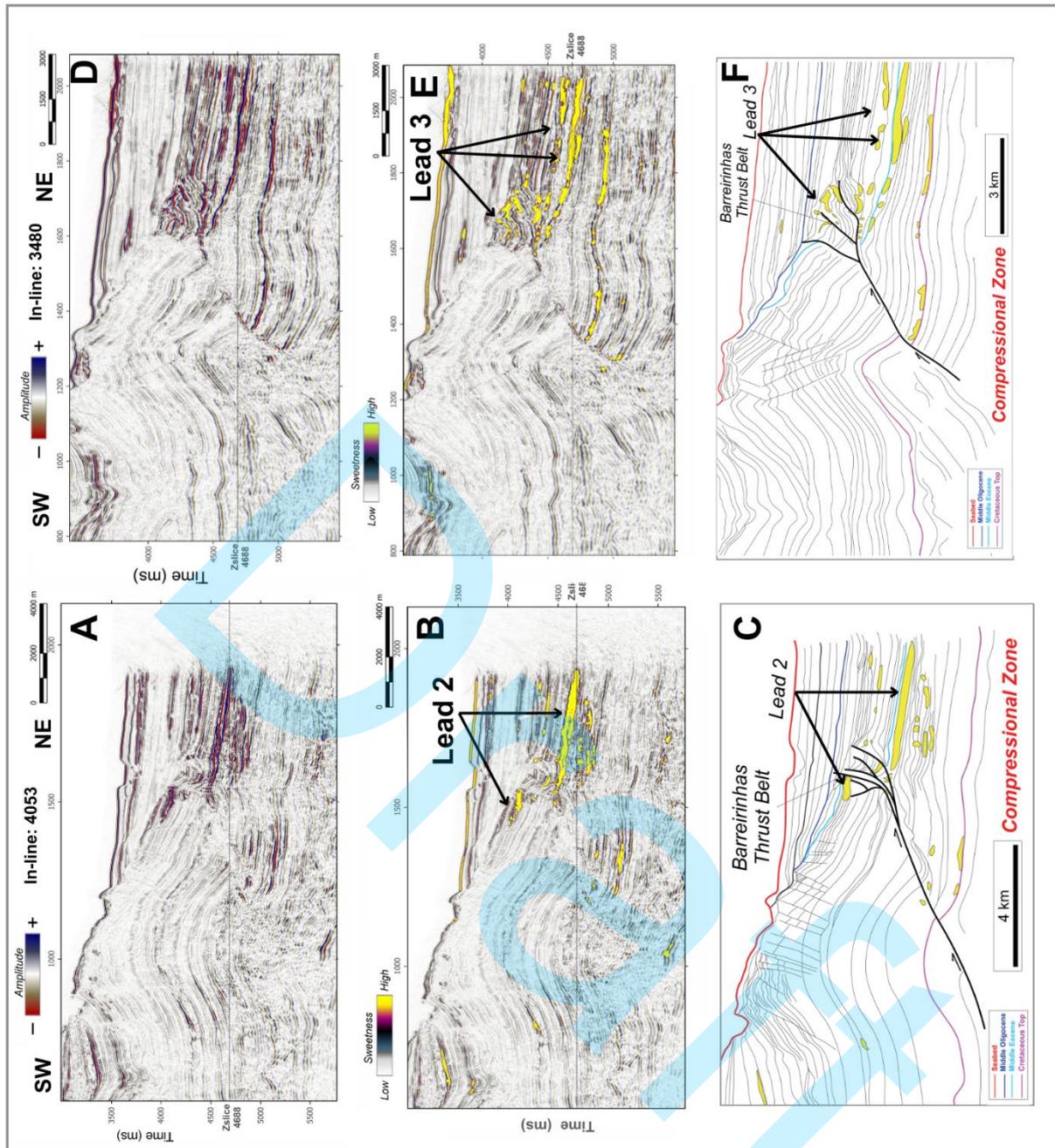
Figure 8 - Compressional zone of the Barreirinhas Basin, characterized by the Barreirinhas thrust belt. (A and D) Seismic sections highlight structured turbidite reservoirs and carbonate deposits, indicated by high-amplitude reflections. (B) and (E) Sweetness attribute applied to emphasize high-reflectivity zones (yellow), corresponding to potential reservoir targets (Lead 2 and Lead 3). (C and F) Interpreted cross-section showing the location of Lead 2 and Lead 3 relative to the Barreirinhas thrust belt, which functions as the primary trapping mechanism within this compressional zone (seismic line location see Figure 1).

