

Sedimentary evolution of the Alagamar Formation in the southeast portion of the Potiguar Basin, Brazil, based on gamma ray spectral logs

Evolução sedimentar da Formação Alagamar na porção sudeste da Bacia Potiguar, Brasil, com base em perfis espectrais de raios gama

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ABSTRACT

The Alagamar Formation plays an important role in the dynamics of the petroleum systems that occur in the Potiguar Basin, Brazil, as this formation could act as reservoir, source, and/or seal. Although its importance, most of the publications focus on its biostratigraphic record and little is published about its role in hydrocarbon production. In this paper, we investigate the sedimentary evolution of the Alagamar Formation in the southeast portion of the Potiguar Basin, employing detailed well-log correlation and the identification of alluvial fan stages. Using spectral gamma ray logs (SGR), the results reveal two stratigraphic sequences comprising five distinct stages, each characterized by unique lithological and geochemical signatures. The lower stages (1-3) exhibit characteristics indicative of continental depositional environments, influenced by fluctuations in sedimentary supply and tectonic activity, with a decreasing upward pattern in the Th/K log. High Th/U ratios suggest oxidizing conditions, while variations in Th concentration highlight the impact of tectonism on sedimentation dynamics, as Th is directly related to detrital and proximal sources. In contrast, stages 4 and 5 signify a transition to marine incursions, marked by lower Th/U ratios and the deposition of thin marine sediments in a more reducing environment, with increased shale content. The proposed evolutionary schematic model provides a valuable framework for understanding the sedimentary history of the Alagamar Formation in this portion of the basin, shedding light on the complex interplay between tectonic processes, sedimentation dynamics, and environmental conditions. The observed differences between stages underscore the heterogeneity of depositional environments within the study area, emphasizing the importance of integrating geological, geochemical, and tectonic data in understanding these geological processes. Additionally, these proxies allowed us to provide a correlated well-log zonation, offering valuable support for exploration and production (E&P) processes.

Keywords: well logs, paleodepositional and paleoenvironmental proxies, alluvial fans, natural radioactivity, onshore basin.

RESUMO

A Formação Alagamar desempenha um importante papel nos sistemas petrolíferos da Bacia Potiguar, pois pode ocorrer como reservatório, geradora e/ou selo. Apesar dessa importância, a maioria dos estudos se concentra em seu registro bioestratigráfico, havendo pouca discussão sobre seu papel na produção de hidrocarbonetos. Este estudo investiga a evolução sedimentar da Formação Alagamar na porção sudeste da bacia, por meio de correlações detalhadas de perfis de poço e identificação de estágios de leques aluviais. Utilizando perfis de gama espectral (SGR), foi identificada uma sequência estratigráfica composta por cinco estágios, cada um definido por características litológicas e geoquímicas distintas. Os estágios inferiores (1-3) apresentam feições típicas de ambientes continentais, moldadas por variações no suprimento sedimentar e na atividade tectônica, com um padrão Th/K decrescente para o topo. Altas razões Th/U indicam condições oxidantes, enquanto variações nas concentrações de Th refletem a influência tectônica na sedimentação, já que o Th está associado a fontes detríticas e proximais. Os estágios 4 e 5 marcam uma transição para condições marinhas, evidenciada por menores razões Th/U e pela presença de depósitos marinhos delgados em ambientes mais redutores, acompanhados por um aumento no teor de folhelho. Essas mudanças indicam uma transição de ambientes deposicionais continentais para marinhos. O modelo evolutivo proposto oferece uma estrutura abrangente para interpretar o desenvolvimento sedimentar da Formação Alagamar, enfatizando a interação entre tectonismo, suprimento sedimentar e mudanças ambientais. O contraste entre os estágios destaca a heterogeneidade dos ambientes deposicionais na área de estudo e reforça o valor da integração de dados geológicos, geoquímicos e tectônicos. Além disso, esses proxies possibilitaram o estabelecimento de um zoneamento da formação, fornecendo suporte relevante para as atividades de exploração e produção de hidrocarbonetos na região.

Palavras-chave: raios gama espectral, proxies paleodeposicionais e paleoambientais, leques aluviais, radioatividade natural, bacia terrestre.

1. INTRODUCTION

The Brazilian Equatorial Margin developed under a complex dextral transform tectonic setting, stemming from the rupture of the Gondwana Palecontinent, which gave rise to a series of rift grabens (Bertani et al., 1990; Matos, 1992, 1999, 2000; Milani et al., 2000). The onshore Potiguar Basin, part of this geological context, covers an area of almost 21,500 km² (Pessoa Neto et al., 2007).

Although the Alagamar Formation has historical importance for oil and gas exploration and production in the Potiguar Basin, very little has been published about its stratigraphy and reservoir characteristics (Ferreira et al., 2024). While most publications focus on biostratigraphic characterization (Dino, 1992; Spigolon, 2003), significant amount of the oil and gas production from this formation comes from the onshore portion of the basin, where the depositional systems of Alagamar are mainly alluvial-fluvial-deltaic, with highly heterogeneous and discontinuous sand bodies (Bertani et al., 1990; Araripe and Feijó, 1994; Pessoa Neto et al., 2007; Monteiro, 2012; Pereira, 2020; Ferreira et al., 2024), making reservoir zonation a challenging task for geoscientists.

The Alagamar Formation marks the transitional phase of the Potiguar Basin and is characterized by a transgressive system tract. Its stratigraphic record begins with fandeltaic and fluvial conglomerates and sandstones of the Canto do Amaro Member deposited in some grabens of the basin (Pessoa Neto et al., 2007). These are overlain by sandstones and mudstones of the Upanema Member. Above this, the first major marine flooding event in the basin is recorded by the Ponta do Tubarão Beds (CPT), which consist of shales, mudstones, and calcilutites, and this event is followed by mudstones and sandstones of the Galinhos Member at the top of this geological formation (Araripe and Feijó, 1984; Vasconcelos, 1995; Pessoa Neto et al., 2007).

In the study area, the Alagamar Formation is represented by the sandstones and mudstones of the Upanema Member, shales and calcilutites of the CPT, and, at the top, mudstones and sandstones from the Galinhos Member. Although some thin layers of conglomerates occur in the area, these rocks were not associated with the Canto do Amaro Member in the last stratigraphic chart of the basin, published by Pessoa Neto et al. (2007).

Due to the high gamma-ray values, together with well core description data, the reservoir interval of these rocks, Upanema Member, were initially interpreted as shales and shaly sandstones, although the neutron and density logs indicated otherwise. However, with continuous drilling campaigns, well logging and correlation with pre-existing well cores, this understanding changed to overly complex alluvial fan deposits composed of arkoses and conglomerates with

very high porosity and permeability (Ferreira et al., 2024). The main objective of this work is to understand and characterize the stages of evolution of the Alagamar Formation in the study area, integrating spectral gamma-ray proxies, log curves, and petrophysical laboratory data.

2. GEOLOGICAL SETTING

The Potiguar Basin, located in the Brazilian Equatorial Margin, is the easternmost sedimentary basin in this region, divided into onshore and offshore portions (Bertani et al., 1990; Araripe and Feijó, 1994; Pessoa Neto et al., 2007). Most of the basin lies within the Rio Grande do Norte state and partially in the Ceará state. Geologically, it is bounded by the basement to the south, east, and west (Bertani et al., 1990). The Fortaleza High defines its northwestern limit with the Ceará Basin, while the Touros High defines its southeastern limit with the Pernambuco-Paraíba Basin (Pessoa Neto et al., 2007).

This sedimentary basin was generated during the initial stages of the breakup between the South American and African plates in the Early Cretaceous, resulting from a NW-SE-oriented extensional regime, which later experienced a counterclockwise rotation, changing its direction to E-W during the final stage of rifting (Chang et al., 1988; Matos, 1992; Melo et al., 2016). The Potiguar rift consists of a system of horsts and grabens bounded by fault systems (Bertani et al., 1990). Melo et al. (2016) define these fault systems as a major fault zone composed of a set of smaller faults with the same trend.

The study area is in the southeastern portion of the Potiguar Basin (Figure 1). The stratigraphic record of this area, represented in Figure 2, shows the geological formations from three main tectono-sequences defined by Pessoa Neto et al. (2007): Rift I (Berriasian to Lower Barremian), Post-rift (Upper Aptian to lowermost Albian - mostly in the Alagoas local stage), and Drift (Lower Albian to Holocene).

