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Review of the lithostratigraphy of the Mesozoic basins of the Borborema Province, Northeastern Brazil

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Abstract

Several Phanerozoic sedimentary basins developed over the rocks of Borborema Province. The formation and opening of the Atlantic Ocean influenced tectonic events that reactivated large internal lineaments of the province (Transbrasiliano, Senador Pompeu, Patos, and Pernambuco). This event culminated with the production of several structures, including the grabens, where intra-continental sediments were deposited. This deformation played a fundamental role in the development of the continental margin basins that form the WNW-ESE and N-S segments of the Brazilian northeast. In this work we address the terrestrial portion of the Mesozoic basins of the Borborema Province and provide a lithostratigraphic review in addition to unpublished data of the interior basins and the Jatobá Basin. The descriptions of the marginal basins were subdivided by the following structural domains: dextral equatorial, orthogonal, and sinistral south branching. The Ceará and Potiguar basins are part of the equatorial margin. The orthogonal domain encompasses the Pernambuco and Paraíba basins and comprises the crustal block limited by the Pernambuco and Patos lineaments. Finally, the Sergipe-Alagoas basins are located in the sinistral branch. The intra-continental basins are equivalent to the *failed rift arms*, which are composed of aborted rifts and half-grabens of the interior basins of northeastern Brazil. The Recôncavo-Tucano-Jatobá rift system was aborted in the Lower Cretaceous and represents the North Tucano and Jatobá basins in Borborema. The interior basins are concentrated in the Transversal Zone. However, to the north of the Patos Lineament, important basins occur, such as Iguatu and Rio do Peixe. The basins of the orthogonal domain correspond to the final stretching rift in a late rupture in Aptian due to the rigidity of the basement. Due to the potential of oil exploration, the marginal basins are the ones that present the data available in the literature the most. Both marginal basins with lower oil potential (such as the Pernambuco and Paraíba basins) and the interior basins of the northeast, covering the Jatobá, need a more consistent lithostratigraphic update to consolidate and validate newly proposed units.

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1. Introduction

The Mesozoic sedimentary basins inserted in the Borborema Province extend almost throughout the Brazilian northeast, covering the states of Ceará, Rio Grande do Norte, Paraiba, Pernambuco, Sergipe, and Bahia (Figure 1). These basins have their origin and evolution directly related to the opening of the Atlantic Ocean and the breaking of the Gondwana supercontinent, inheriting several structures belonging to the Neoproterozoic tectonic shift of the Borborema Province (BP).

The Borborema Province consists of a mosaic complex of tectonic blocks composed of rocks from the Archean to Neoproterozoic ages. Extensive shear zones limit these blocks. Nevertheless, they are common among the Neoproterozoic granitic intrusions generated in the Brasiliano-Panafrican orogeny in 620-580Ma and gave rise to the Western Gondwana continent (Cordani et al. 2000; Brito Neves et al. 2000; Van Schmus et al. 2008). The current boundaries of the province are Parnaíba Basin by the west, the São Francisco Craton to the south, and north and east, covered by the sediments of the marginal basins.

The BP is divided into three major domains: northern, central/Transversal, and external/southern (Delgado et al. 2003). The main shear zones that separated these domains are Patos, Pernambuco, Transbrasiliano (Sobral - Pedro II), and Senador Pompeu (Brito Neves et al. 2000). These shear

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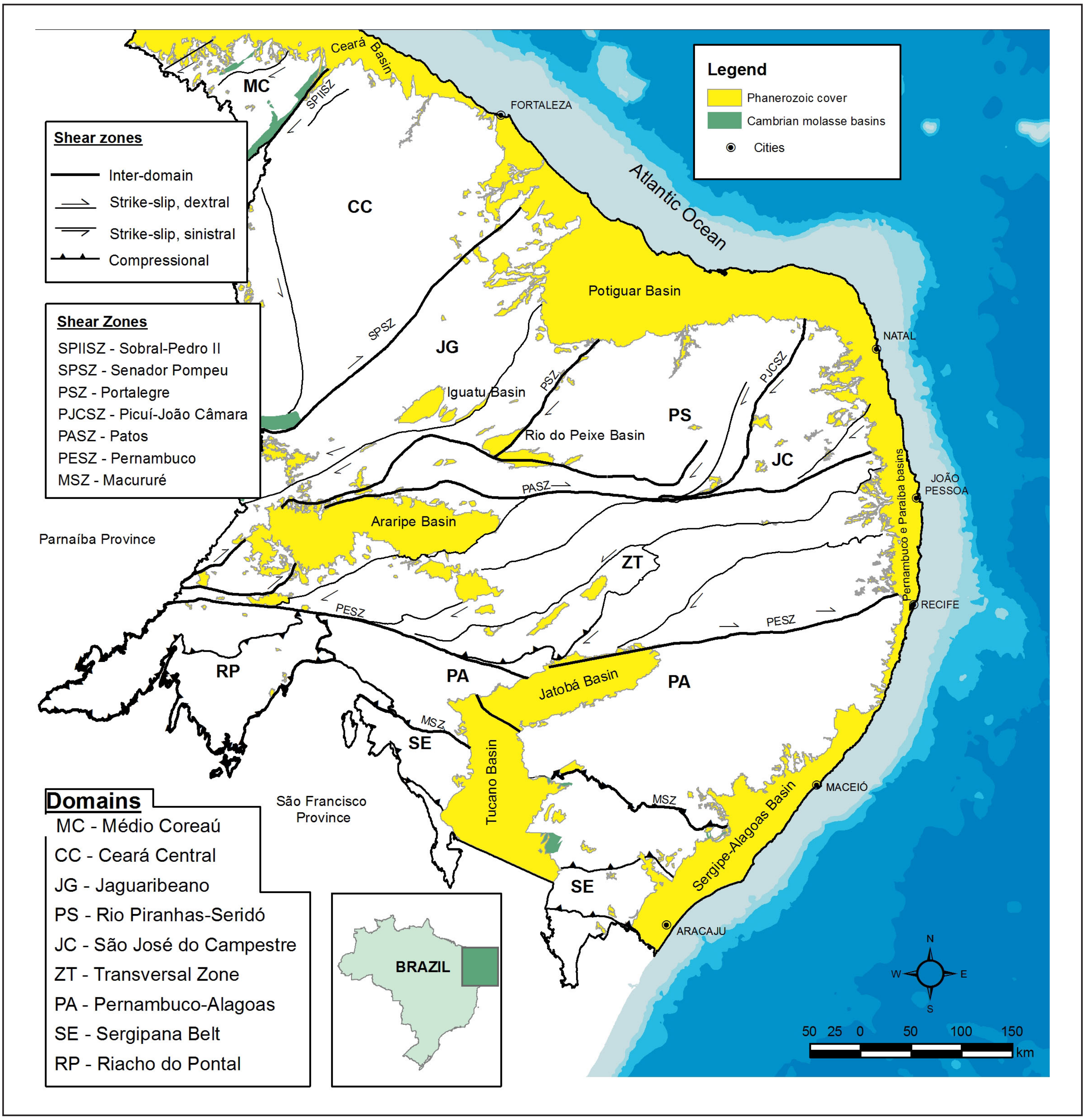

FIGURE 1. Location of Borborema Province with emphasis on sedimentary basins (modified from Medeiros et al. 2017).

zones and their reactivations generated several structures, which together played a fundamental role in the evolution of the Phanerozoic sedimentary basins (Cordani et al. 2013). From the Phanerozoic, many sedimentary basins developed in the continental portion of the Borborema Province. They form the so-called interior basins of the Northeast and the basins of the Jurassic-Cretaceous aborted rift, related to the fragmentation of the Gondwana supercontinent, which also includes remnants of Paleozoic intracratonic basins deposited after the Brasiliano Orogeny (Morais Neto 2009). Along the Atlantic coast of BP, the Cretaceous basins form the WNW-ESE, and N-S segments of the Brazilian continental margin, respectively called the Equatorial and East margins.

The Mesozoic basin covers in Borborema Province were gathered in this article that reviews the lithostratigraphic units contained in the emergent portions of the segments of the interior basins of the Northeast, the East margin, and the Jatobá and Tucano Norte subsystem. Geological texts and maps of geological leaves were consulted in the 1:100,000 scale, state geological maps, geophysical-geological maps, and regional geological maps, along with an interpretation of remote sensing products (satellite images, SRTM and airborne geophysical maps), geological cartography and regional integration. A specific field survey was also carried out with outcrops descriptions and stratigraphic profiles in the Interior Basins of the Northeast, in the region of the Transversal Zone area of BP, to resolve some regional inconsistencies. Part of the work of updating the sedimentary units subsidized the integration published in the Geological Map of the Borborema Province (Santos et al. 2021).

2. Phanerozoic evolution of Borborema Province and its relation with sedimentary basins

In the Mesozoic, great tectonic activity in Borborema Province refers to the fragmentation of the Gondwana supercontinent with the opening of the South Atlantic Ocean. This movement started approximately 140 Ma ago and counted on the Proterozoic structuring of BP as a strong resistance in the rupture process (Matos et al. 2021). Because of this episode, several sedimentary basins were shaped by the basement's pre-existing weak lines (Szatmari et al. 1984).

The Gondwana supercontinent began to suffer crustal extension from the Triassic (Szatmari et al. 1987) where, at the end of the Jurassic, there was a crustal stretching and thinning caused by distensive efforts, giving rise to a depression called the Afro-Brazilian Depression (Ponte 1971). These distressing efforts were predominantly NW direction and took advantage of the structural discontinuities of the basement, generating normal faults during the Jurassic and culminating in the formation of half-grabens (Milani 1987) in a large extent of BP.

In the Lower Cretaceous, tectonism was more intense, and this time was responsible for the formation of divergent margin rifts, but on a smaller scale in the region of the Borborema Province. In Lower Cretaceous, the South American plate underwent a clockwise rotation in relation to the African Plate (Szatmari et al. 1987). The crustal rupture, controlled by the Precambrian structural alignments and associated with the rotation of the South American plate, provided the individualization of the microplate of the Brazilian Northeast (Szatmari et al. 1987). This microplate had relative anti-clockwise movement, with an axis located east of the Jatobá Basin, which was responsible for forming the intracontinental rifle system of Recôncavo-Tucano-Jatobá (Milani 1987). Then in Aptian, the main rifting axis migrated from the continent to the opening of the Atlantic Ocean, forming the Sergipe-Alagoas Basin and abandoning the interior rift (Matos 1999).

The Pernambuco – Ibimirim shear zone interrupted the distensive rifting of the South Atlantic at the height of the Recôncavo, Tucano e Jatobá basins. This rheological shield generated the transform zone Sergipe–Alagoas and the Recôncavo–Tucano–Jatobá Aulacogen (Bueno 2004).

Matos et al. (2021) subdivided the South Atlantic Cretaceous rift System into five stages II, III, IV, V), and (I, which are regional events that have significantly impacted the tectonostratigraphic environment at specific locations on the east margin. The Province of Borborema went through all stages that affected the margin and intercontinental portions, with the formation of the aborted Recôncavo-Tucano-Jatobá rift and the interor basins of the Northeast. In the spatial contour of the marginal basins in the area of the Province of Borborema, Matos et al. (2021) recognized three structural areas: Dextral Equatorial, Orthogonal, and Sinistral South (Figure 2).

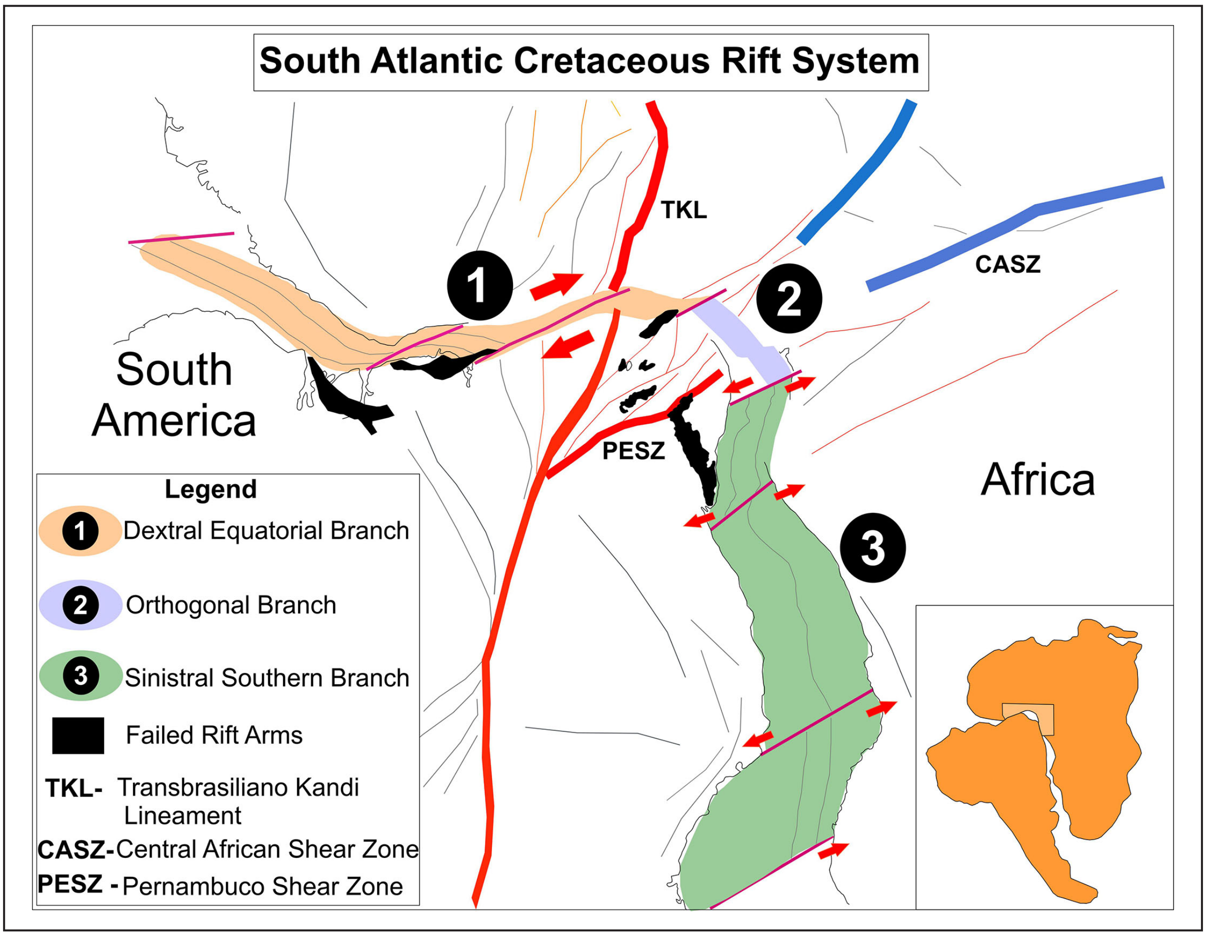

FIGURE 2. The three main structural domains of the South Atlantic Cretaceous rift system (modified from Matos et al. 2021).