In the Pará-Maranhão Basin, seismic sections and integrated attribute analysis also reveal key geological features and possible hydrocarbon leads. Figure 9A and B present cross-sections highlighting significant units, including Late Cretaceous turbidites (Lead 1), structured turbidites (Lead 2) and carbonate horizons (Lead 3), alongside hydrocarbon migration pathways and source rocks. Figure 9C and D emphasize the application of sweetness attributes, which

enhance seismic contrast by highlighting lithological and fluid variations, improving the identification of hydrocarbon leads. These figures collectively demonstrate the basin's exploration potential.
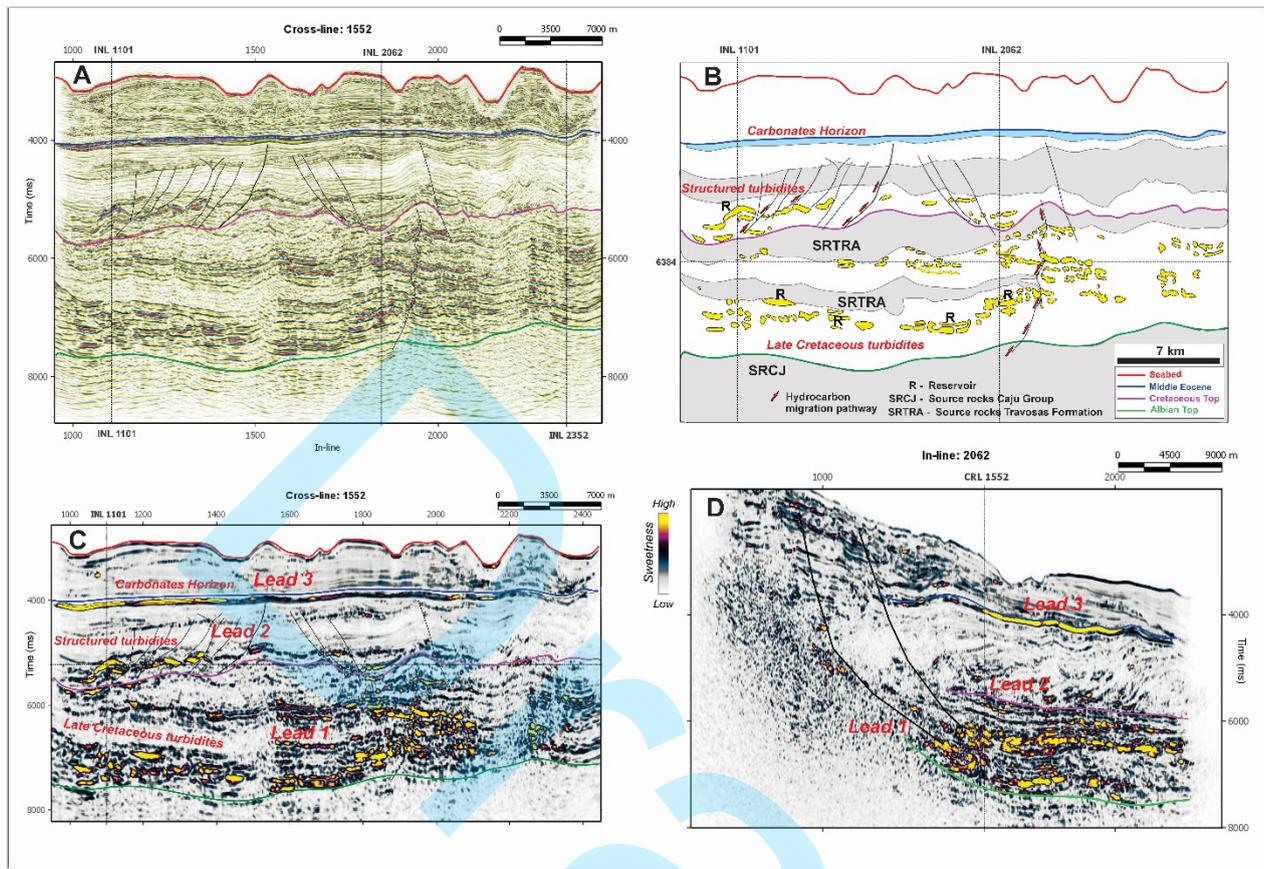