This work focuses on the evolution of the Alagamar Formation during its deposition, which consists of sediments deposited over the Pendência Formation, between the Upper Aptian and Early Albian. This formation marks the transition from continental depositional systems to marine environments between the rift and drift tectonic sequences (Araripe and Feijó, 1994). The dominant tectonic regime during this period, known as the post-rift phase or transitional phase, is characterized by the predominance of thermal subsidence as the main mechanism generating accommodation space, with relatively tectonic quiescence.

However, the study area is located near the Carnaubais Fault System (CFS), one of the most significant fault systems in the Potiguar Basin, extending almost 150 km (Bertani et al., 1990). The movement of

these NE-SW oriented faults, still active during the early post-rift phase, led to the deposition of continental systems such as alluvial and deltaic fans systems (Pessoa Neto et al., 2007), which are one of the main oil and gas reservoirs in the onshore portion of the basin. These sediments graded upwards to a lagoonal saline environment under arid climatic conditions, characterized by microbial carbonates interbedded with organic black shales, associated with evaporites (Bertani et al., 1990; Vasconcelos, 1995). This represents the first record of marine incursions in the basin (Araripe and Feijó, 1994; Vasconcelos, 1995; Spigolon and Santos Neto, 2005; Pessoa Neto et al., 2007).

The studied interval is bounded at the base by the Lower Barremian Unconformity (LBU) at the top of Pendência Formation rocks, while there are no stratigraphic records of the Pescada Formation that occurs only in the offshore portion of the basin (Pessoa Neto et al., 2007). This unconformity represents the erosion of the upper portion of the Pendência Formation in the Potiguar Basin, and at the top by the shales and thin

sandstones of the Galinhos Member of the Alagamar Formation (Figure 2). Due to the proximity to the Carnaubais Fault System, as published by Ferreira et al. (2024), the sandstones of the Upanema Member in the study area have a high concentration of feldspars. This complicates the use of gamma ray logs for well correlation, requiring the use of spectral gamma-ray logs to identify shaly intervals. Spectral gamma ray logs are also crucial for correlating the Galinhos Member strata, which are characterized by shales with high uranium content in the area (Ferreira et al., 2024).

According to Monteiro (2012), in the southeastern portion of the Potiguar Basin it is possible to identify the presence of paleogeomorphological features, similar to canyons, that cut the stratigraphic sequences below Alagamar Formation. These features occur on the edge of the basin in the CFS with SW – NE orientation and could act as pathways of the sediments from the upper portions of the CFS to basinward. The sediments were deposited as alluvial fans, frequently reworked and superposed by the transgressive and regressive cycles.

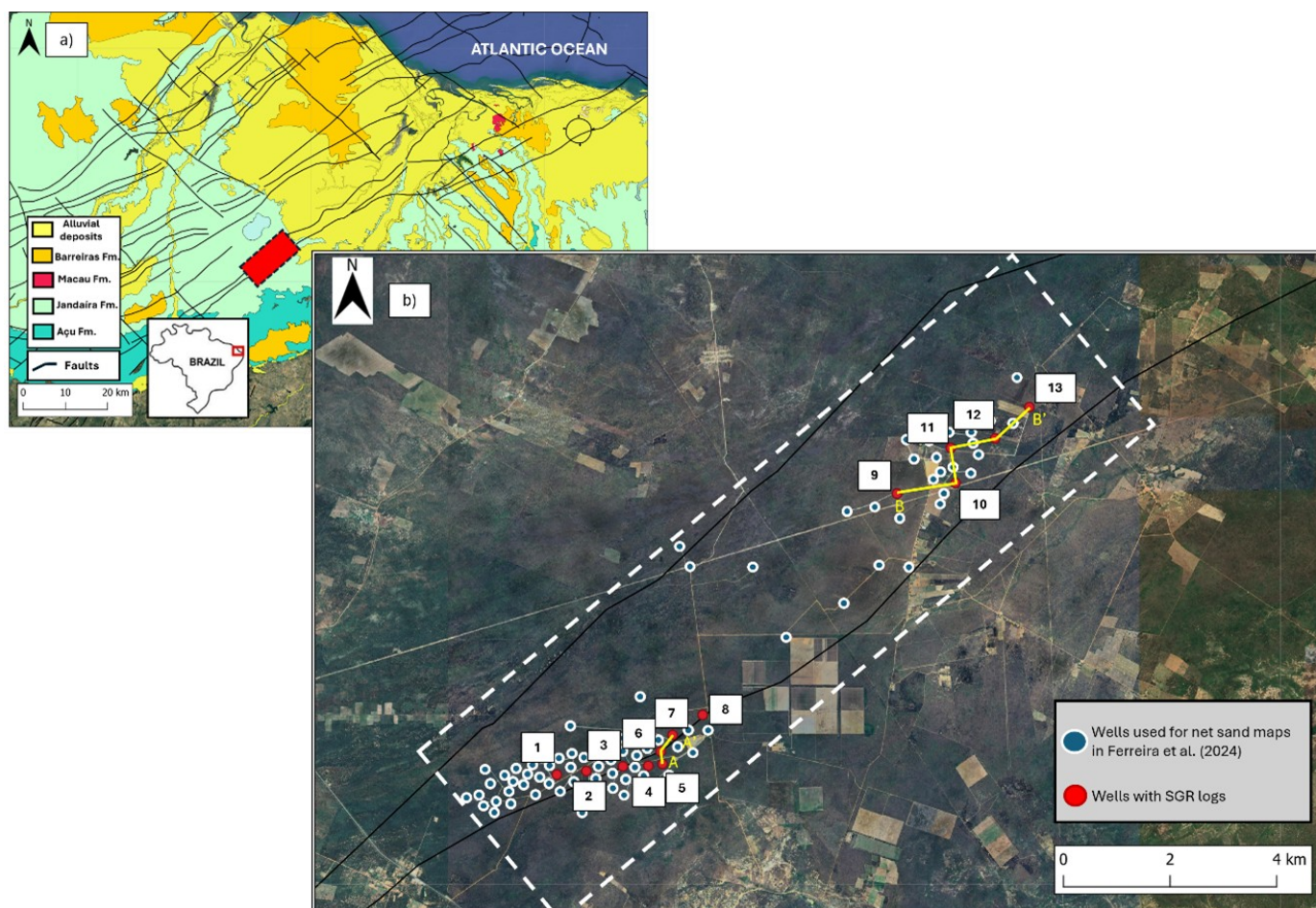


Figure 1. A. Geological map of the Potiguar Basin obtained in the Brazilian Geological Survey web site (<https://siagasweb.sgb.gov.br/pmapper/map.phtml>) showing the study area highlighted in the red rectangle. B. Detailed satellite image map with the position of the red wells for the ones with SGR logs and blue for the ones with triple combo logs and used for the net sand maps calculated and published in Ferreira et al. (2024). The study area is represented by the grey dashed rectangle and well correlations shown in this article (yellow lines).

