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An overview on Callovian-Cenomanian intracratonic basins of Northeast Brazil: Onshore stratrigraphic record of the opening of the southern Atlantic

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ABSTRACT

A number of small Callovian-Albian sedimentary basins occur in the NE-trending Araripe-Potiguar topographic lowlying area. These basins developed in a fairly narrow zone of Precambrian supracrustal rocks from the Middle Jurassic onwards, as a consequence of the reactivation of ancient fault lines. The basin formation and subsidence took place during five tectonic stages related with the opening of the Southern Atlantic Ocean and the split of South America from Africa. The tectonic-sedimentary sequences that fill these basins record successive evolutionary stages. 1) Proto-rift stage, with minor episodes of (a) pre-rift (Callovian-Tithonian) with basin formation and deposition of coarse to conglomeratic sandstones in alluvial fan and braided river systems; (b) tectonic quiescence with continuing subsidence, resulting in hundreds of meters of pelites accumulated mainly in lacustrine and foodplain environments (Tithonian-Berriasian). 2) Syn-rift stage: (a) tectonic reactivation with erosion and deposition of sandstones in alluvial fan and braided to low-sinuosity river systems; (b) during more quiet periods, accumulation of fine-grained deposits in lacustrine, palustrine and foodplain environments took place (Berriasian-early Barremian). 3) Erosional stage that would correspond to a transitional proto-oceanic gulf phase in the southern Atlantic and a shift of rifting to the equatorial Atlantic area, causing erosion in the study area (late Barremian-early Aptian). 4) Post-rift stage: (a) related to the beginning of drift in the Atlantic Ocean. This stage is characterised by deposition in the area of shallow lacustrine fine-grained siliciclastics, limestones and gypsum under dry climate (late Aptian-early Albian); (b) two short marine transgressions affected the area and, as a consequence, shallow marine limestones were deposited (late Aptian and Albian); (c) a marine regression resulted in a return to continental conditions with deposition of coastal and lagoonal limestones, lacustrine rhythmites and fluvial sandstones (Albian-early Cenomanian?). Some of the lacustrine to fluvial dominated sequences as well as the marine deposits in these basins include highly fossiliferous units (i.e. Crato and Romualdo Fms. of the Santana Group), with very diverse, exceptionally well preserved fossil assemblages (insects, fishes and reptiles, among others), although they are mainly endemic. 5) Uplift stage: last stage of tectonic calm and slow uplift and erosion (since Cenomanian). On the basis of our proposals further sedimentological and paleontological studies have been undertaken, which confirm the existence of an alternative connection between the equatorial and southern parts of the Atlantic Ocean in Aptian-Albian times. Moreover, the last break-up stages between Brazil and Africa took place probably in the Campanian.

KEYWORDS **Tectonic-stratigraphic sequences. Intracratonic rift basins. Jurassic-Cretaceous. Araripe-Potiguar depression. Borborema province.**

INTRODUCTION

There is still no general agreement about the exact evolution of the last intercontinental link between South America and Africa, which is supposed to have occurred in Northeast Brazil (Rand and Mabesoone, 1982; Françolin and Szatmari, 1987). Therefore, it is necessary to identify what happened in this region before the final break-up and split between Brazil and Africa. The existence of a SW-NE oriented structural lowlying area within the so-called Northeast Fold Belt or Borborema tectonic province, that extended into Africa before the continental break-up took place (Berthou, 1990), is suggested in this paper.

A number of sedimentary basins, some of these rather small, of Middle-Late Jurassic to middle Cretaceous age occur in the states of Pernambuco, Paraíba, Rio Grande do Norte, Ceará and Piauí (Fig. 1). These sedimentary areas, which are known in the literature as the intracontinental basins of Northeast Brazil (Ponte, 1992), show great similarities in their origin and evolution. These basins originated as a consequence of the tectonic movements which resulted in the separation of South America and Africa (Mabesoone, 1994). Their formation and development was controlled by fault reactivation that affected the Precambrian basement. They all occur north of the western Pernambuco lineament shear zone and show a SW-NE orientation determined by the structures and competent supracrustal rocks within the Borborema province. This lowlying trend has been called the Araripe-Potiguar depression (Mabesoone, 1994).

The most extensive of these basins is that of Araripe, and the second largest is that of Rio do Peixe. In addition, there are many other, smaller-sized basins, generally half-grabens which developed within the metamorphic basement as a consequence of the activity of extensional faults (Fig. 2; Ponte and Ponte Filho, 1996).