Figure 9 - Seismic sections of the Pará-Maranhão Basin illustrating key geological horizons and potential hydrocarbon leads. (A and B) display interpreted cross-sections with significant units such as the carbonate horizon, structured turbidites, and Late Cretaceous turbidites, along with hydrocarbon migration pathways and source rocks. (C and D) show the application of the sweetness attribute, which enhances lithological and fluid changes, allowing the identification of hydrocarbon leads (Lead 1, Lead 2, and Lead 3) through improved seismic contrast for exploration purposes (seismic line location see Figure 1).

The carbonate reservoirs (Lead 3) are distinctly marked in the upper part, particularly at the middle Eocene horizon, a prominent feature across the Pará-Maranhão, Barreirinhas and Foz do Amazonas basins. This horizon is characterized by high sweetness amplitudes, indicating the presence of well-developed carbonate deposits.

The seismic strike section (0275-27000) marks the southeastern boundary between the Foz do Amazonas and Pará-Maranhão basins. Figure 10A shows an uninterpreted section with high sweetness values (in yellow), indicating exploratory leads across the basins. Figure 10B provides an interpreted section with the key stratigraphic horizons: seabed, middle Miocene, middle Eocene and Cretaceous top alongside significant fault lines and magmatic intrusions. Lead 1 and Lead 2 correlate with high sweetness anomalies, highlighting the potential hydrocarbon accumulations within these structural and stratigraphic traps.