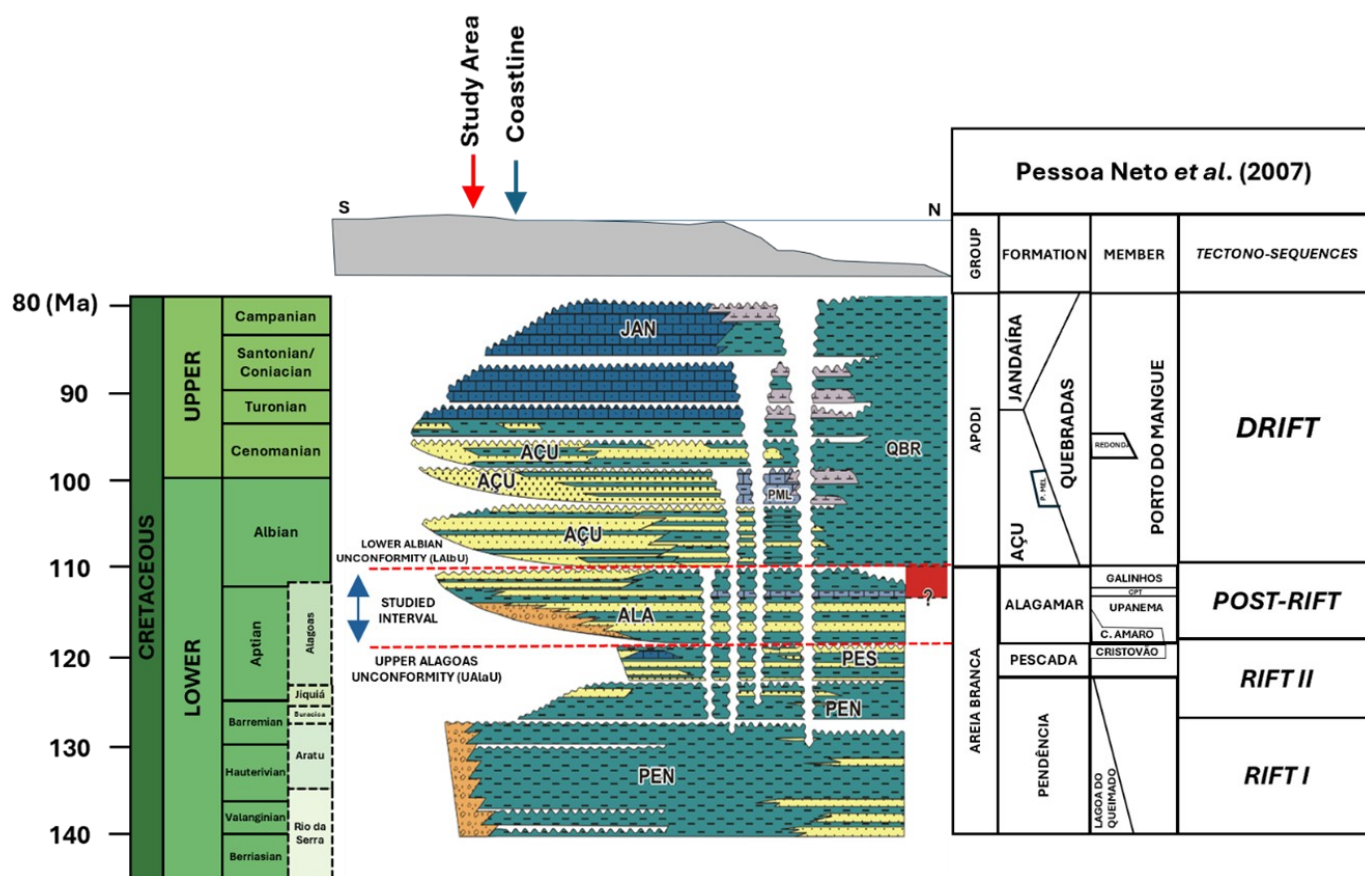


Figure 2. Stratigraphic chart modified from Pessoa Neto et al. (2007). The approximate location of the study area in the stratigraphic chart is represented by the red arrow with the Alagamar Formation unconformities (Upper Alagoas and Lower Albian) highlighted in red, with the Upanema and Galinhos members, and CPT occurring inside the study area.

2.1. Spectral gamma-ray and geochemistry of potassium, thorium and uranium

Schlumberger (1982) describes the Spectral Gamma Ray (SGR) log as a tool that measures natural radioactivity from key isotopes: uranium (U^{238} , U^{234} , U^{235}), thorium (Th^{232}), and potassium (K^{40}). The SGR logs used in this study were acquired by wireline through water-based KCl mud. These concentration logs have numerous applications, as summarized by Klaja and Dudek (2016) in tables 1 and 2. The application of gamma ray spectral data can be either qualitative or semi-quantitative, depending on the understanding about the geology of the area or an excellent correlation between rock samples and well logs.

Qualitative applications include detailed stratigraphic correlation, stacking pattern of sedimentary sequences, recognition of rock types of different facies, identification of high permeability and fractures, and location of watered-out intervals. Semi-quantitative applications (Rider, 2002) include determination of reservoir clayiness, assessment of source rock potential in argillaceous sequences, and estimation of potassium concentration (Fertl, 1979).

Table 1: Summary of the characteristics of the three main radioactive elements in sedimentary rocks. Modified from Klaja and Dudek (2016).

Element	Characteristics
Thorium	Insoluble in water
	Usually combined with shales, may supply certain information on the clay content (usually occur in detrital illites)
	Combined with heavy minerals in igneous rocks
Uranium	Usually not linked to the clay contamination of rocks
	Depends on the organic matter content (good association with kerogen)
	The most soluble of the radioactive elements
Potassium	One of the basic components of shale rocks (usually occur in detrital illites)
	Indicator of the presence of feldspars and micas
	Mainly occurs in oxidized form (K_2O)
	Stabilizes clay minerals as KCl

Table 2: Summary of the main applications of spectral gamma ray logs in sedimentary basins from Klaja and Dudek (2016).

Ratio	Significance
Th/U	Analysis of sedimentary conditions such as: Th/U > 7 is associated with continental environment, oxidizing conditions, weathered soils, etc.
	Th/U < 7 indicates marine sediments, grey and green shales, greywackes.
	Th/U < 2 could be interpreted as marine black shales, phosphorites, reducing conditions.
	Estimation of the organic matter content in claystones.
	Detection of basic discontinuities.
U/K	Used in stratigraphic correlations by determining transgressive-regressive and oxidizing-reducing conditions.
	Evaluation of the organic matter content in clay sediments.
	Used in stratigraphic correlations.
	Detection of diagenetic changes in clay and carbonate sediments.
Th/K	Used in correlation of natural fissure system in deeper formations.
	Recognition of types of sediments representing various facies.
	Determination of sedimentary condition types, distance to paleoshoreline, etc.
	Determination of diagenetic changes in clay sediments.
	Determination of the type of clay minerals; Th/K increases in the following direction: glauconite > muscovite > illite > mixed-layer minerals > kaolinite > chlorite > bauxite.

Many long-lived radioactive nuclides occur in nature, but for the petroleum industry, the most important ones are potassium, thorium, and uranium. Over the last 50 years, numerous studies have discussed the distribution of these elements in sedimentary rocks (Hassan et al., 1976; Fertl, 1979; Schlumberger, 1982; Nielsen et al., 1987; Fabricius et al., 2003). Here is a summary of the main aspects of each element:

- **Thorium (Th):** Thorium is a common trace element in most geological environments. It tends to be insoluble during weathering and is typically concentrated in residual deposits such as bauxite, clay minerals, and heavy minerals (Fabricius et al., 2003). The presence of Th in clay minerals is highly debated. Pure clay samples typically contain 5-30 ppm of Th. Due to its large ionic radius (0.97 nm), Th cannot be accommodated in the layer structure of clay minerals, so it is assumed to be fixed by adsorption (Adams and Weaver, 1958). However, Hurst and Milodowski (1994) suggested that the origin of Th in clay minerals

is unclear and may be due to inclusions of clay-sized heavy minerals. The most common assumption when analyzing sedimentary thorium is to consider it of detrital origin and chemically inert (Bessa, 1995).

- **Potassium (K):** Potassium is a major element in many rock-forming minerals. The most common K-bearing minerals in sedimentary rocks are K-feldspars, mica, and glauconite. K-feldspars and mica have a higher K content than illite. Although the use of total gamma-ray to estimate shale content in rocks is widespread in the industry, the gamma-ray flux is only a measure of clay content in the absence of significant K-feldspars (Cowan and Myers, 1988).
- **Uranium (U):** Uranium is commonly associated with organic matter. Under neutral pH conditions, the uranyl ion (UO_2^{2+}) forms ionic complexes with carbonates, which control its dispersion and mobility in nature. This ion also forms numerous complexes with organic compounds, facilitating its fixation by organic and mineral matter (Fabricius et al., 2003). Hassan et al. (1976) showed that the precipitation of UO_2 causes the correlation between U and organic carbon in sedimentary rocks under reducing conditions. Through the ratios of these radioactive element concentrations (Th/K, Th/U, and K/U), it is possible to obtain valuable information about sedimentation processes, the intensity of chemical weathering, and the homogeneity of provenance (Basu et al., 2009).

The Th/K ratio can indicate depositional trends. An increasing Th/K ratio towards the top of a sequence suggests a retrogradation deposition stacking pattern. Fluctuations in Th and K concentrations can reflect variations in sedimentary input. The Th/K ratio is also useful in identifying clay types. Higher Th/K values correspond with higher concentrations of certain clay minerals such as glauconite, muscovite, illite, mixed-layer clays, kaolinite, chlorite, and bauxite (Fertl, 1979). However, Hurst (1990) stands a critical point of view about the use of SGR logs when identifying the type of mineral within sedimentary rocks, putting light on the impact of the imprecision of this workflow caused by bad hole conditions, different calibration for different service companies, and low natural radioactivity in these types of rocks. According to Bessa (1995), the presence of both highly soluble and highly insoluble elements in the Th/K ratio may indicate that the concentrations resulted from primary deposition processes rather than diagenetic reactions.