The total separation of South America from Africa is considered between the end of the Aptian (Alagoas Stage) and the end of the Albian (i.e., 112-100 Ma) (Matos et al. 2021; Heine et al. 2013). According to Ponte et al. (1978), the formation process of the entire Atlantic Ocean would have been completed at the end of the Aptian. For Dias-Brito (1987), the final opening would have occurred only from the Neo Albian, which according to fossil and paleoecological records of this same section, in several basins, a normalization of salinity between the Northern and Southern portions of the Atlantic was verified, corroborating for a compelling connection between the waters of the two portions.

The continental rift basins evolved according to the three major stages: pre-rift (Neo-Jurassic), rift (Early-Barremian), and post-rift (Neo-Aptian) (Matos 1999) based on the model proposed by Lambiase (1990). For the continental margin basins, the pre-rift, rift, post-rift, and drift Super sequences constitute the fundamental stratigraphic tectonic framework (Milani et al. 2007).

3. Aborted rift basins

The Jatobá, Tucano, and Recôncavo basins (Figure 3) form a Mesozoic rift system that was originated by distensive efforts resulting from the separation of Gondwana and the formation of the South Atlantic Ocean. Unlike the continental margin basins that evolved to the passive margin stage, these basins constitute a branch of the South-Atlantic aborted rift in the Neo-Aptian (Costa et al. 2007). For Matos et al. (2021), this system was the oldest in the opening process of the Atlantic, is inserted in the Rift I Stage (145-140Ma), and was triggered only by intracontinental distribution and breakup, with little magmatic activity.

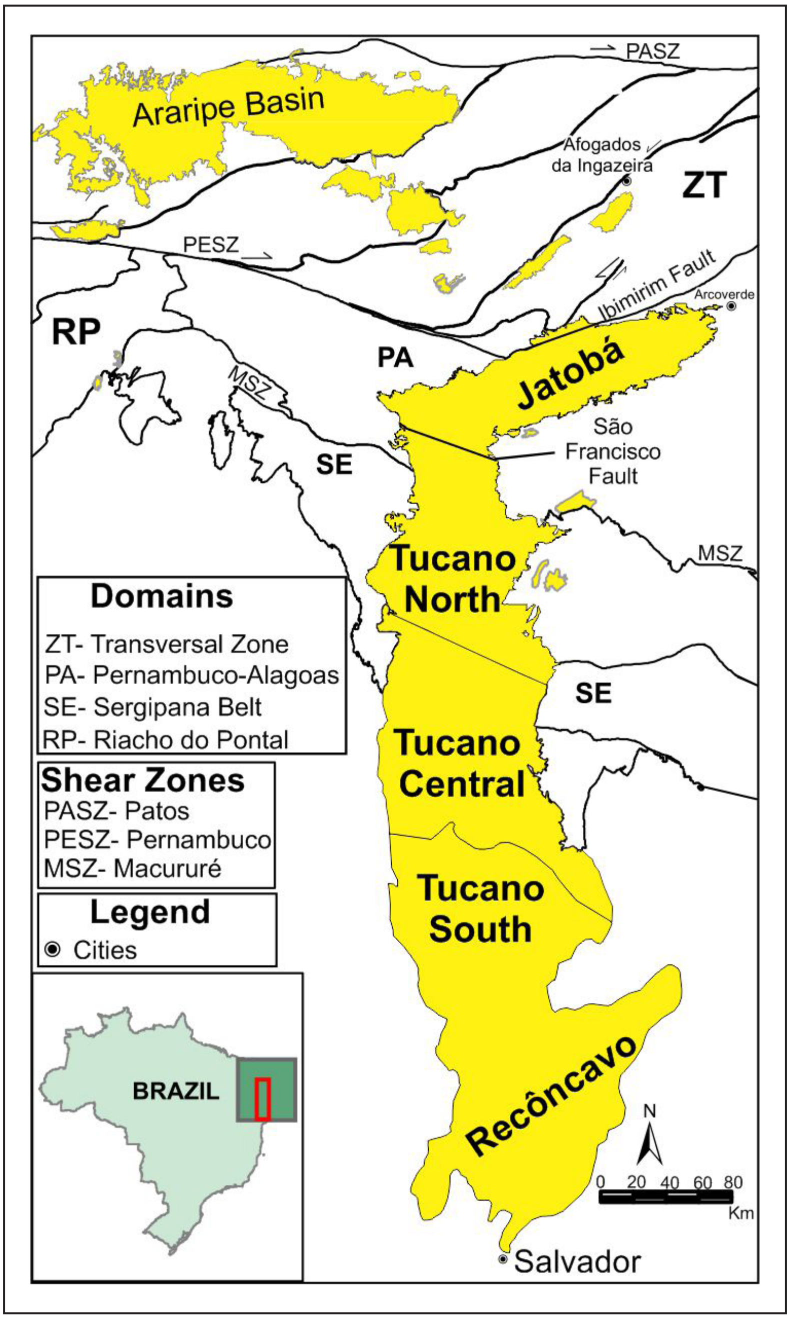

FIGURE 3. Location of the Recôncavo-Tucano-Jatobá rift system, Northeast of Brazil.

The configuration of the Jatobá and Tucano basins reflects the performance of extensional efforts amid a heterogeneous crystalline basement (Magnavita 1996). The change in the direction of the rift opening, which passes from the S-N direction in the Tucano Norte, to E-W/ NE-SW, in the Jatobá Basin, is perhaps the most explicit example of the control exercised by pre-existing basement structures (Costa et al. 2007). The Pernambuco Lineament possibly conditioned this strong inflection (Santos et al. 1990; Costa et al. 2007). This structure was reactivated during the Lower Cretaceous, generating gravitational tailings of approximately 3.000 meters (Cordani et al. 2009).

In the Borborema Province context, the aborted intracontinental rift extension covers the Jatobá Basin, the Tucano Norte Sub-basin, and the northern end of the Tucano Central Sub-basin. The sedimentary filling of the basins is similar, and in this article, the Jatobá and Tucano Norte basins will be described.

3.1 Jatobá Basin

The Jatobá Basin extends over approximately 5.000 km² with a NE-SW orientation, covering the central-south part of the state of Pernambuco in northeast Brazil. The basin has a typical half-graben geometry limited to the west and north by the São Francisco and Ibimirim faults, respectively (Costa et al. 2007) (Figure 1). Along the Southern and Eastern borders, contact with the basement is discordant by small normal faults systems. These faults occur in the flexural edge, are synthetic in relation to edge fault, and have preferential orientation for NE with dipping toward the depocenter (Costa et al. 2007).

The Jatobá Basin has a NE-SW orientation, the result of reactivation in the Cretaceous of the Pernambuco shear zone, generating the Ibimirim Fault and the inflection of the rifting tensions (Santos et al. 1990; Costa et al. 2007). The Ibimirim Fault has continuity in the crystalline basement with Cruzeiro do Nordeste Shear Zone (ZSCN). The fragile reactivation of the ZSCN is characterized by normal faults overlapping the mylonitic foliation, and this fragile reactivation process may be associated with the opening of the South Atlantic Ocean. Miranda et al. (2020) dated these normal faults through calcite - slicken fibers and obtained a U-Pb age of 135 ± 4.7 Ma.

The beginning of sedimentation in the Jatobá Basin involves a Paleozoic sequence (Silurian-Devonian) of the Jatobá Group with the Tacaratu and Inajá formations (Costa et al. 2007). These sedimentary sections are pre-existing and occupy the same geographic context in previous cycles but do not have a genetic relationship with the basin (Milani et al. 2007).

The Tacaratu Formation (Silurian-Devonian), whose age was established through stratigraphic correlations and palynological data (Regali 1964), consists of the intercalation of sandstones with stratified conglomerate layers and deposited in a large-sized braided river system (Figure 4A). In addition, local conglomerates, siltstones, and clay stones can occur, which are interpreted as deposits of areas outside the main channel, representing a possible flood plain (Accioly and Morais 2018).

The Inajá Formation is restricted to the Jatobá Basin, dated from the Upper Devonian through palynomorph and macrofossils (Regali 1964; Muniz 1976). The presence of heterolytic sediments (Figure 4B) containing fossils and ichnofossils typical of a wave-dominated tidal plain environment (Muniz 1976; Morais et al. 2021) characterizes it. The ichnofossils were classified as invertebrate marks and the fossils identified were brachiopods and bivalve mollusks (Muniz 1976).

The pre-rift sedimentation (Upper Jurassic) is a vestige of the Afro-Brazilian Depression. The sediments of the Sergi and Aliança Formations characterize the Jatobá Basin. The Aliança Formation is subdivided into two members in the basin; there are only records of the Capianga Member since the presence of the Boipeba Member's sandstones is still uncertain. (Costa et al. 2007). The Capianga Member is differentiated by intercalation of ostracod calcarenites, shales, and clays (Figure 4C). The age of the Aliança Formation is attributed to the Dom João Stage based on the non-marine ostracods. The depositional environment is typically a large-scale lake (Viana et al. 1971) and relatively deep, according to the studies of paleo ichthyofauna (Silva et al. 2011).

The Sergi Formation (Figure 4D) is composed of medium sandstones to conglomerates, massive or stratified, sometimes interspersed with siltstone, and more rarely with clay pockets. The existence of conglomerate lags and silicified fossil trunks is ordinary. The age of the Sergi Formation is indicated by the presence of non-marine ostracods of the Upper Jurassic (Viana et al. 1971). Scherer et al. (2007) interpreted the environment of the Sergi Formation as fluvial-eolian, and fine sediments correlated to a lacustrine environment.

The basis of the rifting sequence comprises the Candeias and Salvador formations (Figure 4E and Figure 4F) (Costa et al. 2007). The Candeias Formation consists of gray to green shales, siltstones, fine sandstones, and sometimes oolitic and bioclastic calcarenites, with wave-formed ripples (Figure 5A). This unit usually occurs interspersed with the Salvador Formation (Horn and Morais 2016). These rocks are interpreted as lacustrine and biostratigraphic data indicate that the deposition would have occurred during the Berriasian (Costa et al. 2007).

The Salvador formation results from the tectonic activity on the faulted edge reactivated in the Lower Cretaceous. It consists of conglomerates typical of fan deltas and is polymictic, supported clasts, with grain sizes ranging from pebble to boulder and paleocurrent predominantly to the south (Figure 4E). They occur interspersed with immature sandstones and may contain carbonate cementation and an abundance of bivalves (Figure 4F) (Horn and Morais 2016). This sandstone can sometimes be called coquinas, with shells that contain articulated and fragmented valves (Figure 4F). There still need to be a precise taxonomic identification of these specimens, and now they are being preliminary assigned to the Palaeoheterodonta subclass (Unionacea Order) (Figure 4F).

Isotopic analyses of C and O in a limestone shell and the host rock show values of $\delta^{13}C$ of -2.82 and -2.75 ‰ e $\delta^{18}O$ of -6.25 and -6.71 ‰ (both VPDB). These isotopic values fall within the limits of variation for lacustrine carbonates (e.g., Talbot 1990).

In Neo-Berriasian/Early Valanginian, there was a reduction in tectonic activity and programming of deltaic systems of the Ilhas Group (Figure 5B) (Costa et al. 2007). Tectonism was attenuated until the Aptian and the deposition of sandstones (Figure 5C) of fluvial-eolian systems of the São Sebastião Formation (Costa et al. 2007).

The post-rift sequence (Neo Aptian) is characterized by thermal subsidence and is represented by the Marizal Formation (Caixeta et al. 1994; Costa et al. 2007). However, this formation outflows very little in the basin and is composed of conglomerates and sandstones of alluvial deposits. Rocha (2011) interpreted that the Crato, Romualdo, and Exu formations were also deposited in a sequence correlated to the Araripe Basin. The presence of laminates distinguishes the Crato Formation (Figure 5D), the Romualdo Formation (Figure 5E) is characterized by greenish shales interspersed with clays, and both are covered by the sandstones of the Exu Formation (Figure 5F).

3.2 North Tucano Sub-basin

Like the Jatobá Basin, the North Tucano Sub-basin has a typical half-graben geometry, occupies an area of approximately 8.800 km^2, and has an N-S. Orientation. Its boundary with the Jatobá Basin is the São Francisco Fault, northeast. To the south, the Vaza-Barris Arch separates it from the Central Tucano Sub-basin. The São Saité fault defines the contact with the basement to the west, and by disagreement or faults of small tailings, to the east (Costa et al. 2007).