The co-rendering of Sweetness and amplitude attributes, together the structural mapping, allows for a more detailed visualization of the reservoir geometries and the trapping mechanisms, enhancing the interpretation of the petroleum system within these key horizons.
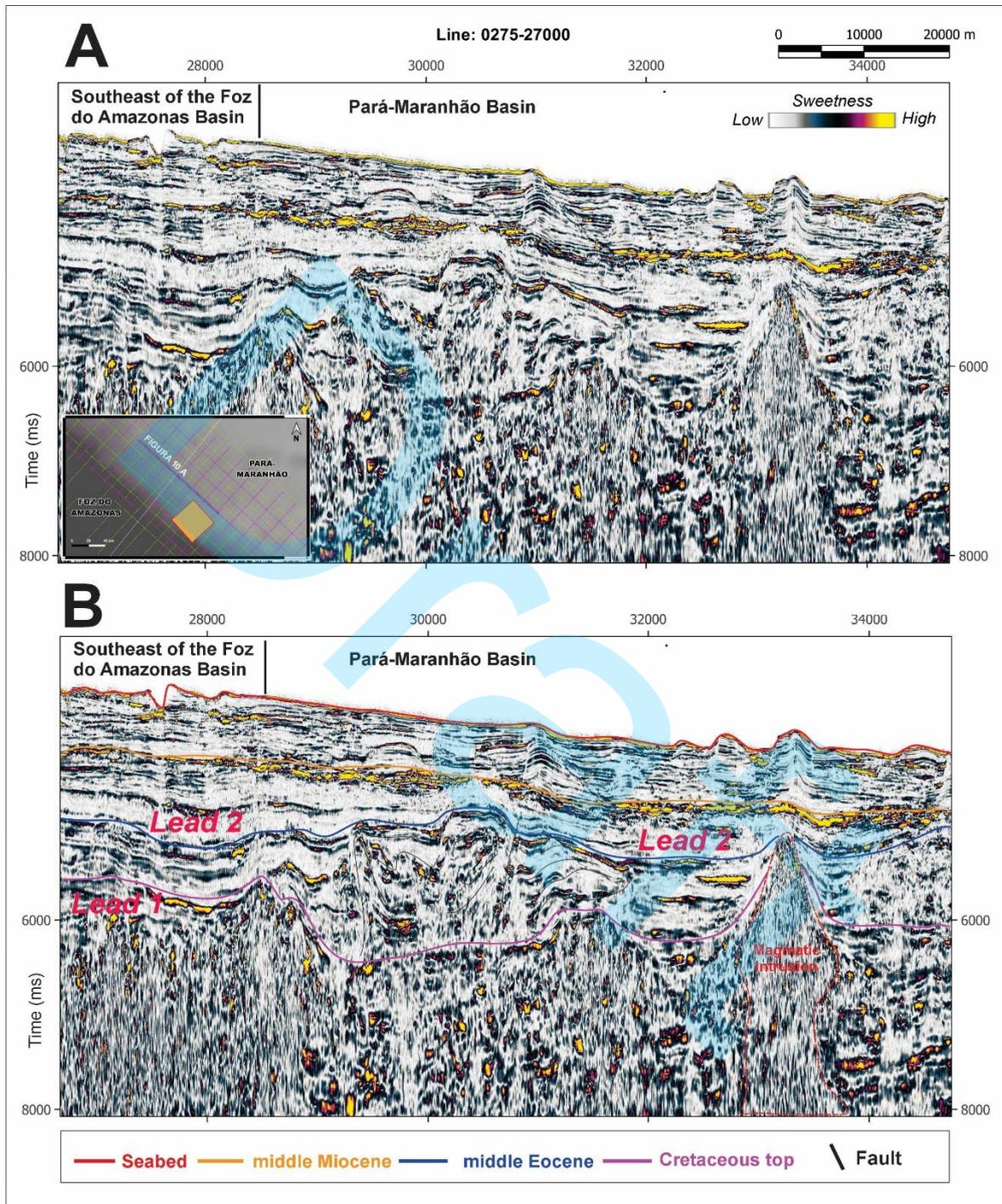

Figure 10 - Seismic strike section (0275-27000) marking the boundary between the southeastern Foz do Amazonas Basin and the Pará-Maranhão Basin. (A) Uninterpreted 0275-27000 seismic section displaying high sweetness values (highlighted in yellow), indicative of key exploratory leads across the two basins. (B) Interpreted 0275-27000 seismic section outlining the major stratigraphic horizons, including the seabed, middle Miocene, middle Eocene and Cretaceous top, along with prominent fault lines and magmatic intrusions. The leads (Lead 1 and Lead 2) are defined and correlated with high sweetness anomalies, suggesting potential hydrocarbon accumulation zones.

Foz do Amazonas Basin

In the Foz do Amazonas Basin, 2D seismic lines were interpreted in both the northwestern area, near the border with French Guiana, and the southeastern, adjacent to the Pará-Maranhão Basin (Figure 1).

For the northwestern area, only sweetness was interpreted and applied to lines 0270-1001, 0270-1003, 0270-1004 and 0270-2007 from the 0270_2D_SPEC_BM_FZA survey.