Th/U and K/U ratios further contribute to understanding the sedimentary environment and processes (Fabricius et al., 2003). For instance, high Th/U ratios suggest oxidizing conditions, while lower Th/U ratios indicate reducing environments. Overall, analyzing these ratios provides insights into the geological history and processes affecting the sediments, helping to interpret depositional environments and provenance characteristics accurately. The Th/U ratio is a significant geochemical indicator used to interpret various sedimentary processes and depositional environments. Most terrestrial igneous rocks exhibit Th/U ratios of approximately 3.8 (Taylor and McLennan, 1985). This ratio is useful in the assessment of sedimentary processes, particularly in estimating redox conditions and characterizing depositional environments (Adams and Weaver, 1958; Basu et al., 2009; Doveton, 1991; Miranda et al., 2023).

In oxidizing environments, sediments typically display higher Th/U ratios due to the loss of uranium in its soluble U^{6+} form. Conversely, lower Th/U ratios are often found in marine intervals, where uranium is concentrated in its insoluble U^{4+} form. Ratios below 3.8 can be diagnostic of maximum flooding surfaces (Davies and Elliott, 1996), potentially representing marine condensed sequences and indicating reducing conditions that facilitate uranium fixation (Myers and Wignall, 1987).

The K/U ratio is a valuable tool in the investigation of potential source rocks for argillaceous sediments. High uranium concentrations in shaly rocks are often associated with organic matter content, making this ratio particularly useful for identifying such source rocks.

Additionally, the K/U, together with Th/U ratio, can aid in stratigraphic correlations, helping to identify unconformities and diagenetic changes within argillaceous sediments (Fertl, 1979).

Well logs are frequently employed to unravel the sedimentary history within traditional stratigraphic models for nonmarine settings (Shanley and McCabe, 1993; Wright and Marriott, 1993; Posamentier and Allen, 1999; Catuneanu, 2006), particularly in alluvial-fluvial-deltaic deposits (Bourquin et al., 1998) as in the study area.

3. DATASET AND METHODOLOGY

The Alagamar Formation of the Potiguar Basin is the focus of this study, utilizing the available data in REATE CPRM with the total gamma ray (GR), spectral gamma ray (K (%), Th (ppm), and U (ppm), density, and neutron logs from 13 wells drilled in the basin's southern portion. Due to the absence of cores and sidewall core samples (SWC) in the selected wells, well-log responses and well-to-well correlations, especially with the cored wells in the studied area, were employed to infer the subsurface distribution of the identified stratigraphic stages. Although only 13 wells have spectral gamma ray logs, for correlating the mineral composition of Upanema Member sandstones with these logs, there were used core samples taken from another four wells, where there is available x-ray diffraction analysis from five SWC published by Ferreira et al. (2024) and 57 SWC descriptions using Folk (1968) sandstone classification (Figure 3).

A)

Well	Plug Sample	Depth (m)	Clay Minerals				Carbonates		Other minerals				TOTAL		
			Chlorite	Kaolinite	Illite/Mica	Mixed Illite/Smectite	Calcite	Siderite	Quartz	K-Feldspars	Plagioclase	Pyrite	Clays	Carbonates	Others
52	1	511.9	Tr	Tr	1	24	2	0	32	31	9	1	25	2	73
	2	544.3	Tr	Tr	1	15	3	0	40	34	7	Tr	16	3	81
	3	568.7	Tr	2	1	7	6	0	36	34	14	Tr	10	6	84
73	4	555.5	0	1	7	2	1	1	44	22	19	0	10	2	90
	5	557.9	0	2	7	0	0	0	33	26	29	1	8	0	92
AVERAGE			0	2	3	10	2	0	37	29	16	1	14	3	84

*Tr = trace mineral concentration below 1% and not considered for the average calculation.

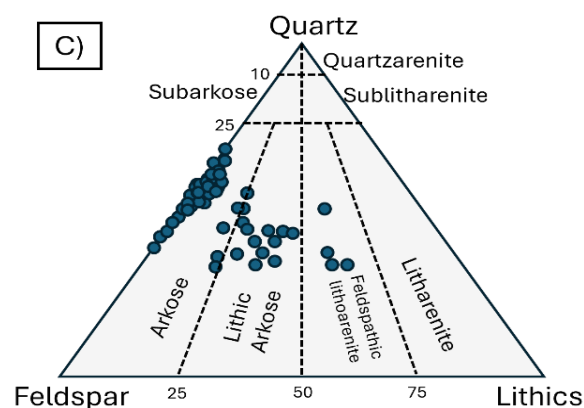
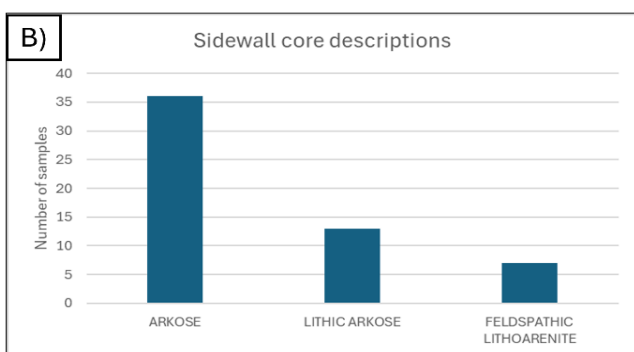


Figure 3. A. Modified from Ferreira et al. (2024), showing x-ray diffraction data of five plug samples in neighbors wells evidencing the high content of feldspars, especially k-feldspars. B. Bar chart of all 57 sidewall core samples macroscopic descriptions using Folk (1968) classification. C. Ternary plot, modified from Folk (1968), of 52 thin sections descriptions available of Upanema Member sandstones in neighbors wells, extracted from four wells, in the study area.

Besides the x-ray diffraction and SWC data highlighted in Figure 3, the net sand maps, also published by Ferreira et al. (2024) and derived from the petrophysical evaluation of 73 wells in the studied area for the Upanema Member rocks, were also instrumental in inspiring and supporting the development of the conceptual depositional models. This integration of SWC, x-ray diffraction from SWC, petrophysical evaluation from conventional well logs, and spectral gamma ray was fundamental to constructing the evolutionary schematic models discussed in Section 5 (Discussion), offering a multi-scale perspective on the sedimentary architecture of the Alagamar Formation in the studied area.

Following the methodology of Shier (2004), GR normalization was applied to eliminate systematic errors from logs, as these logs were acquired under varying drilling conditions especially because these reservoirs have low overburden, borehole environments, and over different years. Normalization is essential for quantitative comparison across different zones and wells (Neinast and Knox, 1973). The normalization workflow begins with defining the intervals in the wells with bad hole conditions and reference wells based on Caliper logs cut-offs, that usually have the GR values attenuated. After that, the histogram of these intervals from the two types of wells are compared and then the method of two-point normalization, also known as 'stretch and squeeze' method (Figure 4) (Shier, 2004), for each well with bad hole condition is applied. The key parameters for this method are defining the values obtained from percentiles such as the 5th (low value) and 95th (high value) percentile (Crain, 2020) using the one available GitHub Python code for GR normalization (McDonald, 2020).

$$Curve_{norm} = Ref_{low} + (Ref_{high} - Ref_{low}) * \left(\frac{CurveValue - Well_{low}}{Well_{high} - Well_{low}} \right)$$

Where:

- Ref_{low} – Low value from the reference well
- Ref_{high} – High value from the reference well
- $Well_{low}$ – Low value from well being normalized
- $Well_{high}$ – High value from well being normalized
- $CurveValue$ – Input value from well being normalized

Figure 4. Reference equation for the method of two-point normalization from Crain (2020).

Another important step is to define the cut-offs for the interpretation of the radioactive concentrations and ratios. The ratio cut-offs were defined using the literature available, as shown in item 2.1, while the cut-offs for the radioactive concentrations (K, Th and U) were defined based on combined interpretation of them with total gamma ray (GR), neutron (NPHI) and density (RHOB) logs.

Basically, qualitatively where the crossover of the neutron and density indicates shaly rocks ($RHOB > NPHI$ – scale for RHOB is 1.95 to 2.95, and for NPHI is -0.15 to 0.45), the Thorium concentration log (Th) is greater than 16.

The workflow used in this study (Figure 5) outlines the methodology tied with well log information for generating the proposed depositional model. All normalizations were performed using Python, while well log plotting, and well-to-well correlations were in SLB Techlog®.