At the limit with the Central Tucano Sub-basin, there are the transfer faults of Caritá and Jeremoabo, which, together

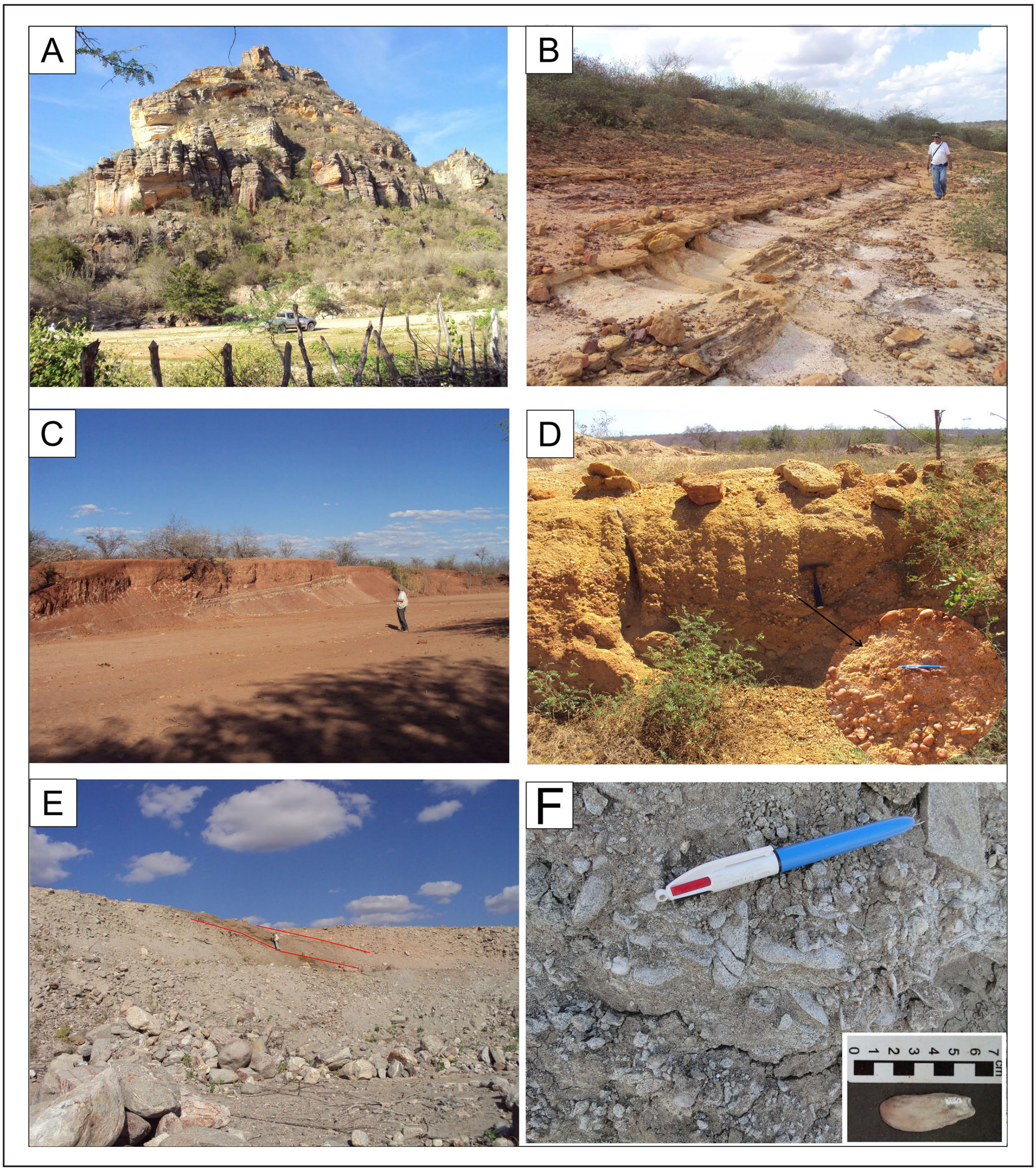

FIGURE 4. A) View of outcrops of the Tacaratu Formation. B) Facies of the Inajá Formation. C) Reddish brown Clay stones interspersed with gray calcarenites of the Aliança Formation. D) Conglomerates of the Sergi Formation, detail of quartz clasts. E) Outcrop of the Salvador Formation in red the level of the fossiliferous facies. F) Facies of sandstones with bivalves, detail with the articulated bivalve.

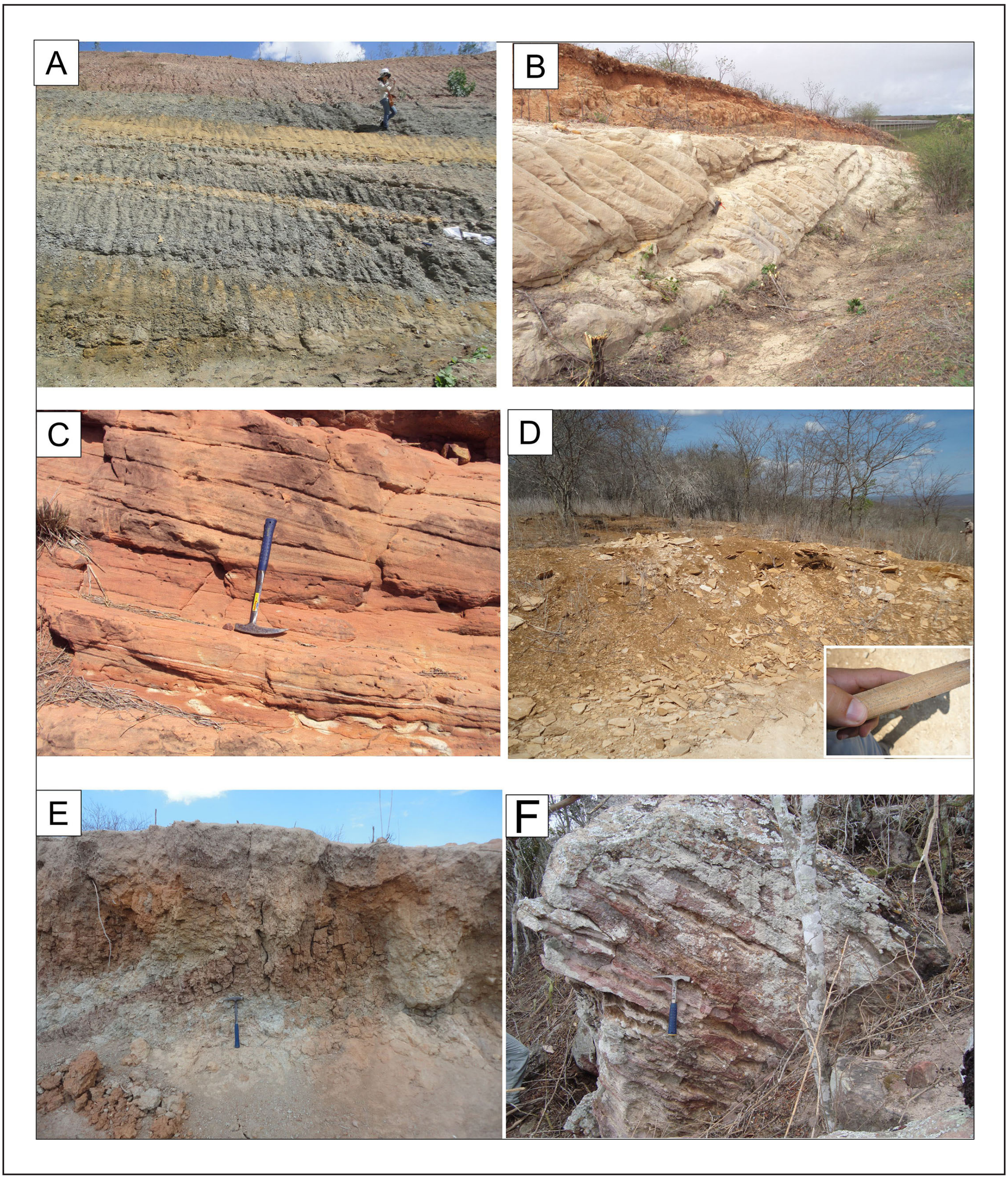

FIGURE 5. . A) Greenish shales of the Candeias Formation interspersed with sandstones of the Salvador Formation. B) Sandstones with sigmoidal cross-stratification of the Islands Group. C) Sandstone with cross-stratification of the São Sebastião Formation. D) Outflow of Crato formation, detail for limestone lamination. E) Shales and clay stones of the Romualdo Formation. F) Lithified sandstone with tabular cross-stratification of the Exu formation.

with high Vaza-Barris, constitute an accommodation zone, responsible for the reversal of the half-graben asymmetry (Magnavita et al. 2003; Costa et al. 2007). In the North Tucano, unlike the southernmost sub-basins, the strata dip westwards toward the São Saoté fault. In the lower Salgado do Melão, the basement is estimated to be more than 7,000 meters deep (Magnavita et al. 2003).

The sedimentary filling of this sub-basin is similar to the Jatobá Basin. Initially, the deposition of the Paleozoic sequence that behaved as a basement for the basin is established. These rocks occur in the graben region of Santa Brígida, which contains a complete Paleozoic section of the Recôncavo-Tucano-Jatobá aborted rift (Costa et al. 2007).

In probable disagreement with the sandstones and conglomerates of the Tacaratu Formation (Silurian-Devonian), a Permian-carbonate sequence is succeeded in a shallow marine environment. In this sequence, the sandstones and shales of the Curituba Formation with striated sandstone pavements that show a glacial action in the Carboniferous, followed by sandstones, calciferous siltstone, and bituminous dolomites of the Santa Brigida Formation (Permian) (Magnavita et al. 2003).

The pre-rift sequence is differentiated from the Jatobá Basin by the presence of fluvial-eolian sandstones of the Boipeba Member of the Aliança Formation. The red sediments of this Jura-Cretaceous sequence are followed by the lacustrine shales of the Itaparica Formation of the Santo Amaro Group of the Lower Barremian age (Costa et al. 2007).

According to Costa et al. (2007), following the rift from the Jatobá Basin and North Tucano Sub-basin, the sediments formally described as Candeias Formation (top of the Santo Amaro Group) were deposited, the Massacará Group with the São Sebastião and Salvador formations and the undivided fluvial-deltaic sediments of the Ilhas Group.

The Marizal Formation (upper Aptian) of the post-rift sequence is much more representative in the Tucano Norte Sub-basin than in the Jatobá Basin and is characterized by conglomerates and alluvial sandstones. Above these deposits, in Serra do Tonã region, in the Tucano Norte Sub-basin, there are greenish shales and Albo-Aptian limestones correlated with the sediments of the Santana Group of the Araripe Basin. The deposition of this post-rift section occurred in a sag-type basin that would have extrapolated the rift's current limits during a thermal subsidence phase (Magnavita et al. 2003; Costa et al. 2007).

4. Interior basins of the Brazilian Northeast

The interior basins of the Northeast remain a system of isolated Lower Cretaceous rifts, developed along fault zones in the pre-Cambrian basement of the Borborema Province, and are located west of the states of Paraíba, Rio Grande do Norte, Pernambuco, and South of the States of Ceará and Piauí. Most of the Borborema Province's intra-continental basins are concentrated in the center-west portion. (Figure 6) (Milani and Davison 1988).

The deformation that controlled the development of these basins connected with the Neoproterozoic structures of the crystalline basement (Matos 1999). The rocks of the upper crust control the structural framework; these structures are areas of discontinuous fragility and act as concentrators of the associated deformation. Some discontinuities, such as the Patos and Pernambuco lineaments, were partially derived from the Transbrasiliano Lineament and reproduced an essential role in the lateral escape of masses (Ganade et al. 2014) that were effectively reactivated in the Cretaceous (Destro et al. 1994; Lopes et al. 2019; Vasconcelos 2018; Miranda et al. 2020).

For Matos et al. (2021), the interior basins of the Northeast are inserted in stage II (140-160 Ma) of the opening process of the South Atlantic. The mechanism of origin of these basins occurred through the Cariri-Potiguar Rift system, with the main direction of extension NW-SE (Matos 1992). The Cariri-Potiguar-West Africa rifting axis was formed as the West African rifting system spread west, opening the way for the Cariri-Potiguar rift axis in Brazil, which is part of the Brazilian Northeast rifting system (Matos 1992, 1999).

Most of the interior basins of the Northeast are characterized by a semi-graben geometry and limited by normal faults and structural alignments east-west of the Brazilian Northeast, such as the Pernambuco and Patos lineaments, which played a fundamental role in the tectonic control of the basins formed in Mesozoic (Cordani et al. 2009; Chang et al. 1992).

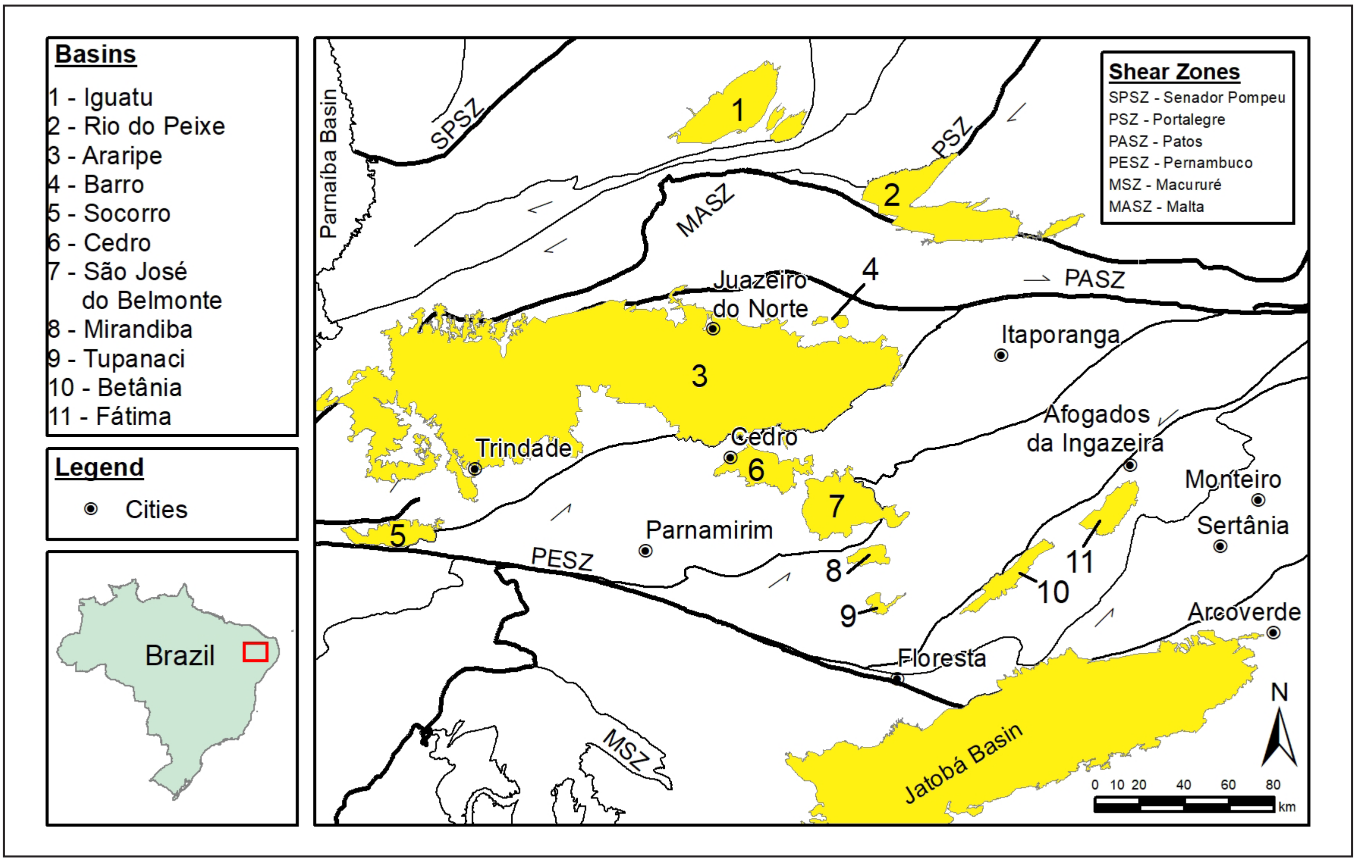

FIGURE 6. Location of the Interior Basins of the Northeastern Brazil.