The sweetness attribute proved crucial in analyzing all these seismic lines, effectively highlighting the Late Cretaceous deep- and ultra-deepwater sandstone turbidites, characterized by high sweetness values and occasional intercalation with calciturbidites (Lead 1). Additionally, the carbonate sequences marked by chaotic reflectors, indicative of calciturbidites, were identified. Figures 11A-D illustrate these configurations comprehensively, showcasing the structural and depositional patterns associated with these leads.

In the southeastern area, the sweetness seismic attribute was interpreted and applied to lines 0275-3660, 0275-4300 and 0275-4940 from the 0270_2D_SPEC_BM_FZA survey. The sweetness attribute application resulted in the clear delineation of continuous and plane-parallel layers interrupted by extensional faults, with high sweetness intensities associated with the Late Cretaceous sandstone turbidites below the Cretaceous top horizon (Figures 12A–D and Figure 13A).

The middle Eocene-middle Miocene interval is marked by sigmoidal clinoforms with a "S"-shaped lateral arrangement, formed through progressive growth along surfaces that gently dip into deeper waters. This type of clinoform suggests a low sediment supply rate, continuous subsidence, or a rapid relative sea-level rise within a low-energy depositional environment (Figure 13 C).

Moreover, the integration of seismic attributes, including sweetness and amplitude, has improved the ability to identify subtle stratigraphic traps, particularly in the southeastern area. This methodology enhances the precision of reservoir characterization, aiding in the delineation of high-potential leads for further exploration and development.
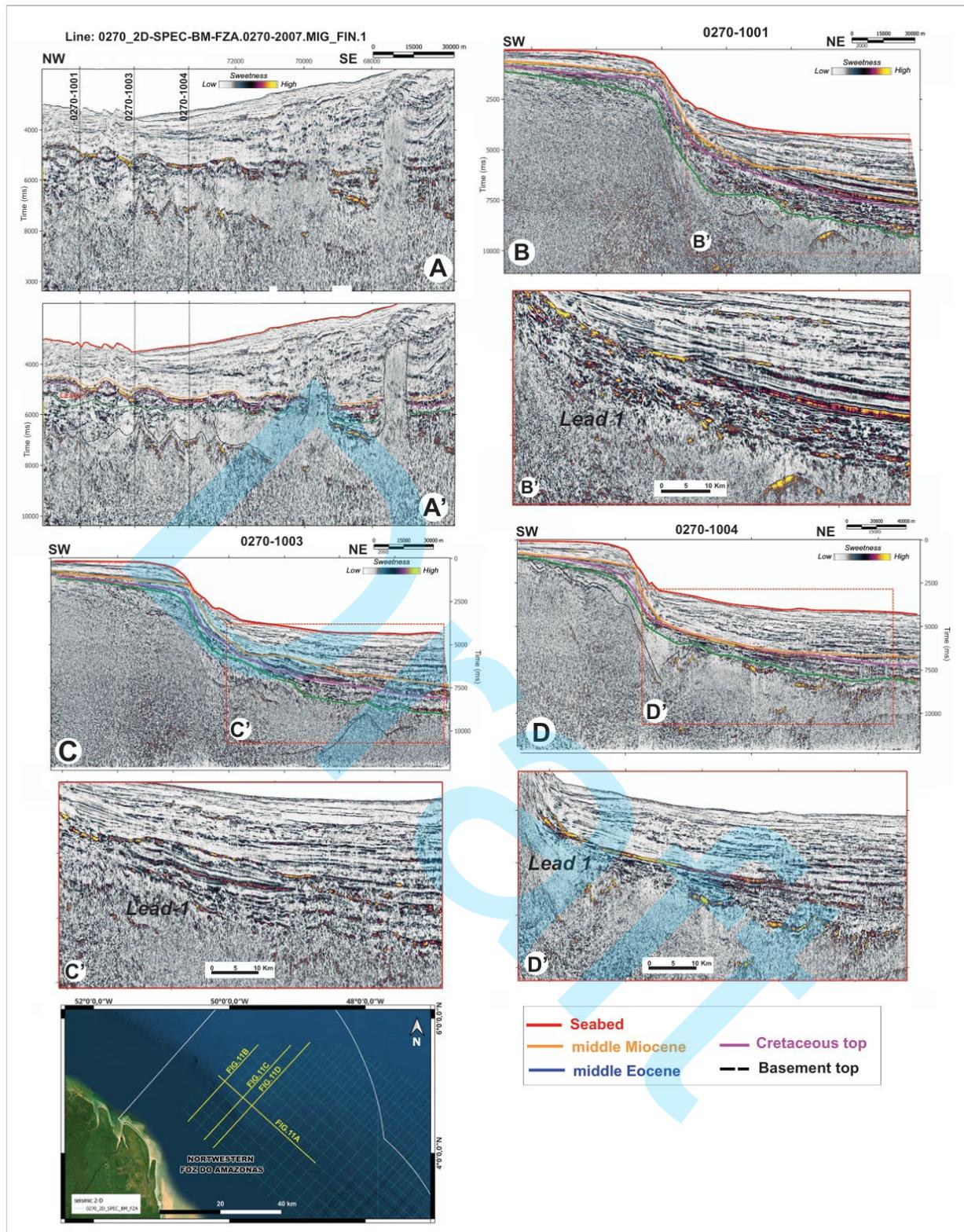
Figure 11 - Seismic sections from the northwestern sector of the Foz do Amazonas Basin displaying the sweetness attribute and highlighting potential hydrocarbon accumulations. (A) Strike-oriented seismic section (line 0270-2007) illustrating the stratigraphic framework and attribute responses. (B, C, D) Dip-oriented seismic sections (lines 0270-1001, 0270-1003, and 0270-1004, respectively) showing lateral variations in reflectors and the identification of potential leads. (B′, C′, D′) Detailed zoomed views of Lead 1 highlighting prospective reservoir zones characterized by high sweetness values, suggesting favorable conditions for hydrocarbon accumulation.
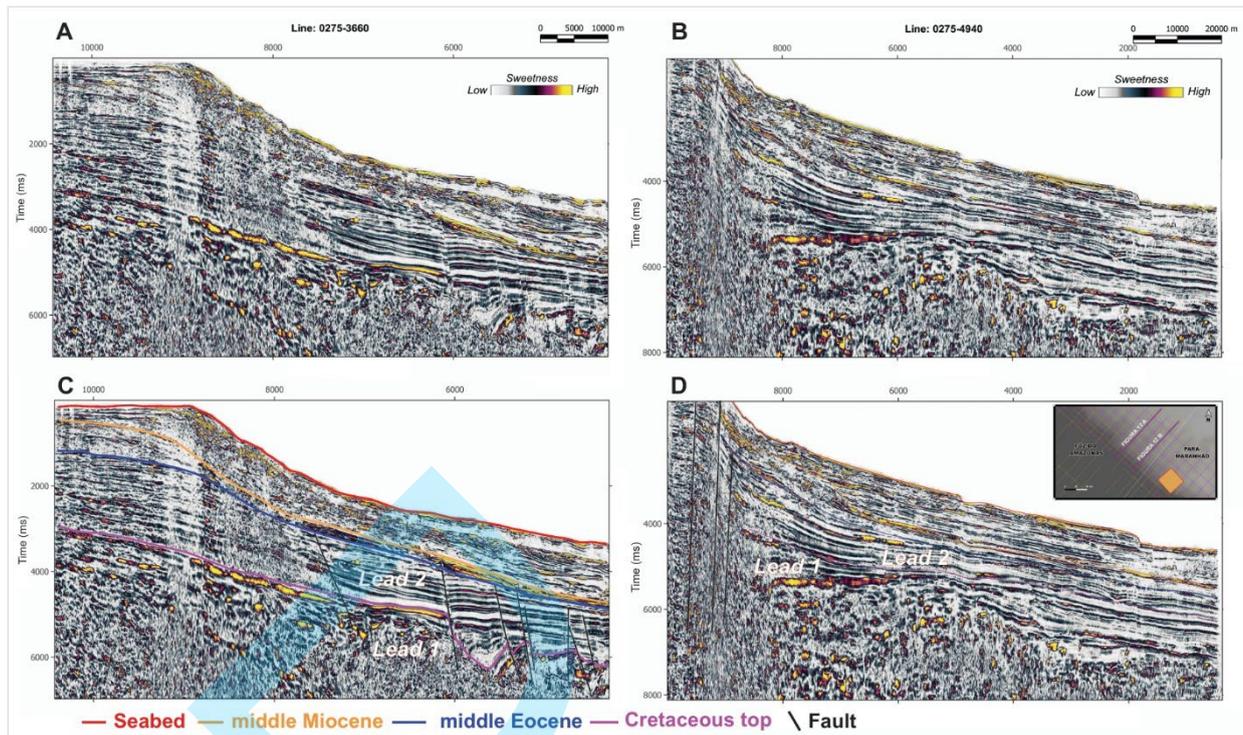