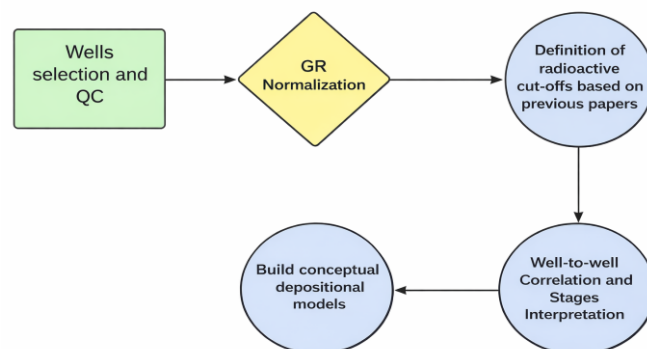


Figure 5. Workflow used in this present work to produce depositional models for the Alagamar Formation in the southeastern portion of the Potiguar Basin.

In this study, a key step during the well-to-well correlation was the adoption of the Lower Albian Unconformity as a regional datum. The subdivision and stage identification practiced in this paper combine well-log stacking patterns with the interpretation of radioactive isotope concentrations (Uranium, Potassium, and Thorium) and their ratios. This approach aims to build a conceptual model for the evolution of the Alagamar Formation in the study area of the Potiguar Basin. As detailed in tables 1 and 2, the cut-offs used for thorium concentration log were based on the integration between mud logging description of the wells and the log curve values, while cut-offs of Th/U and K/U were based on Fertl (1979).

4. RESULTS

Well correlation was done based on spectral gamma ray concentration logs (K, Th, and U) and radioactive ratios (Th/K, Th/U, and K/U), identifying five evolutionary stages of Alagamar Formation in the study area, named stages 1 to 5, from top to bottom, and their log curves shapes are summarized in Table 3. Along with the correlation between the stages and each log curve shape, the mean values were calculated for all logs used in this workflow (Table 4).

Table 3. Description of the qualitative interpretation of SGR logs and their ratios. The first column has the number of stages and their average thickness, the second column has the mean shape of the total gamma ray, from the third to the eighth columns there are the log motifs the radioactive curves.

Evolutionary Stage	TOTAL GR	K	Th	U	Th/K	Th/U	K/U
<p>5</p> <p>Average Thickness: 37.1 meters</p>		Cylindrical	Funnel	Slightly funnel	Funnel	Cylindrical	Cylindrical
<p>4</p> <p>Average Thickness: 30.3 meters</p>		Bell	Bell	Serrated	Funnel	Cylindrical	Cylindrical
<p>3</p> <p>Average Thickness: 28.2 meters</p>		Cylindrical	Bell	Cylindrical	Bell	Serrated	Serrated
<p>2</p> <p>Average Thickness: 23.3 meters</p>		Bell	Funnel	Funnel	Bell	Funnel	Funnel
<p>1</p> <p>Average Thickness: 24.3 meters</p>		Cylindrical	Cylindrical	Funnel	Cylindrical	Serrated	Serrated

Table 4. Each radioactive element's average concentration and ratios are estimated by the SGR log curves.

Stage	K (%)	Th (ppm)	U (ppm)	Th/K	Th/U	K/U
5	3.18	17.67	3.12	5.65	6.19	76.05
4	2.93	16.56	2.6	5.84	7.04	132.19
3	3.9	15.03	1.26	3.94	15.28	394.55
2	3.75	18.45	1.88	5.25	12.4	280.87
1	4.05	15.47	2	3.99	10.04	262.68
Average	3.56	16.64	2.17	4.93	10.19	229.27

5. DISCUSSION

5.1. Evolutionary stages and correlation with the existing stratigraphic units

As well addressed by Ferreira et al. (2024), the Alagamar Formation deposits in the southeast portion of the Potiguar Basin exhibits a high natural radioactive response in the gamma ray log. These well logs response are attributed to the significant concentration of K-feldspars and Thorium (Th) adsorbed in the clay mineral structures. Based on the well-to-well correlation, five distinct stages were identified in the stratigraphic interval studied within the Alagamar Formation.

In Table 4, the sedimentary record of the Alagamar Formation exhibits similar potassium and thorium concentrations across the identified stages, while stages 4 and 5 have higher uranium concentrations compared to the other three stages. For the radioactive ratios, it is notable that Th/U and K/U are higher in the first three stages. Combining mud logging data with the interpretation of the SGR logs, it is possible to affirm that stages 1 to 3 represent the Upanema Member rocks, a typical reservoir in this formation (Araripe and Feijó, 1994; Pessoa Neto et al., 2007), and that stages 4 and 5 represent the Galinhos Member rocks that showed an increased uranium content compared to the Upanema Member.

A thorough analysis of spectral concentration logs, particularly focusing on the ratios of thorium (Th), uranium (U), and potassium (K) in sedimentary sequences helps in interpreting the depositional environments and stacking patterns over distinct stages:

- Stage 1:** The basal stage lies on the top of the Upper Alagoas Unconformity and is characterized by an almost constant concentration of potassium (K) and thorium (Th), while uranium (U) shows a decreasing concentration towards the top. This decrease in U could be related to the higher polymictic conglomerate content at the base, as indicated by mud logging descriptions. An aggradational stacking pattern based on the Th/K ratio and few variations in the Th/U and K/U ratios suggest that this interval has few variations in its sedimentary conditions, such as sedimentary supply and accommodation space. This homogeneity is likely related to a late reactivation of the rift tectonics creating accommodation space in the Carnaubais Faulted System (CFS) and to the erosion of the basement providing sediment input. Although these rocks belong to the Alagamar Formation, which is part of the post-rift phase of the basin (Pessoa Neto et al., 2007), tectonic activity is
- still observed, suggesting ongoing structural influence during deposition. Prominent levels of Th/U could be indicative of oxidizing environmental conditions, which could result in low levels of organic matter in its composition, as demonstrated by high K/U values.
- Stage 2:** Characterized by a distinct pattern in the potassium (K) concentration log, with lower values at the base and higher values towards the top. Thorium (Th) and uranium (U) typically exhibit the opposite behavior, with higher values at the base representing thick mudstone layers and variable values at the top indicating lithological intercalation. This pattern is related to the thick shale at the base, which has low K and high Th, and sand bodies with low Th, demonstrating that the thorium content of this stage is associated with clayiness. Th/K Ratio shows decreasing values upward, forming a funnel shape, suggesting a progradational stacking pattern, indicating that sediments were deposited in a way that reflects the outward growth of the depositional system. This could be associated with a deltaic environment or advancing shoreline. Th/U and K/U Ratios have an increase in an upward pattern, with higher values than in Stage 1. The increase in these proxies suggests a more oxidizing condition or periods of subaerial exposure, which would lead to the leaching of uranium. The higher values suggest that these environmental conditions were maintained throughout the stage.
- Stage 3:** K and U values are constant throughout the stage, while Th values show a bell shape with decreasing concentration to the top, suggesting a retrogradational stacking pattern. This implies a reduction in coarse sediment supply, potentially related to fewer tectonic activities and predominance of thermal subsidence during this stage. Th/K Ratio shows a slight funnel shape supporting the idea of a retrogradational stacking pattern, indicating a reduced sediment supply, while Th/U and K/U ratios have a serrated shape with higher values than in the first two stages. The serrated shape and higher values of these ratios indicate periods of subaerial exposure and oxidation. Higher Th/U and K/U ratios suggest that U was oxidized and leached away during these exposure periods.
- Stage 4:** K and Th concentrations are increasing toward the top, forming a bell shape, which suggests a retrogradational stacking pattern once the increase of these curves could be

related to higher shale content. Uranium (U) concentration shows a serrated shape and with much higher concentration values compared to the first three stages, which was interpreted as a more reducing conditions or an environment where uranium could be better preserved. Th/K ratio shows a funnel shape with higher values than the rest of the stages also indicating a retrogradational stacking pattern and a reduction in sediment supply. Th/U and K/U ratios in a cylindrical shape with lower values due to increased U concentration indicate a shift in depositional conditions, with thicker mudstone beds as noted in mud logging description, and as described by Fertl (1979), the abrupt change in Th/U log is suggestive of a geological unconformity marking a major shift in depositional conditions or a period of erosion and non-deposition. The described characteristics of Stage 4 align with the first marine incursions known as the Ponta do Tubarão Beds (Araripe and Feijó, 1984; Vasconcelos, 1995; Pessoa Neto et al., 2007). The marine incursions would have introduced new sedimentary environments and geochemical conditions, reflected in the increased all SGR logs as indicated by Klaja and Dudek (2016).