The framework of these basins is similar, but they have distinct sedimentary sequences. Arai (2006) made a lithostratigraphic review and listed particularities among them, such as the non-deposition north of the Patos Lineament of the Afro-Brazilian Depression sequences, that constitutes the deposits of the Dom João local stage (Figure 7). This geographical limitation of the stage would have been caused by the substantial relief that developed along the lineament, inhibiting the deposition of the Pre-Rift sequence in these areas (Ponte and Ponte Filho 1996). Another significant regional hiatus covers the basins north of the Pernambuco Lineament (Figure 7), characterized by the absence of the Aratu Stage interval and the lower part of the Alagoas Stage (Ponte Filho et al. 1990). According to Matos (1992), this hiatus was due to the Pernambuco Shear Zone accommodation zone, which prevented, at the time, the propagation of the rift along the Cariri-Potiguar trend.

Among the various basins that originated in this context, the most representative is on the Geological Map of the Borborema Province (Santos et al. 2021) and will be described below according to their distance from the Patos and Pernambuco lineaments. Unfortunately, the interior basins do not have a well-defined denomination, and this work adopted the most used denominations in the literature and the most appropriate ones for each basin (Figures 6 and 7).

4.1 Basins of the Transversal Zone Domain

In the Domain of the transversal zone of the Borborema Province are the Araripe, Cedro, Barro, Socorro, São José do Belmonte, Mirandiba, Tupanaci, Betânia and Fátima basins, located among the states of Ceará, Pernambuco, and Paraiba. Due to the proximity and similarity of sedimentary deposits, these basins have lithostratigraphic units correlated with the Jatobá Basin and Araripe Basin units (Figures 6 and 7). The Transversal Zone (Almeida et al. 1981; Brito Neves et al. 2000; Santos et al. 2004) is limited to the North by the Patos shear zone and the South by the Pernambuco shear zone. Matos et al. (2021) call this area the Orthogonal Branch. In the crystalline basement, this segment of BP is characterized by a variety of lithotectonic units that reflect the systematic stages of crustal growth and shear zones of regional scale, interpreted as possible crustal limits.

4.1.1 Araripe Basin

The Araripe Basin occupies an area of approximately 9.000 km², occurs beyond the Chapada do Araripe, and extends through the Vale do Cariri, deposited in the direction E-W (Assine 2007). The basin is deposited on a structured framework according to faults direction NE and WNW, resulting

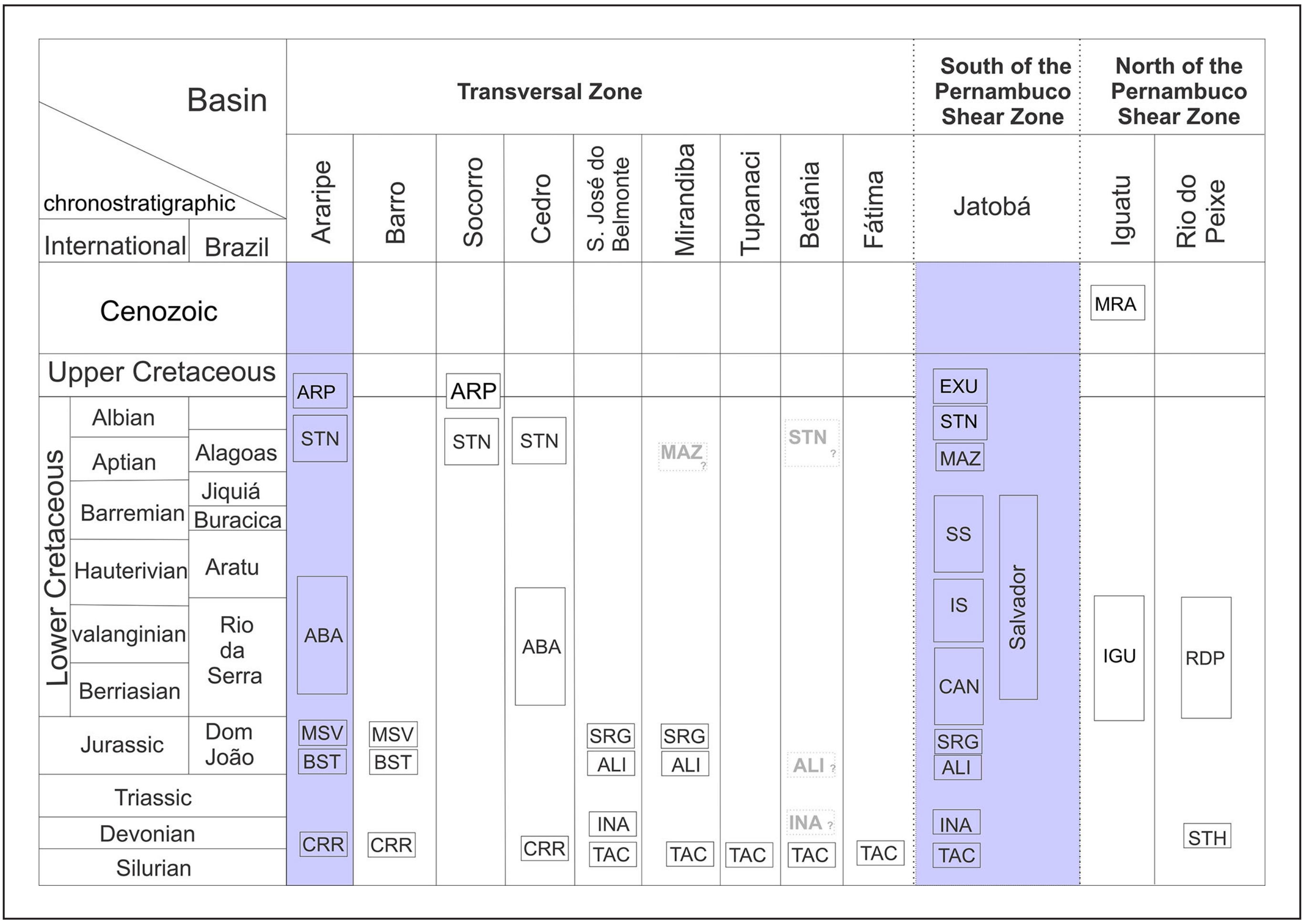

FIGURE 7. Lithostratigraphic diagram of the interior basins of the northeast in correlation with the Jatobá Basin. ABA: Abaiara Formation; ARP: Araripe Group; ALI: Aliança Formation; BST: Brejo Santo Formation; CRR: Cariri Formation; IS: Ilhas Group; MAZ: Marizal Formation; MSV: Missão Velha Formation; STN: Santana Group; SRG: Sergi Formation; SS: São Sebastião Formation; TAC: Tacaratu Formation; INA: Inajá Formation; CAN: Candeias Formation; STH: Santa Helena Group (adapted from Arai 2006).

from the tectonic stress of the rupture of the Gondwana supercontinent (Matos 1992; Ponte and Ponte Filho 1996). This configuration of faults built a system of grabens and horsts where the Mesozoic sequences are available, which for Matos (1992) sectioned the basin into two sub-basins: Feira Nova and Vale do Cariri.

Of the interior basins, the Araripe Basin is the one that presents the most complex geology. These sedimentary deposits were divided into five tectonic sequences: Paleozoic, Pre-Rift, Rift, Post-Rift I, and Post-Rift II (Assine 2007; Neumann and Assine 2015). There are several proposals for lithostratigraphic columns for the Araripe Basin, those of Assine (2007), and Neumann and Assine (2015) considered the most widespread. In this work, the proposal of Neumann and Assine (2015) was adopted.

The basal sequence is the Paleozoic substrate, composed of a single stratigraphic unit. The nomenclature of this unit was used in many works as Mauriti Formation, but Beurlen (1962) originally named it Cariri Formation. By the priority of the use of the term, Fambrini et al. (2020) proposed the maintenance of the Cariri Formation, as already suggested by Assine (2007). Immature sandstones, generally well lithified, with conglomerate layers and stratification typical of a braided river system (Assine 2007), characterize the Cariri Formation. However, its age is still uncertain, and inferred by stratigraphic correlations such as Upper Ordovician/Lower Devonian (Assine 2007) or Siluro-Devonian, by similarity with Tacaratu Formation and Serra Grande Group of the Parnaíba Basin (Braun 1966; Caputo and Crowell 1985). Recently, Cerri et al. (2022), through U-Pb dating of detrital zircon, suggested that the deposition of the Cariri Formation began after the Cambrian (~509-486 Ma) and probably extended through the Ordovician.

In the Pre-Rift phase, the Brejo Santo formations were deposited with shales, clays, and siltstones of lacustrine origin, dated by the occurrence of non-marine ostracods typical of the Dom João Stage (Braun 1966) and Missão Velha of Jurassic age marked by the presence of palynomorphs (Arai et al. 1989), consisting of deposits of meandering rivers (Assine 2007). The Missão Velha Formation was divided into two sequences, with the upper portion in the rift sequence (Scherer et al. 2014).

The Abaiara Formation represents the Rift phase, still of Jurassic age, composed of a significant lateral and faciological vertical variation of deposits of fluvio-lacustrine systems (Assine 2007). However, Costa et al. (2014) stated that facies associations are equivalent to a sizeable deltaic system. The Abaiara Formation is a unit that still needs to be better characterized, according to Assine (2007).

The Post-rift phase was divided into sequences II (Neumann and Assine 2015; Assine 2007; Santos Filho et al. 2019) and I. In Post-rift I, the sediments of the Santana Group were deposited during the Alagoas Stage (Aptian-Albian), constituted from the base to the top of the formations: Barbalha, Crato, Ipubi, and Romualdo (Assine et al. 2014; Neumann and Assine 2015; Fambrini et al. 2017).

The Alagoas Stage, Post Rift I phase, was divided into three depositional sequences (Assine et al. 2014). The first one belongs to the lower part of the Barbalha Formation, which presents a vertical succession of fluvial channel facies and closes with the deposition of lacustrine pellets. The intermediate sequence is fluvial cycles of the upper portion of the Barbalha Formation, which later gave place to shales and laminated limestone of lacustrine origin of the Crato Formation, and ends with the deposition of evaporites (gypsum/anhydrite) of the Ipubi Formation in conditions of extreme aridity. Finally, the upper sequence is a complete transgressive-regressive cycle of the Romualdo Formation, with shales rich in organic matter and marine ingression of upper Aptian age (Assine et al. 2014).

Lúcio et al. (2020) suggested an Aptian deposition for the Ipubi formation based on absolute ages of Re-Os (123 + 3, 5 Ma) in pirobetuminous shales. With these isotopic data, these authors proposed a Barremian age at the beginning of the Aptian for the Crato Formation. However, this proposal has inconsistency with the bio-stratigraphic data already consolidated in the literature (Coimbra and Freire 2021).

The paleogeographic development of the Alagoas stage is controversial, and it has proposals of marine ingression direction in the basins: Sergipe-Alagoas, Recôncavo-Tucano-Jatobá and from the Parnaíba (Assine 2007). Through U-Pb analysis in detrital zircons, Souza et al. (2022) elaborated a paleogeographic reconstruction model for the Mesozoic of the Araripe Basin. They claimed that the main route of connection between the basin and the opening of the South Atlantic Ocean during the Jurassic period until the middle of the Cretaceous was through the Potiguar Basin. This conclusion differs from previous models that postulate this maritime route from the northwest or the south.

In disagreement with the units of the Post-rift I tectono-sequence, the lithostratigraphic units of the Post-rift II tectono-sequence were deposited. Therefore, the Post-rift II phase is interpreted as a sag phase of the basin, composed of the Araripina and Exu formations, characterized by clayey sandstones of channel deposits and floodplain clays, interpreted as meandering rivers (Assine et al. 2014).

4.1.2 Barro, Socorro and Cedro Basins

The Barro, Socorro, and Cedro basins are correlated with the Araripe Basin (Figures 6 and 7). The Barro Basin is a small sedimentary area (15 km^2) located near the eastern edge of the Araripe Basin. As in other semi-grabens of the Lower Cretaceous of the Brazilian Northeast, the paleoenvironments were continental, marked by the deposition of the Brejo Santo and Missão Velha formations (Carvalho 2014). There are also records of the Paleozoic substrate of the Cariri Formation (Arai 2006).

The Socorro Basin is also a remnant of the Araripe Basin located south of the Araripe Basin with an area of approximately 300 km^2. Sedimentary records are from the Aptian-Albian sequence of the Post-rift Phase I of the Araripe Basin (Assine 1994) and Post-rift II with the Araripina Formation (Rocha et al. 2017) and Exu Formation (Rocha et al. 2017; Barros et al. 2017). The Cedro Basin is the largest of these, owning 690 km^2, with the most significant stretch axis according to the East-West direction (Carvalho 2014). The formations from this basin are Cariri, Abaiara, Barbalha, and Crato (Figure 8) (Araújo et al. 2017).