Figure 12 - Seismic lines 0275-3660 and 0275-4940 from the southeastern Foz do Amazonas Basin with sweetness attribute application. (A and B) Non-interpreted strike sections. (C and D) Interpreted sections highlighting the key geological features. Below the Cretaceous Top, high sweetness amplitudes are likely linked to deep- and ultra-deepwater turbidites (Lead 1). The Late Cretaceous interval, between the Cretaceous Top and Middle Eocene horizons, displays plane-parallel to sub-parallel reflectors, disrupted by faults associated with the Amazon Cone overloading (Lead 2).
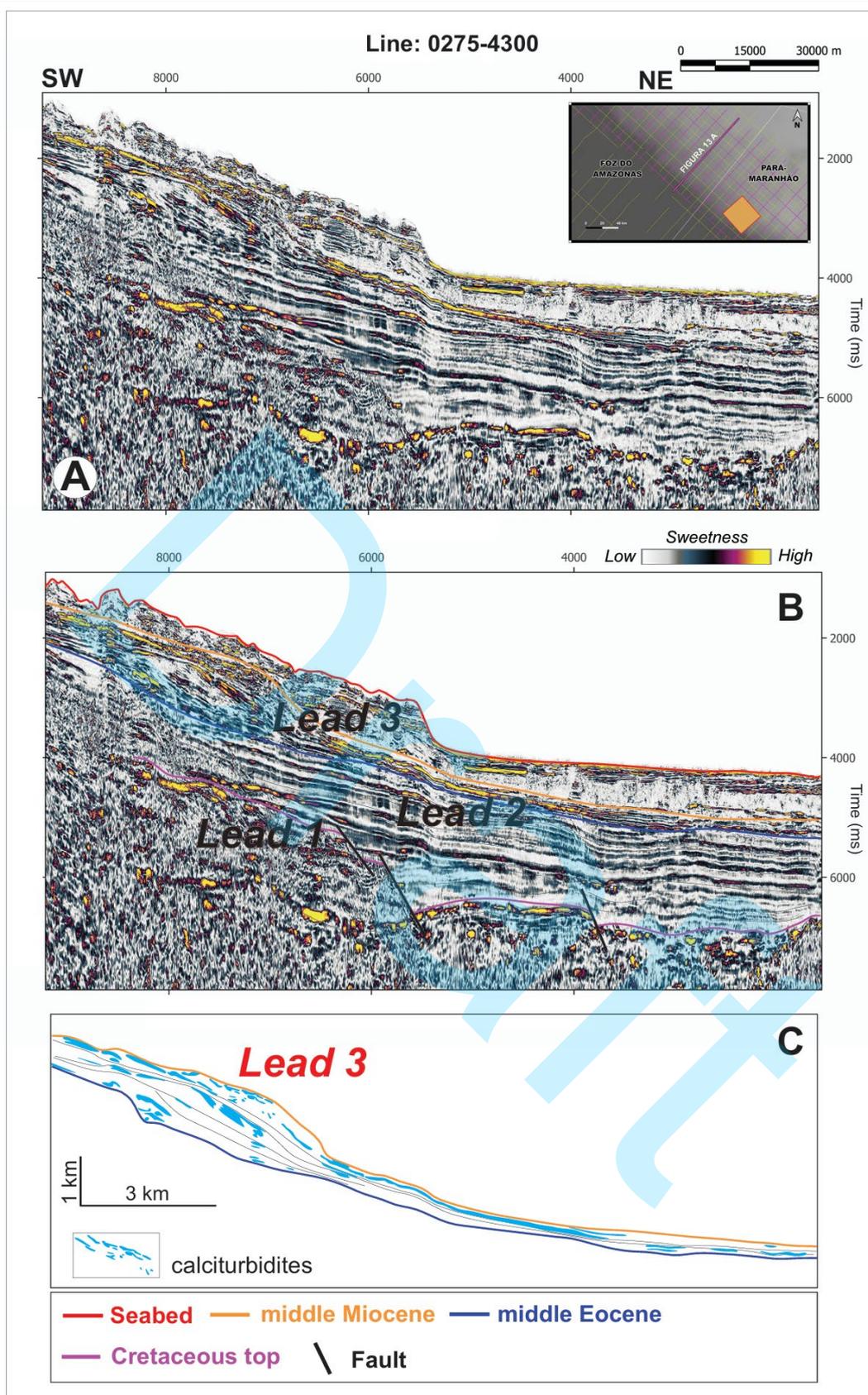
Figure 13 - Seismic interpretation of line 0275-4300 from the southeastern Foz do Amazonas Basin showcasing prospective hydrocarbon leads. (A) Uninterpreted seismic section highlighting stratigraphic configurations with calciturbidite deposits. (B) Interpreted section delineating key leads (Lead 1, Lead 2, and Lead 3) associated with high sweetness values, indicating potential reservoir zones. (C) Schematic representation of sigmoid reflectors confining calciturbidites, transitioning across slope, slope-to-plain, and abyssal plain depositional settings. These reflectors suggest favorable reservoir conditions with potential hydrocarbon accumulations.