- **Stage 5:** K concentration is constant throughout, while Th log has a funnel shape suggesting an increase in coarse sediment supply towards the top, which could be indicative of a progradational stacking pattern. U concentration is remarkably high, similar to Stage 4, indicating the maintenance of reducing conditions during deposition. Th/K log also agrees with this stacking pattern interpretation, which has a funnel shape. Th/U and K/U ratios show low values with cylindrical shapes. This may indicate continued marine incursion at the base, with conditions favorable for uranium preservation (reducing conditions). The cylindrical shape suggests stability in the depositional environment at these levels. Dark grey shales at the base transitioning to

siltstones and shaly sandstones at the top suggests a shift from deeper, lower-energy depositional environments (shales) to shallower, higher-energy environments (siltstones and shaly sandstones). This transition is characteristic of a progradational sequence, where sediment supply increases, and the depositional environment becomes progressively shallower and energy intensive. The change from dark grey shales to siltstones and shaly sandstones is indicative of the Lower Albian Unconformity (LAlbU) between the Alagamar and Açú formations. This unconformity represents a significant geological boundary and changes in depositional environments.

According to Fertl (1979), $Th/U > 7$ are generally common in continental deposits, indicating an oxidizing environment and proximity to the sediment source, and this is seen in stages 1 to 3. In contrast, $2 < Th/U < 7$ usually indicate marine deposits (such as gray and green shales, and graywackes), which aligns with the possibility that stages 4 and 5 represent the initial marine incursions, represented stratigraphically by Ponta do Tubarão Beds (CPT) and Galinhos Member rocks in the study area.

Another significant difference between the two members is that the Upanema Member stages (1 to 3) show a progressive upward increase in the Th/U, indicating oxidizing environmental conditions during deposition. However, in wells located in more distal regions of the alluvial fans, where clay content is higher, distinguishing these first three stages becomes particularly challenging.

In contrast, the Galinhos Member stage has much lower values in this ratio, suggesting reducing environmental conditions. These differences in the Th/U and K/U ratios indicate that these stratigraphic members experienced different tectonic and environmental conditions during deposition, possibly related to the variation of water levels. In tables 3 and 4, there is a progressively higher value of total gamma ray, which indicates, together with mud logging descriptions, a thinning upward sedimentary sequence for the Alagamar Formation (figures 6 and 7).

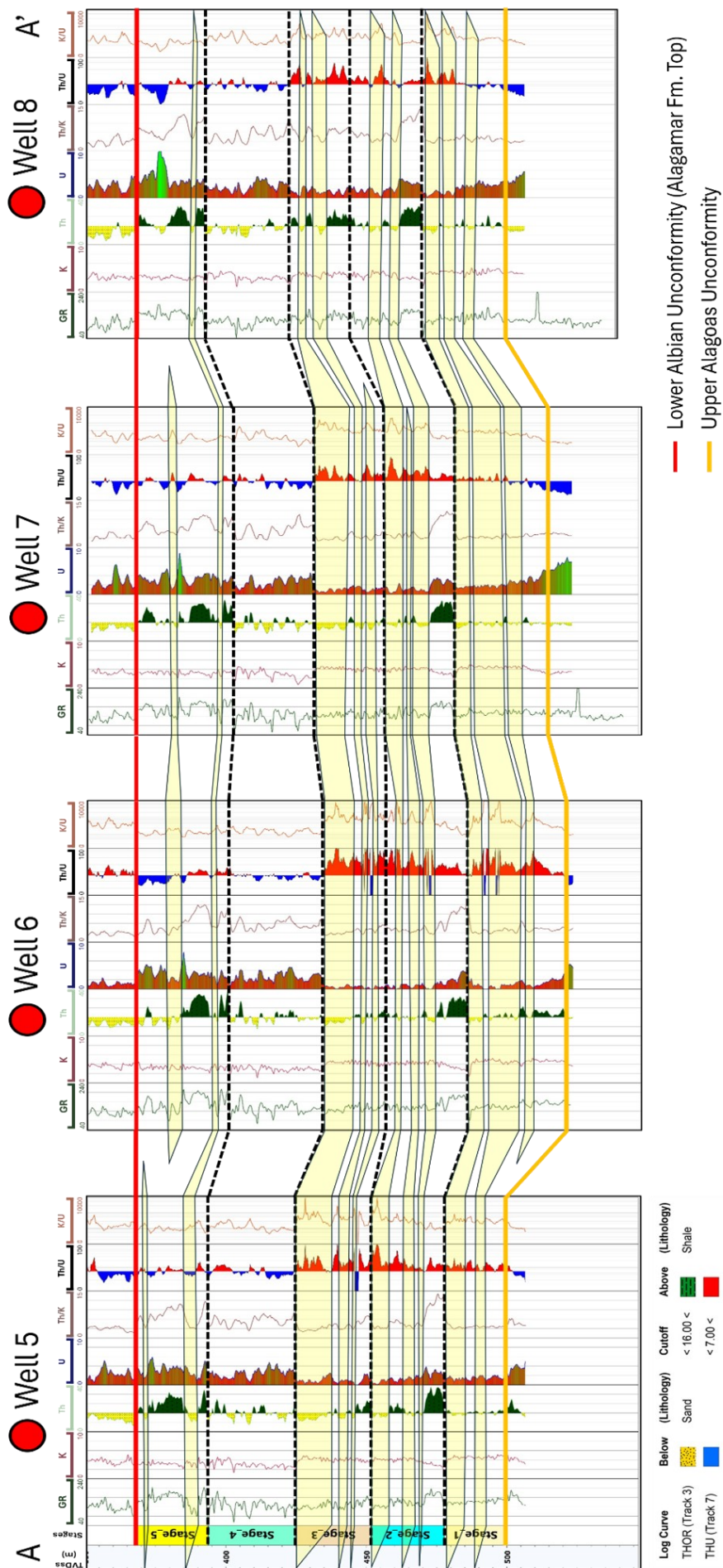


Figure 6. Well correlation section flattened in the Lower Albian Unconformity (LAU), showing the correlation between all five stages proposed in this article. In all stages, the sand bodies (in light yellow) mapped are characterized by low Th, medium-to-low Th/K, and low uranium values. Most of these sandy intervals have high Th/U, showing that they were deposited in an oxidizing environment. In the Th curve, the cut-off used was <16 representing sand, and >16 representing shale; in the Th/U the cut-off was <7 representing sand, and >7 oxidizing based on Fertl (1979).