In the Cedro Basin, medium sandstones with conglomerate layers and cross-stratifications (Figure 8A) characterize the Cariri Formation. The Abaiara Formation consists of a succession of facies with stratified sandstones, conglomerates, siltstones, clays, and shales (Figure

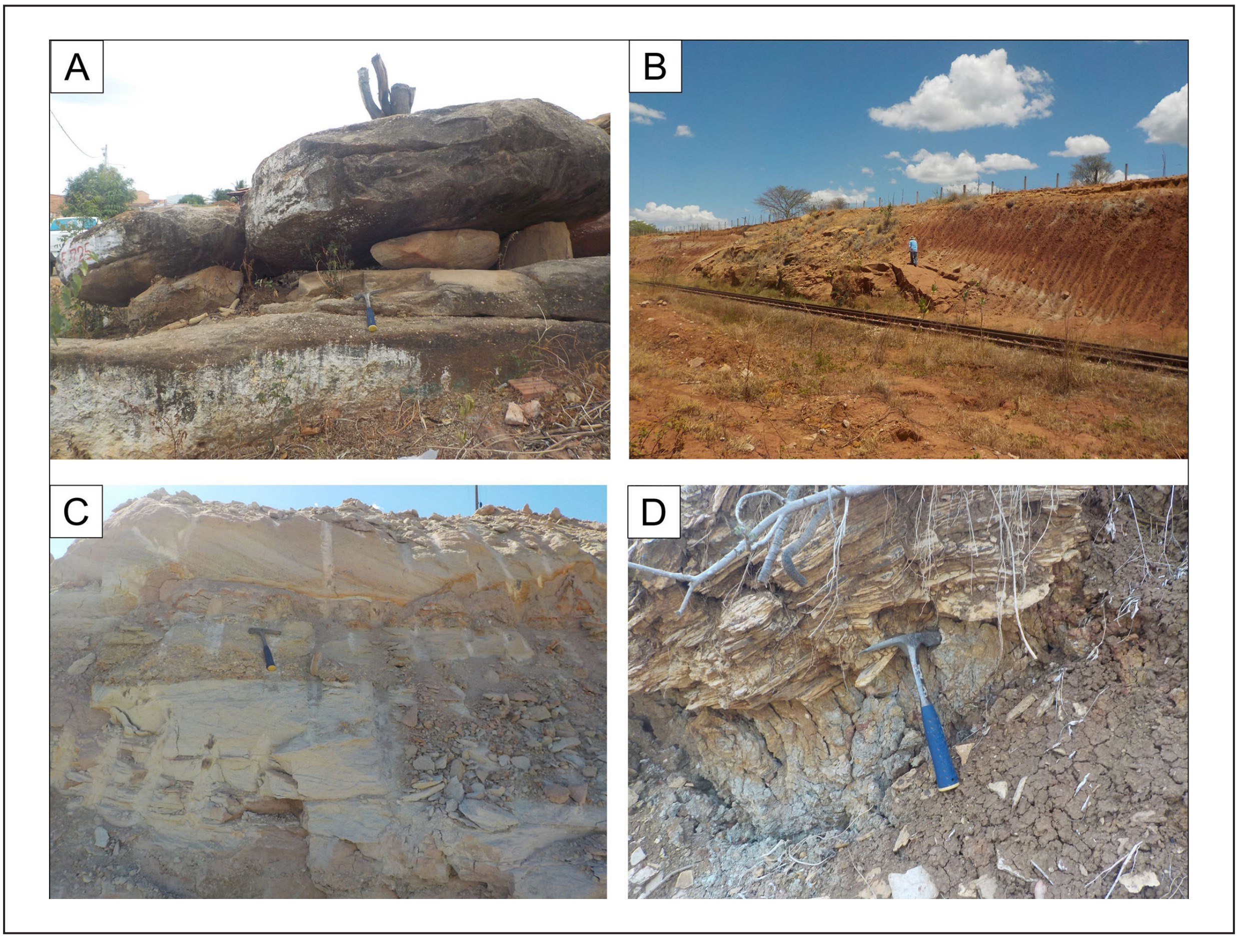

FIGURE 8. A) Cariri Formation sandstones. B) Outcrop overview of the Abaiara Formation. C) Intercalation of sandstones and siltstones of the Barbalha Formation. D) Calliferous shale contact with laminated limestone of Crato Formation.

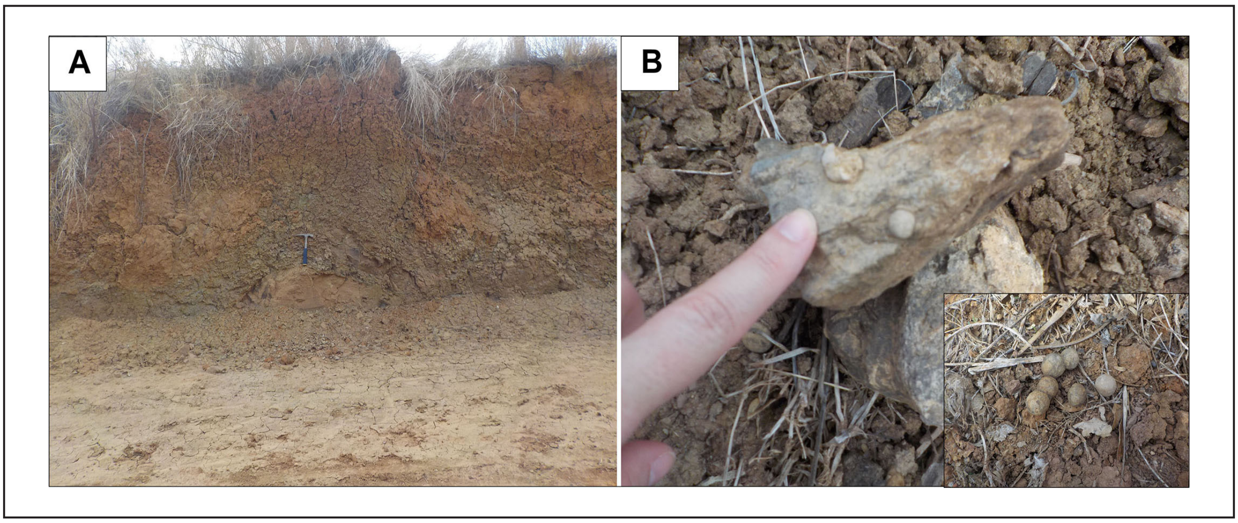

FIGURE 9. A) Outcrop overview. B) Calcarenites with concretions, detail for concretions, probable Romualdo Formation in the Cedro Basin.

8B). The Crato Formation is marked by the presence of laminated limestone (Figure 8D) and the deposits of the Barbalha Formation are characterized by the intercalation of sandstones and siltstones (Figure 8C). In the review of this work, outcrops possibly associated with the Romualdo Formation, consisting of greenish shales with calcareous concretions in calcarenites (Figure 9) were found.

4.1.3 São José do Belmonte, Mirandiba, Tupanaci, Betânia and Fátima Basins.

These basins are located in Pernambuco, and their lithostratigraphic units are correlated with the Jatobá Basin (Figures 6 and 7). Some of these basins had other nomenclatures that are currently outdated, such as the

Tupanaci Basin, formerly called Pajeú, and Carnaubeira da Penha. The Fátima Basin has already been named Afogados da Ingazeira.

The São José do Belmonte Basin has an area of approximately 610 km^2 and has an elongated shape in the east-west direction, limited by normal faults, the São José do Bonfim fault, to the north, the most important (Carvalho 2014). The lithotypes recognized in the São José do Belmonte Basin are from the Upper Jurassic, defined by the biostratigraphic content (Freitas et al. 2018). These authors correlated the units of this basin with the Cariri, Brejo Santo, and Missão Velha of the Araripe Basin; however, Costa et al. (2006) elaborated a geological map for the basin, and the units were correlated with the Jatobá Basin. There is no consensus regarding the nomenclature of the units, and due to the faciological similarity and stratigraphic positioning with the Mirandiba Basin, it is suggested here that both use the stratigraphic chart of the Jatobá Basin for correlation of the units. Thus, the Tacaratu, Aliança, and Sergi formations crops out in the São José do Belmonte Basin. Costa et al. (2006) indicate the occurrence of the Inajá Formation in the Northeastern portion of the basin, but Freitas et al. (2018) and in the field survey for the elaboration of this article, these records were not located.

Mirandiba Basin has dimensions of approximately 120 km^2. Located in the homonymous municipality of Pernambuco, it is preferably elongated in the ENE-WSW direction. The basin has well-defined lithostratigraphy, and the geometric and kinematic arrangement identified in the structures suggests that the basin has a semi-graben shape and was developed by a structural pull-apart system (Morais et al. 2021).

The most extensive sedimentary record of Mirandiba Basin is the Tacaratu Formation. Brasilino et al. (2020) also identified the basin's Inajá, Aliança, and Marizal formations. The Marizal Formation is a cause of controversy in the basin since Pereira et al. (2012) described the outcrops as the Sergi Formation, and Morais et al. (2021) interpreted them as probable sediments of the Salvador Formation. In this work, new outcrops were analyzed, and the same facies of the Sergi Formation of the São José do Belmonte Basin were identified in the Mirandiba Basin (Figure 10) and considered here as Sergi Formation. The edge fault of Mirandiba Basin was probably not active enough for the deposition of fault conglomerates similar to that of the Salvador Formation.

The Tupanaci, Betânia, and Fátima basins are half-grabens with little extension, and on the surface, there are only records of the Tacaratu Formation. In the Betânia Basin, the Inajá and Aliança formations were interpreted in sub-surface (Morais et al. 2021), in addition to a carbonate unit of probable Cretaceous age similar to the Albian-Aptian sequences of the Araripe Basin (Ferreira 2007).

4.2 Basins to the North of Patos Lineament

These basins are located in Paraiba and Ceará states, the largest being the Iguatu and Rio do Peixe basins (Figure 6). They correspond to half-grabens formed by the influence of pre-existing structures that reactivated the Lower Cretaceous faults. Unlike the basins in the Transversal Zone, the basins north of the Patos Lineament do not contain sedimentary records of the Afro-Brazilian Depression of the Dom João Stage (Arai 2006). The intense relief that developed along the lineament, suppressing Pre-rift Sequence in these areas (Ponte and Ponte Filho 1996), would have caused the geographical limitation of the stage.

Some attempts to correlate the Iguatu Basins and the Rio do Peixe Basin were made by some authors, but the information about these basins is scarce, and the attempt to correlate them is problematic (Silva 2018); thus, they have considered two distinct basins with independent lithostratigraphic units (Figure 5).

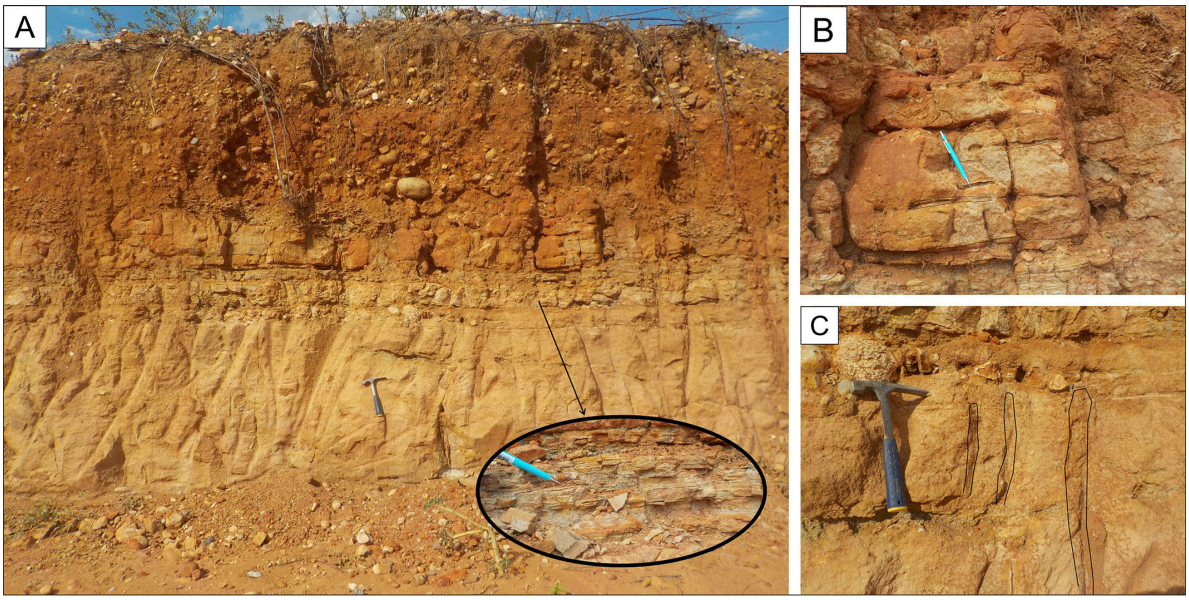

FIGURE 10. A) Overview of the outcrop of the Sergi Formation in Mirandiba Basin, in detail of the lean facies with siltstone. B) Facies with bioturbation, possibly *Skolithos* and *Thalassinoides*. C) Facies with bioturbation, probable *Thalassinoides* galleries.

4.2.1 Iguatu Basin

The Iguatu Basin is located in the middle of the Cariri -Potiguar trend in the inflection of the Orós Belt, the northern portion of the Borborema Province. The basin involves a series of half-grabens called sub-basins: Malhada Vermelha, Lima Campos, and Icó. These depressions clusters occupied an area of approximately 1135 km^2 and were developed in a regime similar to pure shear in extensional systems during the Lower Cretaceous through reactivations of pre-existing structures (Silva 2018).

The structural evolution of the Iguatu Basin suggests a scenario in which the deposition in all half-grabens occurred together with a unique and gradual tectonic event with similar source areas, in which the stacking of depositional environments simultaneously occurs to the development phases of the rift (Silva 2018). The basin units date from the Cretaceous and are covered by Neogene sediments. The age attributed to the sedimentary records of these sub-basins is from the Lower Cretaceous, based on palynomorphs (Lima 1990), conchostraca, and ostracods (Ponte Filho et al. 1990).

The Iguatu Basin is, from the base to the top, consisting of the formations: 1) Icó, composed of sandstones and conglomerates of a river environment; 2) Malhada Vermelha, characterized by the alternation of sandstones, siltstones, and shales of flood plain environments; 3) Lima Campos, formed by fluvial-eolian sandstones; 4) Orós, individualized by flood plain and lacustrine fine sediments, with non-marine ostracods of Hauterivian-Aptian age (Silva 2018; Santos Filho 2020). Finally, these units are coated by the Neogene deposits of the Moura Formation (Silva 2018). The genesis of the Iguatu Basin is widely discussed about the associations between the sub-basins and possible remnants of a single previous Mesozoic basin, which would have suffered intense erosive action, elevations in the basement, and strong influence of transcurrent faults (Silva 2018).

4.2.2 Rio do Peixe Basin

The Rio do Peixe Basin also corresponds to a group of sub-basins shaped half-grabens associated with Lower Cretaceous rifting, called Brejo das Freiras-Triunfo, Sousa, and Pombal, limited by the Portalegre shear zones (direction NE-SW) and Malta (direction E-W) (Matos 1992). The sedimentary filling of the Rio do Peixe Basin comprises three Cretaceous units belonging to the Rio do Peixe Group (Córdoba et al. 2008), namely: Antenor Navarro Formation, Sousa Formation, and Rio Piranhas Formation.