CONCLUSIONS

This study demonstrates the effectiveness of integrated seismic attribute analysis for identifying hydrocarbon reservoirs in the Foz do Amazonas, Pará-Maranhão, and Barreirinhas basins along the Brazilian Equatorial Margin. The combined application of sweetness and spectral decomposition attributes allowed for the detailed delineation of turbidite sandstones and carbonate reservoirs, both structurally controlled by thrust fault systems and stratigraphic traps.

In the Barreirinhas Basin, several promising leads were identified, comprising turbidite sandstones and carbonate bodies confined within thrust belts. These reservoirs exhibit lateral continuity and favorable geometry, indicating significant hydrocarbon potential.

In the Pará-Maranhão Basin, the main prospects consist of late Cretaceous turbidite sandstones and Eocene carbonates, structurally and stratigraphically positioned within favorable trapping configurations.

In the Foz do Amazonas Basin, sandstone turbidites and deep-water carbonate deposits are associated with complex depositional settings, including sigmoidal clinoforms and chaotic reflectors, reflecting the dynamic paleoenvironments of this frontier area.

The integration of these seismic attributes provided critical insights into reservoir geometry, depositional processes, and trapping mechanisms, contributing to a better understanding of the petroleum systems in these underexplored basins. These results support strategic planning and risk reduction for future exploration campaigns in the Brazilian Equatorial Margin.

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