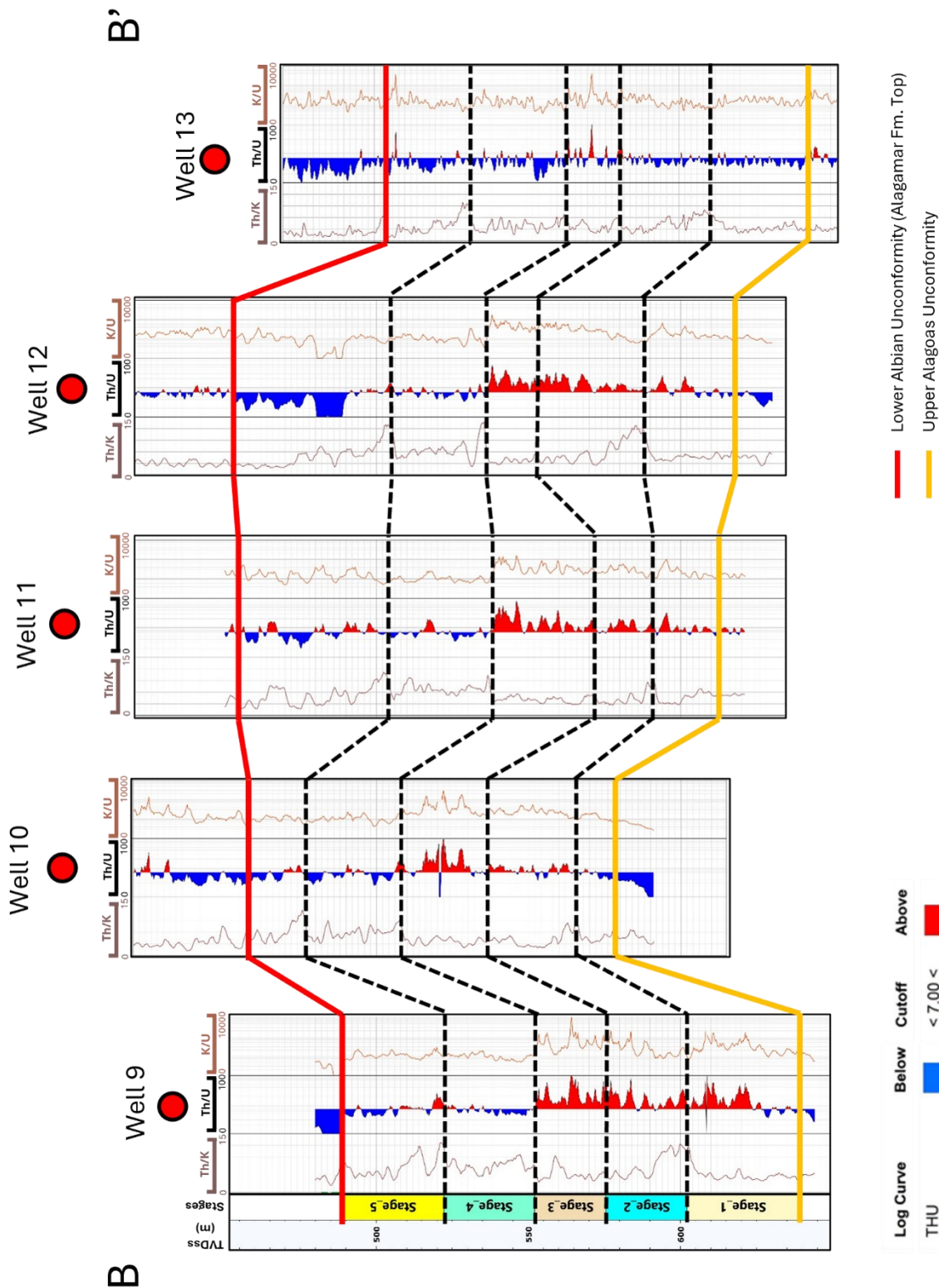


Figure 7. Well correlation section, in TVDss, shows the correlation between all five stages proposed in this article. It is important to note that in this unflattened section, there is some significant variation in the depth of the stages between the wells, evidencing some important tectonic activity after the deposition of the Alagamar Formation. It is important to notice that for the wells located in distal portions of the alluvial fans it is difficult to distinguish between the first three stages, as evidenced by Well 13.

5.2. Tectonostratigraphic evolution of Alagamar Formation

Unifying the well correlation together with the cut-offs explained above, and in the tables, this article

proposes an evolutionary schematic model for the Alagamar Formation deposits in this portion of the Potiguar Basin (figures 8 and 9).

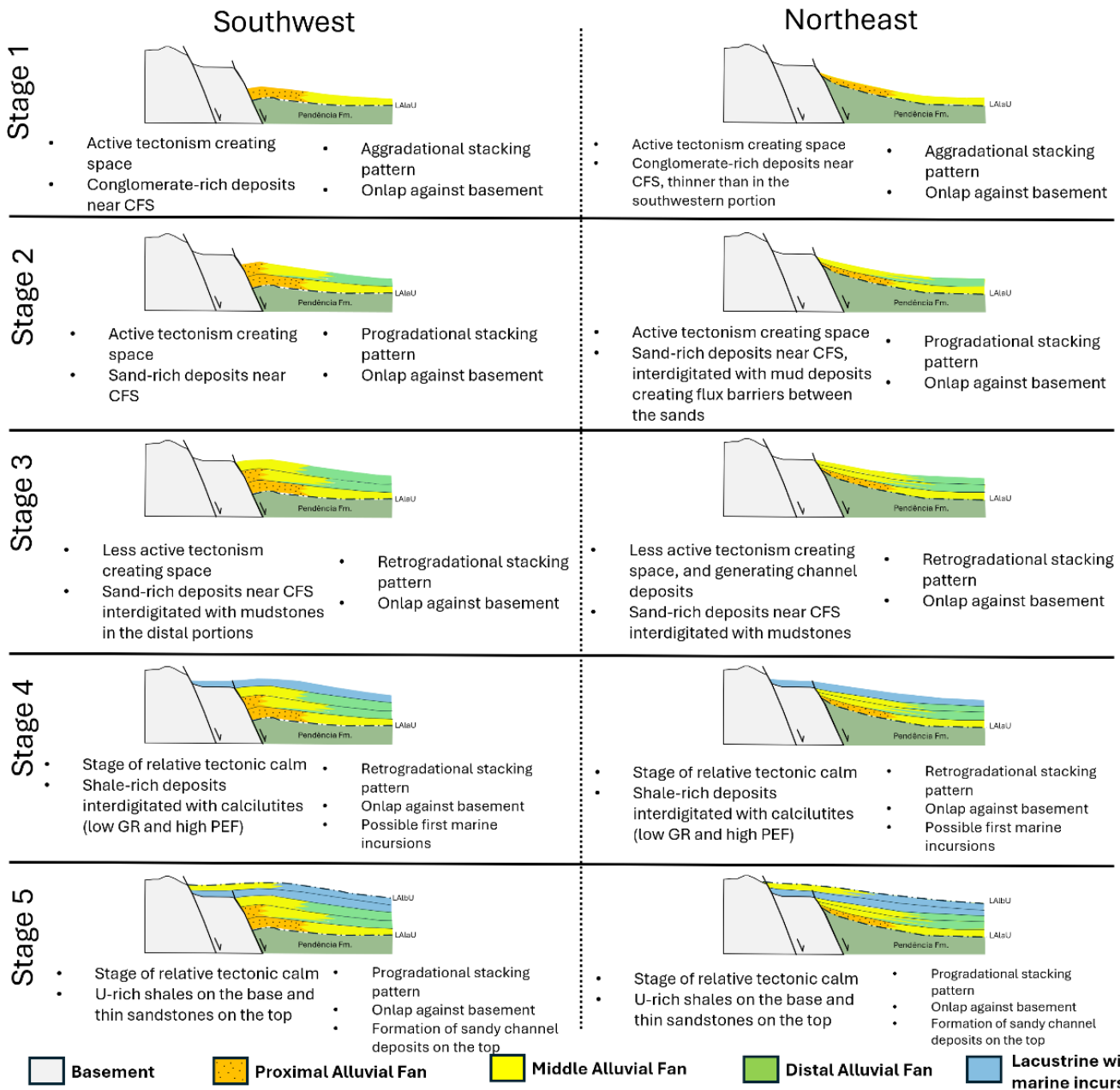


Figure 8. Schematic geological sections built based on the two well correlations presented in the area studied. The left one was generated with the wells located in the southwest portion, using mud logging and log curves as references, where it is possible to note that the stages 1 and 2 have more conglomerate content. The right sections represent the wells located in the northeast part of the studied area, with lower conglomerate content in its first stages, but with the same stacking pattern presented in the southwest sections. These geological sections relate water-level, sedimentary supply, and tectonic of the study area with the stacking pattern identified in the well-to-well correlations.