The presence of conglomerates and sandstones (Figure 11C), representing alluvial fans and braided river systems (Córdoba et al. 2008), characterize the Antenor Navarro Formation. On the other hand, the Sousa Formation (Figure 11A and Figure 11B) is composed predominantly of shales and siltstones interspersed with carbonatic layers of shallow lake environment and terminal lobes of distributary river systems (Lima Filho 1991; Córdoba et al. 2008). In the shales, there is a record of oil, which according

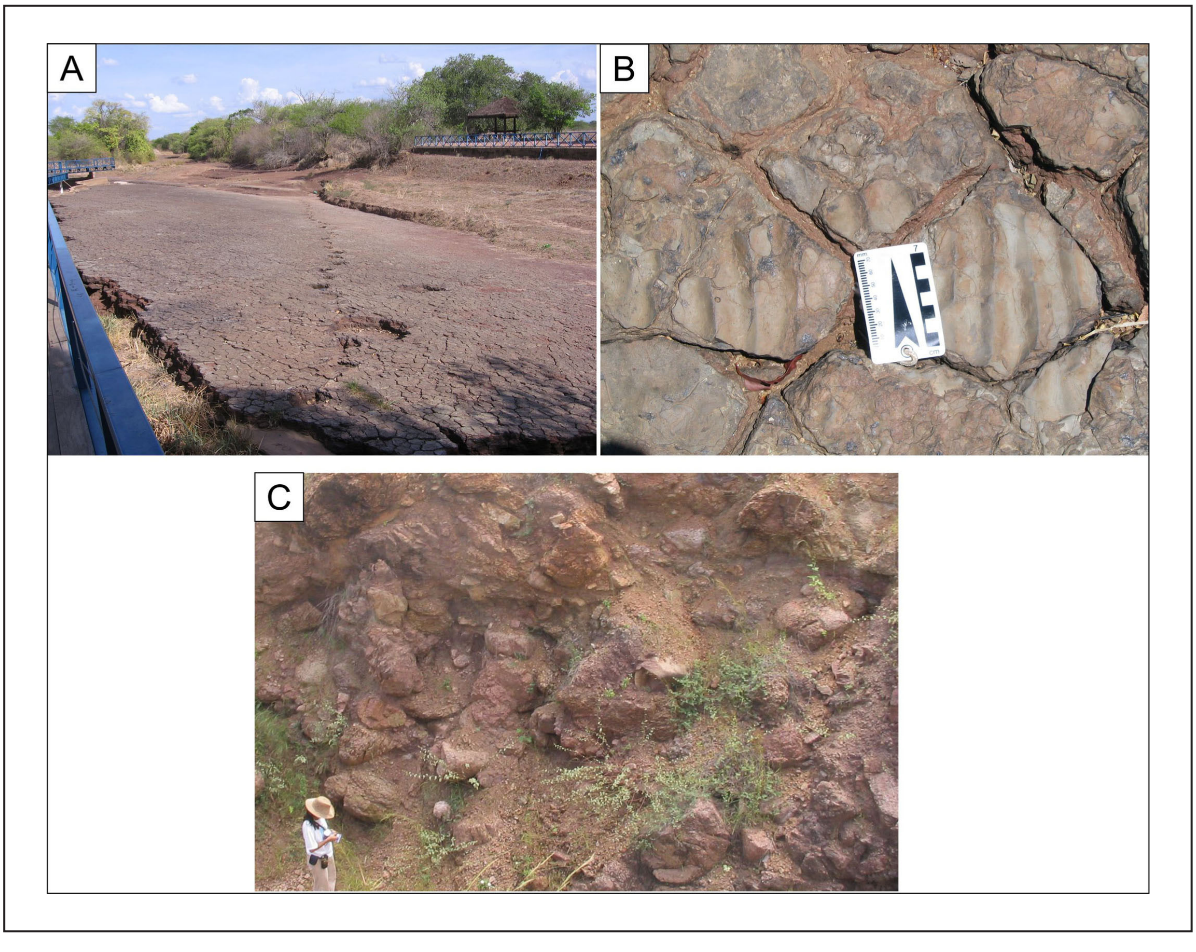

FIGURE 11. A) Dinosaur footprints of the Sousa Formation. B) Detail of the siltstones of the Sousa Formation with dissection slits. C) Conglomerates of the Antenor Navarro Formation.

to Mendonça Filho et al. (2006), has good quality geochemical characteristics (Paraffinic) and is similar to the oil of Pendência Formation in the Potiguar Basin. The Piranhas River Formation, in turn, comprises acceptable to thick sandstones interspersed in pellets associated with a braided river system. Besides, it exhibits facies of alluvial fans with thick sandstones and conglomerates (Córdoba et al. 2008).

Based on palynological analysis of samples from wells, Roesner et al. (2011) identified an older siliciclastic sedimentary section below the Rio do Peixe Group, interpreted as the beginning of the Devonian. Silva et al. (2014) formalized this sequence in two lithostratigraphic units: the Pilões and Triunfo formations together form the Santa Helena Group. This group outcrops at the NW border of Sousa half-graben and is identified in the subsurface by wells and seismic data. The Pilões Formation comprises mudstones and sandstones, interpreted as deltaic to fluvio-deltaic systems. Arkosic sandstones and conglomerates interspersed with mudstones and fine sandstones, related to braided fluvial-deltaic deposits, characterize the overlying Triunfo Formation. On the surface, pyroclastic rocks (ignimbrites and breccias) and fragments of tufts were also described (Silva et al. 2014). Clasts of these volcanic rocks can be found in the Pilões Formation, suggesting that the pyroclastic event is contemporary to the sedimentation of the Lower Devonian or even older (Silva et al. 2014).

5. Divergent margin basins

The Brazilian marginal basins result from the diachronic process of the continental rift and the opening of the South Atlantic Ocean. During the rupture of the African and South American plates, considering the nature and orientation of the regional tension fields during the continental drift phase, three distinct domains can be recognized along the margin: 1) a dominantly distensive region between southern Argentina and the extreme northeast of the Brazilian coast; 2) a segment of transform nature, corresponding to the Equatorial Atlantic; 3) and the region north of Foz do Amazonas, where, again, predominantly extensional processes acted (Milani and Thomaz Filho 2000).

Thus, while a specific segment was already in the spreading of the sea floor phase, others were still in the rift phase, in different degrees of crust extension (Bueno 2004). Matos et al. (2021) reconstructed the South Atlantic Cretaceous rift System into six structural segments, grouped into the three major domains (Figure 2): Dextral Equatorial, Sinistral Southern separated by Orthogonal Branch.

Borborema Province recorded these three ramifications of the rift, which led to the development of the marginal basins of the Equatorial Atlantic and those of the eastern margin. The Potiguar and Ceará basins are inserted in the dextral domain, the Sergipe and Alagoas basins in the sinistral domain, and the Pernambuco and Paraíba basins in the orthogonal zone. The sedimentary filling of the onshore portion of these basins will be described below according to their inserted domain (Figure 12).

5.1 Basins of the equatorial margin

The Brazilian equatorial margin developed as a transform continental margin, with its geological evolution dominated by oblique distension (transtension) and pure transcurrent movements, both of dextral character (Zalan 2012). The Brazilian equatorial margin is characterized by a regular alternation of E-W and NW-SE direction, with coaxial and non-coaxial deformation combinations, reflecting transpressive and transtensive environments (Zalan 2012; Matos et al. 2021). The diachronic deformation occurred due to the degree of the obliquity of each basin at a specific moment, correlated with the tectonic fabric and the rheological nature of the pre-Cambrian basement (Zalan 2012; Matos 2000).

The development of the equatorial branch of the rift occurred by dextral distensive events during the Mesozoic with different tectonic evolution between South America and Africa (Soares Júnior et al. 2011; Matos et al. 2021). This process began approximately 126-123 Ma ago, during stage III of the Atlantic opening process, subdivided into two segments based on the magnitude of displacement of the main fracture zones (Matos et al. 2021). The basins of the northeast (offshore Ceará and Potiguar) are inserted in segment 2, which is dominated by transcurrent structures with protracted displacement.

5.1.1 The Onshore Ceará Basin

The Ceará Basin is located on the continental platform of the Brazilian equatorial margin, covering an area of approximately 34.000 km^2. Its limits are Potiguar Basin by the Alto de Fortaleza to the southeast, Barreirinhas Basin by the Alto de Tutóia to the west. Its southern boundary is given by the crystalline basement, near the coastline of Ceará. To the north, it is limited by the southern branching of the Romanche Trench Zone. Due to distinct tectonic characteristics, the Ceará Basin has four sub-basins in the offshore portion: Piauí-Camocim, Acaraú, Icaraí, and Mundaú, from west to east, respectively (Morais Neto et al. 2003; Condé et al. 2007).

In the onshore area of the basin, there are no records of this tectonic distinction. Also, sedimentary rocks of the Mesozoic do not outcrop (Figure 12). In the onshore area of Alto de Fortaleza, phonolytic intrusions are referred to in the literature as Mecejana Magmatism, dating from 34 to 26 Ma; these rocks are contemporary at the pulse of the Macau Magmatism of the Potiguar Basin, in the Neo-Oligocene (Morais Neto et al. 2003). The sediments that comprise the onshore portion are the quaternary clastic deposits of the Barreiras Formation, which rest on the crystalline basement and interdigitate with the environment sandstones of coastal fans of the Tibau Formation (Paleogene-Quaternary) in the proximal portions of the basin (Condé et al. 2007).

5.1.2 The Onshore Potiguar Basin

The Potiguar Basin is the connecting segment between the Equatorial Margin and the East Margin and occupies an area of 27,000 km^2 in the offshore portion and 22,000 km2 in the land (Milani et al. 2000). Geologically, it is limited to the east with the Pernambuco-Paraíba Basin by the Alto de Touros, to the northwest with the Ceará Basin by the Alto de Fortaleza. Its origin and evolution are part of the trend Cariri-Potiguar, which consists of an axis that comprises the rifts Basins from Araripe to Potiguar (Matos 1992). This segment was named by Matos et al. (2021) as Failed Rift Zone and began to develop in stage II (140-126 Ma) of the rifting process.

The sedimentary filling of the basin is related to the different phases of the tectonic evolution of the rift. Pessoa Neto et al. (2007) described three of these phases and related them to the mega sequences Rift, Post-rift, and Drift. The Pre-rift sequence is absent in the Potiguar Basin and the interior basins located north of the Patos lineament (Arai 2006). The land portion of the Potiguar Basin includes a non-outcrop confined graben, which houses lake sediments of the Neocomian-age rift phase, covered by a package of rocks from Aptian to Campanian age (Milani et al. 2000). In the onshore basin, the rocks of the Açu, Jandaíra, Pendência, Tibau and Barreiras formations (Figure 12) outcrop exclusively.

The Rift Megasequence, in the onshore area of the basin, is divided into II, represented by the fluvio-lacustrine deposits of the Pendência formation (Pessoa Neto et al. 2007) and I. On the other hand, the Post-rift Super sequence, deposited in the subsurface, represented by the Alagamar Formation of the Alagoas stage, is characterized by a fluvio-deltaic sequence, with the first records of marine ingression (Pessoa Neto et al. 2007). Still, during the Early Cretaceous, the Potiguar Basin was subjected to compressive efforts of E-W and N-S-N direction, which caused the post-rift sedimentation to be stopped in the on-shore portion of the basin, and continued the rift in the submerged portion with the deposition of a proto-oceanic sequence (Françolin and Szatmari 1987).

The Drift Megasequence corresponds to the phase of thermal evolution consisting of sets of transgressive

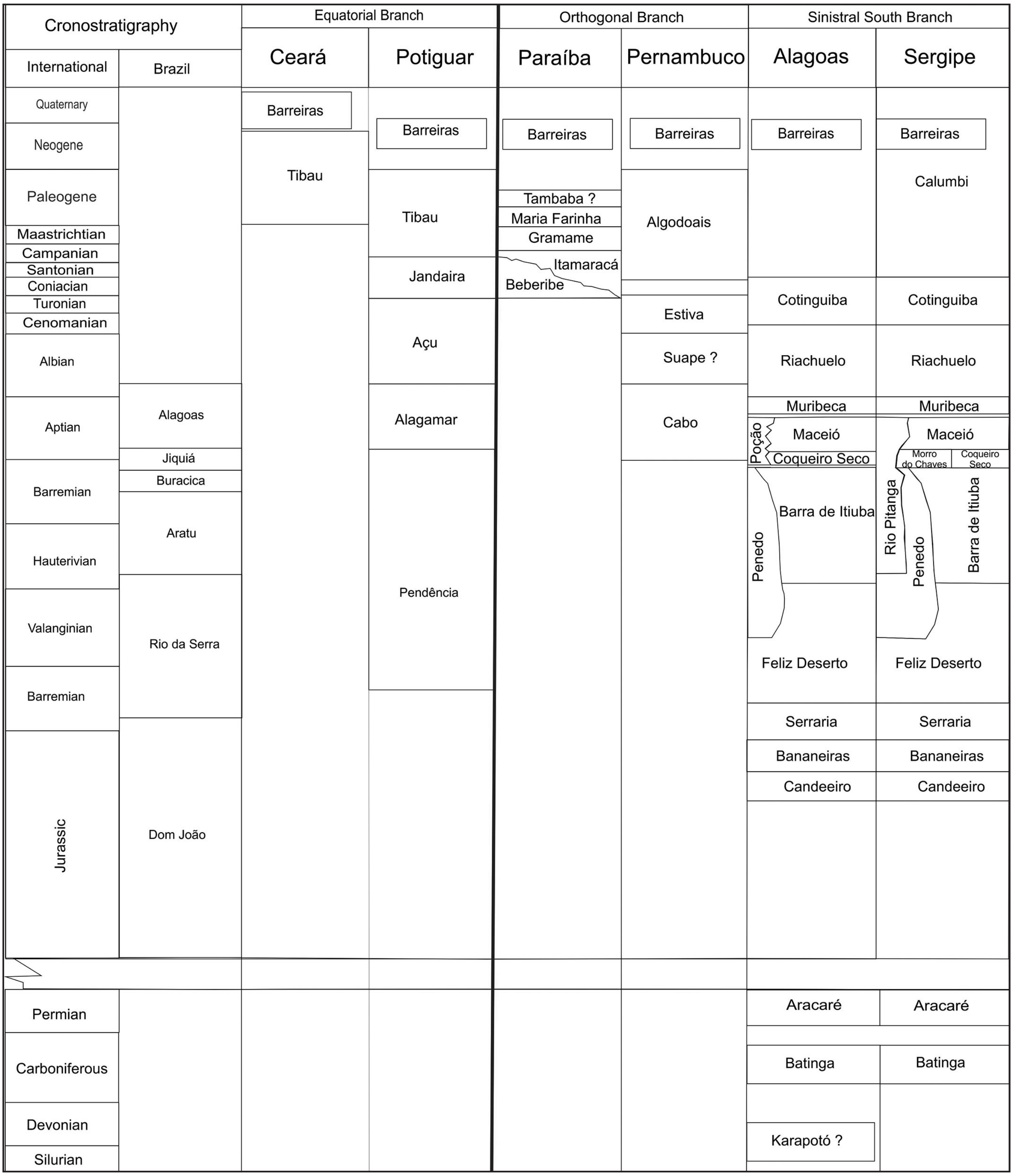

FIGURE 12. Stratigraphic correlation of the units in the emergent portions of the marginal basins.

and regressive marine sequences deposited between the Albian and the recent (Pessoa Neto et al. 2007). The transgression sequence (Early Albian – Early Campanian) is represented by the deposits of alluvial, fluvial, and estuarine fans associated with the Açu formation, of a minimum age of 120 Ma, obtained by the ^{40}Ar-^{39}Ar method, very close to the biostratigraphic age obtained (Maraschin et al. 2010). Subsequently, a new and extensive carbonatic platform dominated by tides (of the Jandaíra depositional environment) was implemented, deposited between the Turonian and the Lower Campanian.

In turn, the regressive marine sequence (Holocene-Campanian) began to be deposited after an erosive event of great magnitude during the Neo Campanian, which was related to a thermal uplifting of the Borborema Province, linked to post-distensional lithospheric processes in conjunction with crustal magmatic underplating (Cremonini et al. 1996; Pessoa Neto et al. 2007). In lithostratigraphic terms, all sedimentary deposits during the Drift stage were collected in the Agulha Group. The onshore area is represented by siliciclastic sedimentation from continental systems defining the Tibau Formation of the Holocene-Campanian (Pessoa Neto et al. 2007). Finally, there is the Barreiras Formation, a relatively newer unit that encompasses even more continuous deposits than the Tibau Formation, which interdigitates laterally (Araripe and Feijó 1994; Pessoa Neto et al. 2007).

Three magmatic events are highlighted in the basin filling the onshore and submerged areas: Rio Ceará-Mirim, Serra do Cuó, and Macau. The first is associated with rifting, occurring as a diabase dike swarm with a trend ranging from E-W to NE-SW (Matos 1992; Pessoa Neto et al. 2007). Dating $^{40}Ar/^{39}Ar$ points to at least one pulse at 132.2 ± 1 Ma (Souza et al. 2003); however, Araújo et al. (2001) document ages ranging from 140 to 110 Ma. The magmatic event Serra do Cuó, in turn, occurred as flows or sills of olive-basalt with age $^{40}Ar/^{39}Ar$ of 93.1 ± 0.8 Ma (Souza et al. 2003). Whereas the Macau magmatism is represented by a series of bare bodies, which in the Potiguar Basin occur mainly as flows interspersed to deposits of the regressive Drift sequence, having ages ranging from 70-65 Ma to 9-6 Ma with peaks between 48.9 ± 2.9 Ma and 31.4 ± 1.5 Ma. Its genesis may be related to the passage of the equatorial margin over the Fernando de Noronha Hotspot or the placement of magmas in relief zones from intraplate tectonic adjustments (Araripe and Feijó 1994; Souza et al. 2003; Pessoa Neto et al. 2007). Souza et al. (2007) suggested applying the term Macau Formation only to outcrops in the homonymous region, with a well-defined age at the age ranges from 30.5 ± 0.5 to 20.5 ± 0.3 Ma.

Still, in the context of the Natal Platform, there is a transition area between the Paraíba Basin and the Potiguar Basin, known as the Canguaretama Sub-basin, limited between the fault of Mamanguape, in Paraíba and Cacerengo in Rio Grande do Norte (Mabesoone and Alheiros 1988; Barbosa et al. 2007). This area constitutes a more recent extension of the Potiguar Basin and is formed by undivided carbonate deposits correlated in time with the carbonate succession of the Paraíba Basin (Barbosa et al. 2007). However, Lima and Dantas (2016) named these sediments Tamatanduba Carbonate, and the age obtained by identifying fossil mollusks points to the Campanian-Maastrichtian period (Hessel and Barbosa 2005).

5.2 Basins of the east margin

The distensive segment includes the basins in the far northeast of the Brazilian margin, in the continental deflection near the Potiguar Basin to the southern boundary of the Pelotas Basin (Milani et al. 2007). The beginning of the rift in the southern portion of South America occurred in the Neo-Jurassic. However, the structural framework of the Pre-Cambrian, in addition to Paleozoic and Triassic structures, played an essential role during Mesozoic rifting (Milani et al. 2000). In this segment of the margin, the structural framework is defined by normal faults oriented preferably in a parallel direction to the coast, segmented locally by transfer zones (Milani et al. 2007).

The rifting process developed diachronically along the eastern Brazilian margin, and therefore the basins share some common characteristics, such as the classic evolutionary tectono-sedimentary stages that include the rift, the transitional phase, and the open marine (Asmus and Ponte 1973). Matos et al. (2021) divided the eastern Brazilian margin between two distinct domains: the Orthogonal Rift branch and the Sinistral Southern Rift branch. Among the basins of this context, which are inserted in the Borborema Province, are the Pernambuco and Paraiba basins, which are in the orthogonal domain, and Sergipe and Alagoas in the South Sinistral domain (Figure 12).

5.2.1 Orthogonal domain of the Rift

The orthogonal branching is located in the Transversal Zone of BP, between the Patos and Pernambuco lineaments, and separates the Dextral Equatorial from the Sinistral South (Matos et al. 2021). A lithotectonic variety characterizes this area at the crystalline basement and with shear zones of regional scale, interpreted as possible crustal limits (Brito Neves et al. 2016). These structural alignments of the east-west direction of the Brazilian Northeast, like the Pernambuco and Patos lineaments, play a fundamental role in the tectonic control of the basins formed in the Mesozoic (Cordani et al. 2009; Chang et al. 1992). The Orthogonal Rift Branch coincides with the Pernambuco-Paraíba/Benue-Rio Del Rey-Douala rift zone and consists of two combined basins: Paraíba/Baixo Benue-Rio Del Rey Basin and Pernambuco/ Duala Basin (Matos et al. 2021).

This area of the Orthogonal Domain between the cities of Recife and João Pessoa behaved as the last link between the African and South American continents (Rand and Mabesoone 1982). Lima Filho (1998) defined the Pernambuco and Paraíba basins as two sedimentary bands with singular depositional histories limited by the Pernambuco Lineament.

In stage IV (123-117 MA) of the South Atlantic rifting process, the branching of the rift reaches the Pernambuco Lineament, and the orthogonal zone still holds the complete opening of the Atlantic. Only in stage IVb (117-113 Ma) did the opening of the rift spread to the north, toward the Alto da Paraiba and Touros, providing the rupture of the Paraíba Basin (Matos et al. 2021).

5.2.1.1 The Onshore Paraiba Basin

The Paraiba Basin is located on the coastal belt of the Northeast of Brazil, covering the Paraiba and the northern coast of Pernambuco states. The Alto de Mamanguape limits the basin to the north and Pernambuco Lineament to the south (Barbosa 2004). The structuring of the Paraíba Basin occurred through a crustal stretch followed by subsidence, which generated a ramp of faulted blocks of smooth gradient, with E-W direction segments perpendicular to the coastline, without edge faults, but with numerous NE direction faults. As a result, the sedimentary wedge would have evolved to a structured homoclinal, with the formation of uneven blocks that suffered differentiated filling, which resulted in the formation of the Olinda, Alhandra, and Miriri sub-basins (Lima Filho 1998; Mabesoone and Alheiros 1988; Barbosa 2004).

The stratigraphy of the Paraíba Basin is relatively simple, with three units of the Upper Cretaceous. Until the Albian, the structural high that surrounded the Paraiba Basin and the Natal Platform remained high, resulting in the absence of deposits of this age in the coastal belt of these basins (Matos et al. 2021).

The sedimentary filling of the Paraíba Basin began, possibly, in the Santonian, with the deposition of the Beberibe Formation (Figure 13A) (Beurlen 1967). Souza (2006) characterized this formation as clastic sediments deposited in a system of alluvial fans with braided fluvial channels of the Campanian-Santonian age. From Campanian to the Maastrichtian, the Itamaracá Formation was deposition (Figure 13C) with the deposits of coastal sandstone to shallow marines in a transgress system tract, containing a phosphatic layer representing the maximum flood surface (Lima Filho and Souza 2001; Moura 2007). Finally, in the Upper Maastrichtian, a system of carbonatic ramps was developed in a high sea system tract represented by the Gramame Formation (Figure 13B) (Lima and Koutsoukos 2002).

In the Lower Paleogene, a marine regression was recorded in the basin, marked by the deposition of carbonate rocks of the Maria Farinha Formation (Figure 13D) (Barbosa et al. 2007). Correia Filho et al. (2015) proposed that the reef limestone of the Eocene, dated by Almeida (2000) and which was previously addressed as part of the Maria Farinha Formation, is part of a new formation called Tambaba (Figure 13). Finally, the Paraíba Basin is covered by the Cenozoic Units of the Barreiras Group and post-Barreiras Deposits.

5.2.1.2 The Onshore Pernambuco Basin

The Pernambuco Basin is limited to the south with the Alagoas sub-basin by the Alto de Maragogi and the north by the Pernambuco Lineament with the Paraíba Basin, covering a belt with 900 km² (Lima Filho 1998). Its evolution is associated with the final events of the Gondwana continent rupture during the Aptian-Albian (125-100.5 Ma; Matos 1999).

The sedimentation in the basin began with a rift phase corresponding to the basal unit, Cabo Formation, deposited in an active tectonic context and composed of alluvial fans and lacustrine systems subdivided into three facies associations. Maia (2012) restricts the Cabo Formation to proximal facies

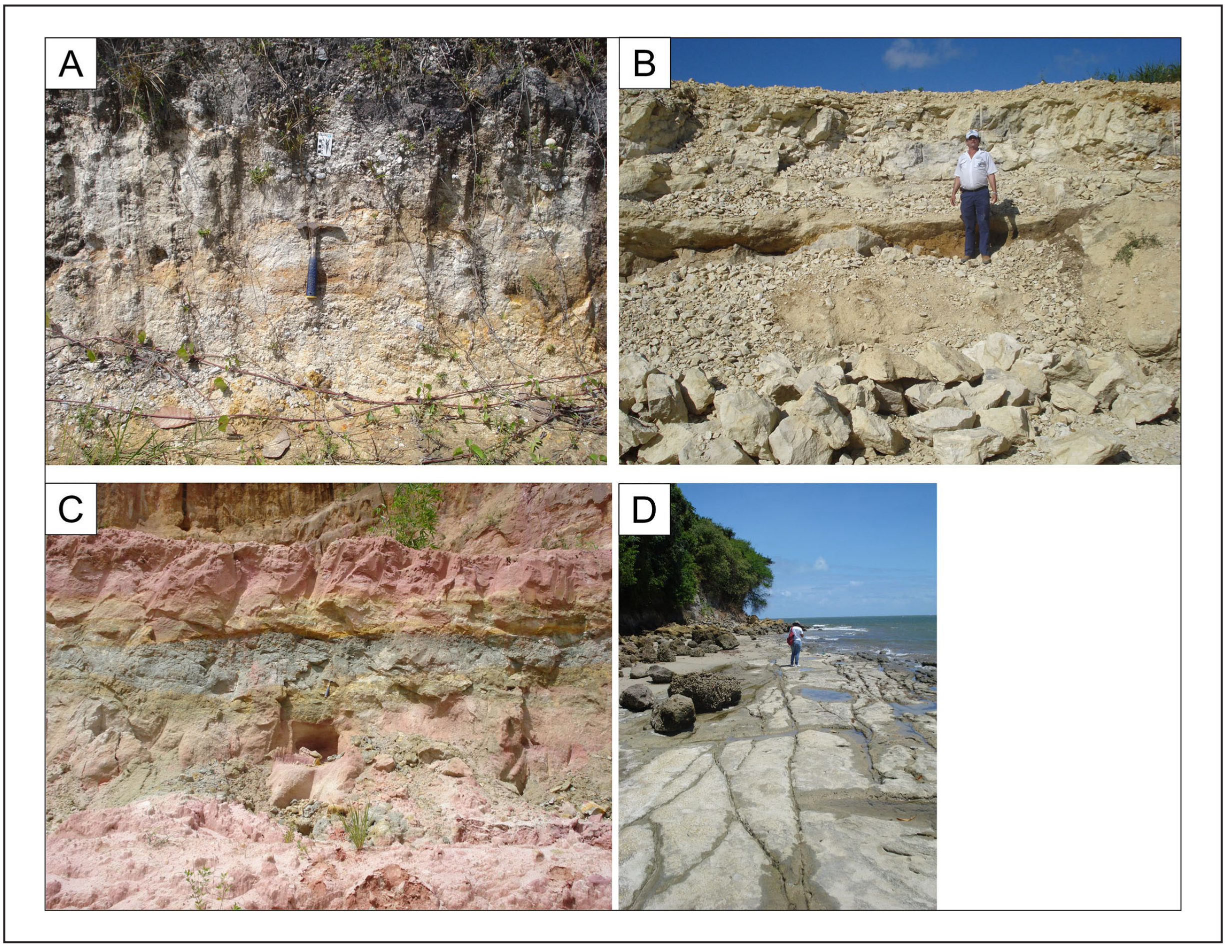

FIGURE 13. A) Sandstones and conglomerates of Beberibe Formation. B) Limestones of Gramame Formation. C) Facies of the Itamaracá Formation. D) Outcrop overview of the Maria Farinha/Tambaba reef limestone formation.

characterized by edge conglomerates, and the other facies are part of the Suape Formation, the intermediate being composed of sandstones and clays deposited in the interlaced fluvial environment and the distal one already representing the first post-rift unit with sediments of marine influence, interpreted as Paraíso Formation (Upper Albian). At the same time as the deposition of the Rift phase of the Pernambuco Basin, there is the basic to acid magmatism of the Cretaceous Age (102-97 Ma), associated with the Ipojuca Magmatic Suite (Nascimento et al. 2004).