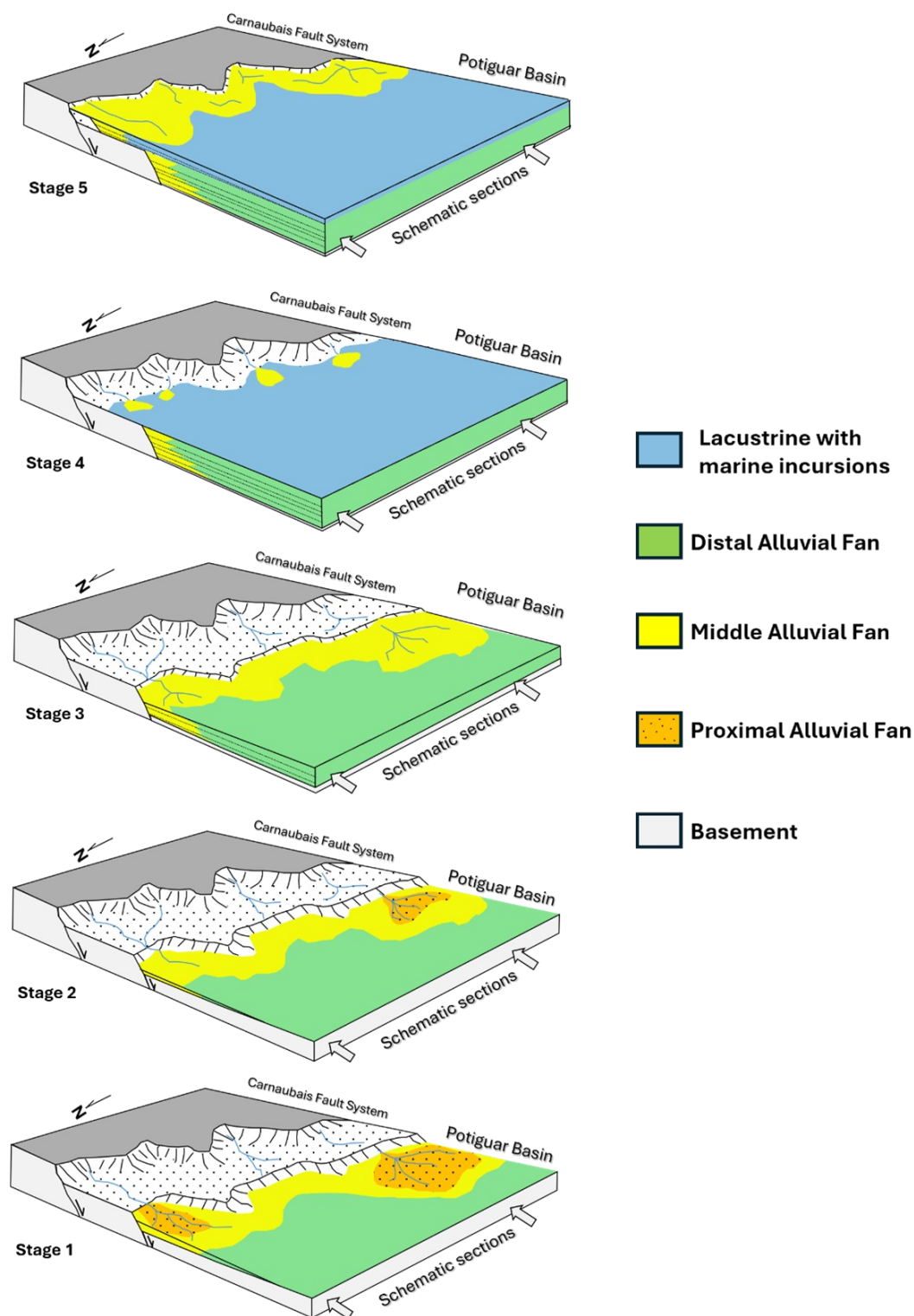


Figure 9. 3D Conceptual model of the sedimentary evolution of the Alagamar Formation in the studied area.

Observing the sections and model, it is important to note that although these groups of wells have the same stacking patterns, there are some differences between them, as shown in the figures 7 and 8. The southwest group of wells presents a higher conglomerate content, and higher Th/U and K/U in stages 1, 2 and 3, probably related to shallower environmental conditions that led to a more oxidizing environment and lower water level

during deposition. These important levels of Th/U could also be associated with the tectonic reactivation events of the Carnaubais Fault System (CFS) once these events are related to high sedimentary supply in an alluvial fan depositional system.

This hypothesis is supported by the fact that Th and Th/K curves show variations in the sedimentary input, where high values represent the deposition of thin grains,

probably related to tectonic quiescence periods, while low values represent tectonic pulses that resulted in coarse grained deposits in an oxidizing environment as shown in figures 6 and 7.

The intense variation on the Th concentration log could be associated with the shaliness in the studied area, as demonstrated by Ferreira et al. (2024), and once this element has a detrital nature and is chemically inert (Bessa, 1995). The variation in its concentration could be related to constant changes in the depositional conditions, such as sedimentary supply, water level, hydrodynamics, and transportation energy, all of them related to tectonism and climate conditions (Fertl, 1979). It is important to state that this tectonic-sedimentation relationship controls the sedimentary supply through time in alluvial fans systems (Morley, 1995), and the variation of the sedimentation rate registered in the Th/K could be linked with the tectonic activity variations of the CFS.

Therefore, the disconnection observed in the sand bodies, in the first three stages (Ferreira et al., 2024), is the geological record of several tectonic pulses throughout the beginning of the deposition of the Alagamar Formation in the Upper Aptian (Ferreira et al., 2024). Besides indicating an oxidizing environment during deposition in these stages, the Th/U ratio also indicates that they are located close to the sedimentary source, and, according to Fertl (1979), this could be linked to rapid uplifted areas during deposition.

Stages 4 and 5 represent the first marine flooding events of this portion of the Potiguar Basin (Araripe and Feijó, 1994; Pessoa Neto et al., 2007), starting the deposition of thin marine sediments above the continental deposits, which could also be inferred by the $Th/U < 7$, as suggested by Fertl (1979). After the maximum flood surface, represented stratigraphically by Ponta do Tubarão beds, a fluvial-alluvial-deltaic depositional environment starts to take place once again in the Galinhos Member deposits, as shown in the figures 7 and 8. These changes in deposition pattern could be related to the tectonic quiescence that stopped the basement uplifting during the deposition of these sediments leading to a drop in coarse sediment supply. These environmental, lithological, tectonic, and depositional differences between the first three stages and the last two were represented stratigraphically by Upanema and Galinhos members, respectively, suggesting that there could have existed an unconformity between them.

6. CONCLUSION

The comprehensive analysis of the Alagamar Formation deposits in the southeast portion of the Potiguar Basin sheds light on the complex interplay of

geological processes that have shaped this region over time. Through detailed well correlation and the identification of evolutionary stages, this study provides valuable insights into the sedimentary evolution of the Alagamar Formation.

The findings reveal a stratigraphic sequence comprising five distinct stages, each characterized by unique lithological and geochemical signatures. These stages offer a glimpse into the dynamic environmental conditions and depositional settings that prevailed during different periods of the Upper Aptian and Early Albian.

- In stage 1 to 3 it is notable the high Th/U values suggesting oxidizing conditions and weathering, together with variations in Th and K concentrations that underscore the influence of tectonism on terrestrial sedimentation dynamics and proximity to the source area. Fluctuations in sedimentary supply and accommodation space are influenced by tectonic activity.
- On the other hand, stages 4-5 represent a shift towards marine incursions, evidenced by lower Th/U ratios and the deposition of thin marine sediments such as calcilutites, and black and grey shales. This transition marks a pivotal moment in the geological history of the Potiguar Basin, reflecting changes in sea level, sediment supply, and a shift in the main subsidence mechanism from mechanical to thermal.
- The observed differences between the stages, particularly in terms of conglomerate content in mud logging, Th/U, and K/U ratios, highlight the heterogeneity of depositional environments within the study area and are consistent with the existing literature that describes this geological formation (Araripe and Feijó, 1994; Pessoa Neto et al., 2007).

These variations illustrate the complex interplay between tectonic processes, sedimentation dynamics, and environmental conditions. The proposed evolutionary schematic model provides a valuable framework for understanding the sedimentary history of the Alagamar Formation.

Overall, this study of the Alagamar Formation deposits in the Potiguar Basin contributes to the stratigraphic sequence recognition and the depositional history of the region. The integration of well correlation, lithological, and geochemical data – provided by spectral gamma ray logs – has led to a nuanced understanding of the environmental conditions and tectonic influences that have shaped this formation and highlighting the fact that this stratigraphic interval has very distinct portions that need to be better understood and addressed.

The evolutionary schematic model proposed herein serves as a robust framework for future research and exploration in the Potiguar Basin, offering insights into the dynamic processes that govern sedimentary basins worldwide. This methodology could be replicated and used in other geological deposits, that have similar radioactivity, to provide valuable insights into the well-to-well correlation using spectral gamma ray logs.

It is important to note, however, that the seismic data available for the study area presented low resolution, which limited its integration with the methodology applied to the wells in this work. As such, the proposed model does not incorporate seismic interpretation, representing a constraint in the spatial extrapolation of the stratigraphic framework. Alongside seismic interpretation, future studies integrating with geological process modeling could significantly enhance the understanding of the lateral continuity and geometries of the depositional units, thereby refining the proposed evolutionary model.

ACKNOWLEDGMENTS

We thank PetroReconcavo for the dataset, support, and technical assistance during this study. The authors are also grateful to the Institute of Science and Technology of Petroleum Geophysics of Brazil for supporting this research.

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AUTHORSHIP CONTRIBUTION STATEMENT

Victor Hugo Lima Ferreira: Conceptualization, formal analysis, investigation, writing –original draft. Antonio Fernando Menezes Freire: Supervision, conceptualization, writing-review and editing. Wagner Moreira Lupinacci: Supervision, conceptualization, writing-review and editing. Filipe Vidal: Conceptualization, visualization, writing-review and editing. Victor Matheus Joaquim Salgado Campos: Conceptualization, visualization, writing-review and editing.

FUNDING SOURCES

This research did not receive any funding from specific public agencies, commercial or non-profit organizations.