The Estiva Formation was defined by Lima Filho (1998) and comprised limestone rocks and shales. The deposition of these sediments is associated with a coastal carbon system of shallow water and high energy, containing a palynological association with the age of the Lower Cenomanian-Turonian (Córdoba et al. 2007), followed by the deposition of volcanogenic sediments of the Algodoais Formation. Córdoba et al. (2007) suggest a possibly Paleogene age due to the occurrence of detrital apatite aged 78.0 ± 6 Ma. However, because the Algodoais Formation is positioned over the Estiva Formation and underneath the Barreiras Formation, Lima Filho (1998) considers the Algodoais Formation a post-Turonian age range reaching, possibly, the Neogene. Finally, the deposition of sandstones and clays related to the Barreiras Group occurs beyond the terrigenous deposits of the Post-Barreiras.

5.2.2 Branch of the Sinistral South Rift

The Brazilian continental margin rift system (mainly in the segment between Sergipe-Alagoas and Santos) was generated because of extensional processes during the Neo Jurassic until the Early Cretaceous (Szatmari et al. 1984; Chang et al. 1992). This process generated a long NNE direction valley called the Rift System of Eastern Brazil (Chang et al. 1992). For Matos et al. (2021), this rift sector is limited by the Kribi fault in Africa until the Florianopólis Failure, containing a sinistral component.

In Borborema Province, this domain is represented by the Sergipe-Alagoas Basin, which began to be formed in stage 1 of the rifting process (145-140 Ma) (Matos et al. 2021). Of the existing basins of the eastern margin, Sergipe-Alagoas is the one that records the complete stratigraphic succession, including remnants of Paleozoic sedimentation (Milani et al. 2000).

5.2.2.1 Onshore Sergipe-Alagoas Basin

The Sergipe–Alagoas Basin is located on the Northeastern continental margin of Brazil, covering the states of the same name and comprises an area of approximately 13,000 km² in the land (Milani and Araújo 2003). This basin has always been approached in several works as a single basin, limited to the northeast with the Pernambuco Basin, in the Alto de Maragogi, and to the southwest with the Jacuípe Basin, with the Vaza Barris fault system (Lana 1985; Feijó 1994). The Alto de Japoatã-Penedo separates the Sergipe sub-basin from the Alagoas sub-basin; it only has expression in the onshore basin and shallow waters and does not characterize a division of basins. In these two areas, there are differences in structural and stratigraphic character, implying the elaboration of two stratigraphic cards: one for the Sergipe Sub-basin and the other for the Alagoas Sub-basin (Campos Neto et al. 2007).

The filling of the Sergipe-Alagoas Basin stands out in the geological scenario because it presents the following five evolutionary stages, the last four common to most coastal basins of the eastern margin of Brazil: Syneclyses, Pre-rift, Rift, Post-Rift or Transitional, and Drift (Campos Neto et al. 2007). The basin has its sedimentary record started during the Paleozoic, under intracratonic syneclises conditions (Campos Neto et al. 2007), possibly with connections with other large Paleozoic syneclyses preserved in the interior of Brazil, such as the Paraná, Parnaíba e Amazonas/Solimões (Souza-Lima et al. 2014; Milani et al. 2007). The oldest records of this phase are the siliciclastic sediments of fluvial deposits of the braided type of the Karapotó Formation, which were interpreted as Silurian/Devonian by stratigraphic correlation with Tucano Norte and Jatobá basins (Souza-Lima et al. 2014).

In the Carboniferous period, the Western Gondwana supercontinent went through a period of glaciation, which was reflected in the glacial deposits in the Sergipe-Alagoas Basin represented by the sediments of the Batinga Formation (Figure 14A) of carboniferous age (Campos Neto et al. 2007). Finally, the last unit of the Paleozoic sequence is represented by the Aracaré Formation (Figure 14B), dating from the Permian period and characterized by desert and coastal deposits with deltaic influences (Schaller 1969).

The Pre-rift Super sequence begins in the Neo Jurassic and goes to the Early Cretaceous, with strictly continental characteristics with the first records of the Bananeiras and Candeeiro formations (Schaller 1969), deposited in the so-called Afro-Brazilian Depression (Ponte 1971), during the Juro-Cretaceous stability of the basin (Campos Neto et al. 2007). The Bananeiras formation is composed of pellets with sandstones and intercalated carbonates deposited in the lacustrine environment of the Upper Jurassic (Feijo 1994). The Candeeiro Formation consists of river sandstones, whose age is also attributed to the Upper Jurassic in correlation to the adjacent formations (Feijó 1994; Schaller 1969). The Bananeiras-Candeeiro system was subsequently overlapped by the braided /eolian fluvial system of the Serraria Formation sandstones (Figure 14C), dated by non-marine ostracod of the Upper Jurassic/Lower Cretaceous (Feijó 1994).

The top of the Serraria Formation marks the beginning of the rift phase of the basin (Souza-Lima and Borba 2008). The drowning of the Serraria system gave rise to the lake Feliz Formation, the first formation of this phase (Campos Neto et al. 2007). A depositional hiatus marks the top of the formation during the passage from Valanginian to Hauterivian, characterized by the absence of two ostracod biozones called Pré-Aratu Unconformity, interlayered with sandstones that limit with the Barra de Itiuba Formation (Galm and Santos 1994; Campos Neto et al. 2007). The Barra de Itiuba Formation, with its deltaic facies (Schaller 1969), represents the Neocomian. Concomitant to the deposition of the Feliz Deserto and Barra de Itiúba formations, in the most proximal portions of the river system that fed this lake, the Penedo Formation was deposited in a river system braided with eolian reworking (Feijó 1994).

In the first tectonic pulse in the stages Aratu, Buracica, and Jiquiá, the basin-edge conglomerates were deposited in the Sergipe Sub-Basin, of the Rio Pitanga Formation, which varies laterally for the Penedo Formation and the coquina carbonates and shales of the Morro do Chaves Formation (Campos Neto et al. 2007). From Neojiquiá to Eoalagoas the conglomerates of the Poção Formation (Figure 14D) on the edge of the Alagoas Sub-basis were deposited, and a fluvio-deltaic to a lacustrine system of Coqueiro Seco Formation, of upper Jiquiá age (Campos Neto et al. 2007). On the lower Alagoas stage was the deposition of sandstones, shales, evaporites, and calcilutite of the Maceió Formation, as well as lithofacies of gravitational flux, turbidites of the lacustrine system, and sabkha type (Arienti 1996; Campos Neto et al. 2007).

The Post-rift Super sequence, characterized by strictly marine deposition along the Atlantic-South rift, is represented in the basin by the upper Alagoas age Muribeca Formation. This formation was deposited in a transitional environment, evolving into a restricted marine system, evidenced mainly by the significant occurrence of evaporites (Feijó 1994; Campos-Neto et al. 2007).

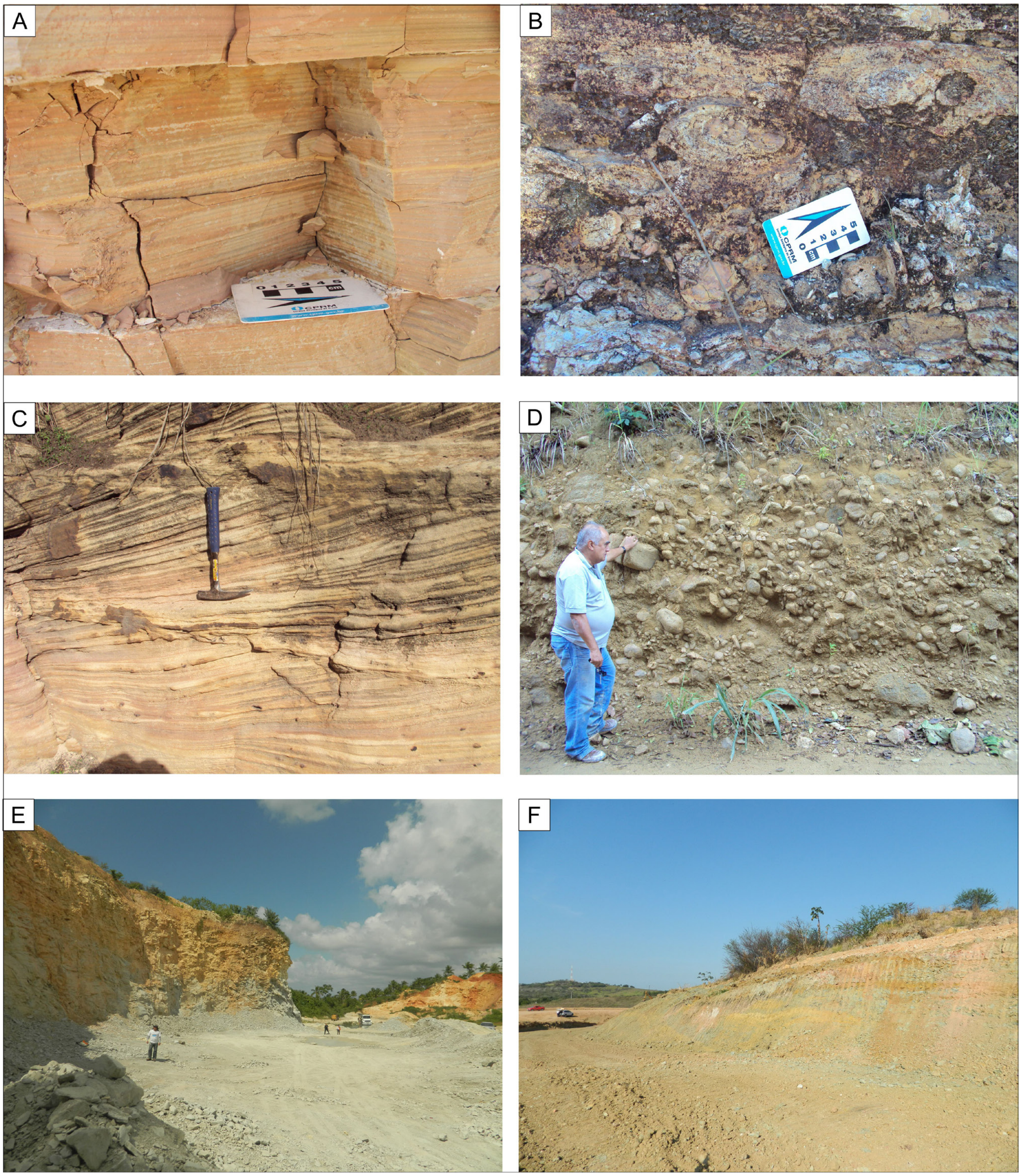

FIGURE 14. A) Varves of the Boacica Member of the Batinga Formation. B) Silicified sandstone with flint nodules of the Aracaré Formation. C) Cross stratification sets in sandstones of the Serraria Formation. D) Clasts supported polymictic conglomerate of Poção Formation. E) Outcrop overview of Cotinguiba Formation limestones. F) Outcrop overview of Calumbi Formation.

The Drift Super sequence is individualized by thermal subsidence under restricted marine environment conditions and later open sea at the end of the Alagoas Stage (Campos Neto et al. 2007). This stage encompasses, in the lower portion, the predominance of carbonate deposits of the Riachuelo and Cotinguiba formations (Figure 14E), and in the upper portion, the predominance of siliciclastic of the Calumbi Formation (Figure 14F) in the Sergipe sub-basin. The other units from Paleogene to the recent Calumbi Formation in the Alagoas Sub-basin are restricted to the offshore portion (Marituba and Mosqueiro formations). The last event in the basin was regressive and allowed the deposition of the Cenozoic sediments of the Barreiras Group (Campos Neto et al. 2007).

6. Final considerations

In the Brazilian Northeast, the collapse of the Gondwana supercontinent allowed the development of several coastal and intra-continental sedimentary basins. The tectonic plot and the rheological nature of the pre-Cambrian basement of the Borborema Province had a strong influence on the tectonic framework of these Mesozoic sedimentary basins, which contains a sedimentary succession that records all the evolution regarding the opening of the South Atlantic Ocean.

Due to oil and gas exploration, the marginal basins are the most studied among the sedimentary basins. However, Pernambuco and Paraiba have no records of hydrocarbons, so these basins need a more consistent lithostratigraphic review with an updated and individualized stratigraphic chart, consolidating the new units proposed by some authors.

Among the structural elements present in the Borborema Province, the most important and that influenced the generation of sedimentary basins are the shear zones of Pernambuco and Patos. In addition, distensional movements, from Proterozoic to Cretaceous, influenced the structure, morphology, and deposition of the basins located within the Transversal Zone area or Orthogonal domain as Matos et al. (2021) named, and the interior basins north of the Patos Lineament.

The interior basins of the northeast have sedimentation correlated with the Araripe or Jatobá basins. It was defined here that the San José do Belmonte Basin units correlate to the Jatobá Basin and proved the deposition of the Sergi Formation in the Mirandiba Basin. However, obtaining a correlation based on micropaleontological analyses is necessary and avoiding simplistic correlations based on lithological similarities is necessary. Furthermore, the post-rift sequence represented by the Marizal Formation does not outcrops the interior basins, and its coverage area in the Jatobá Basin needs to be reviewed. Sedimentation that deserves a more detailed and integrated study are the relicts of Paleozoic sedimentation that occur below the interior basins and extend to the Tucano-Jatobá rift to the Sergipe-Alagoas Basin.

Among all the basins described, the one that has characterized all the evolutionary events of the opening of the South Atlantic Ocean at the end of the Lower Cretaceous is the Sergipe-Alagoas Basin, with sediments of the first marine incursions in continental Paleoenvironments until the development of open marine conditions (Luft- Souza et al. 2022), in addition to the records of the Paleozoic substrate.

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Appendix

Analysis of stable isotopes. In the Jatoba Basin, two samples of the Salvador Formation were analyzed, a limestone shell and a total rock, for C and O isotopes in the NEG-LABISE laboratory of the Federal University of Pernambuco. For extraction of CO_2 gas, 20mg of powder from each sample was used. The sample powder was attacked with orthophosphoric acid at 25ºC to release CO_2. The CO_2 gas obtained was analyzed for O and C isotopes in the Thermofinnigan Delta V Advantage mass spectrometer. The results are expressed in the notation δ in permil (‰) relative to the standard in VPDB and V-SMOW, with an accuracy better than ± 0.1‰. In addition, the isotopic carbon and oxygen data were calibrated with international standards (Vienna Pee Dee Belemnite).

Authorship credits

Author	A	B	C	D	E	F
DMFM	■	■	■	■	■	■
CRMS	■	■			■	
FGS		■			■	■
TRGP					■	
JSS		■				

A - Study design/Conceptualization **B** - Investigation/Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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