The so-called Pendência graben of the Potiguar basin is located towards the NE (Fig. 1). This graben also constituted a rather extensive intracratonic basin before continental drifting. It actually belongs to the equatorial Atlantic coastal Potiguar basin and was invaded by the ocean in Albian times, due to the opening of the equatorial Atlantic Ocean. This area is less well known because its stratigraphic fill does not crop out. Nevertheless, available subsurface data have been presented by Petrobrás (Souza, 1982).

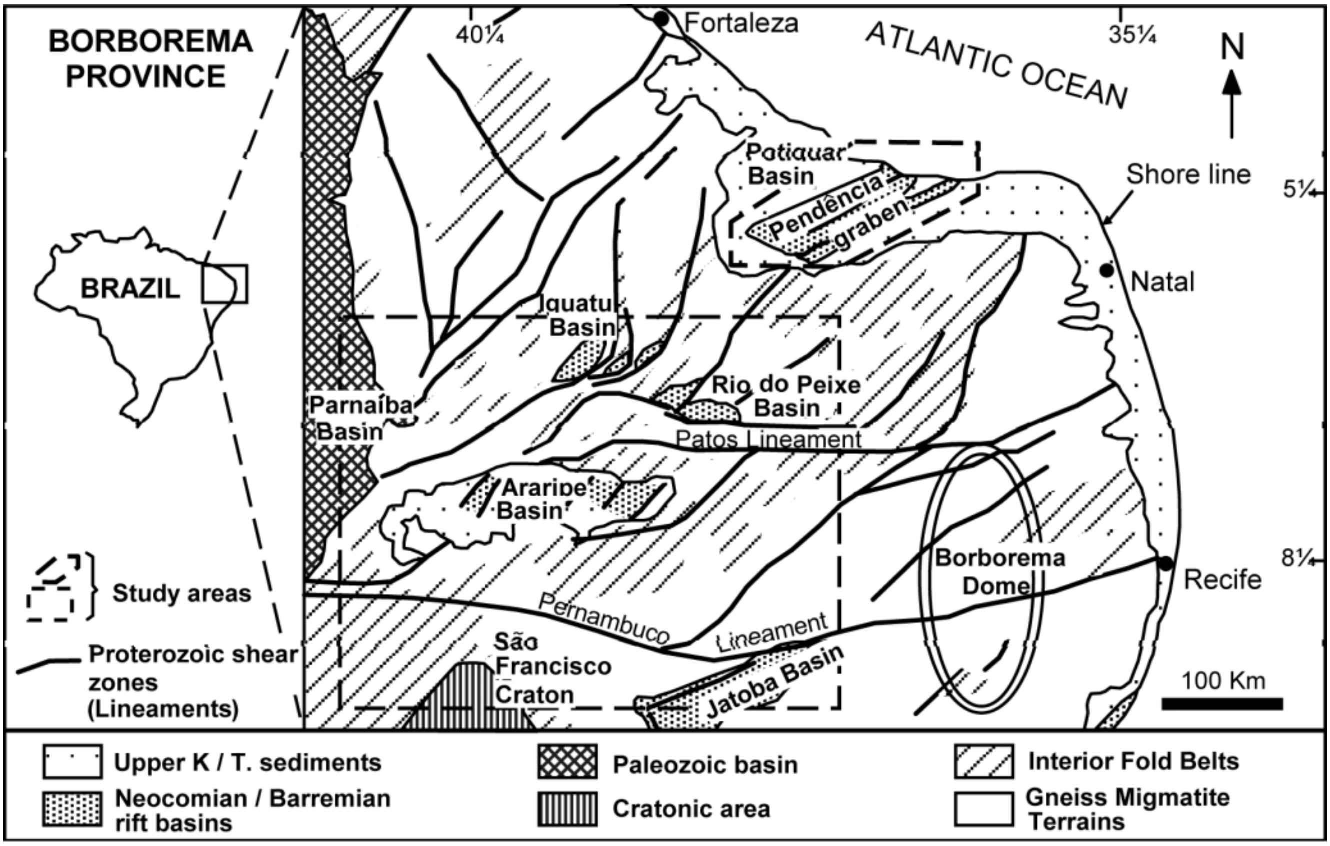

FIGURE 1 | **Geologic Map of Borborema tectonic province in Northeast Brazil, with areas studied in detail.**

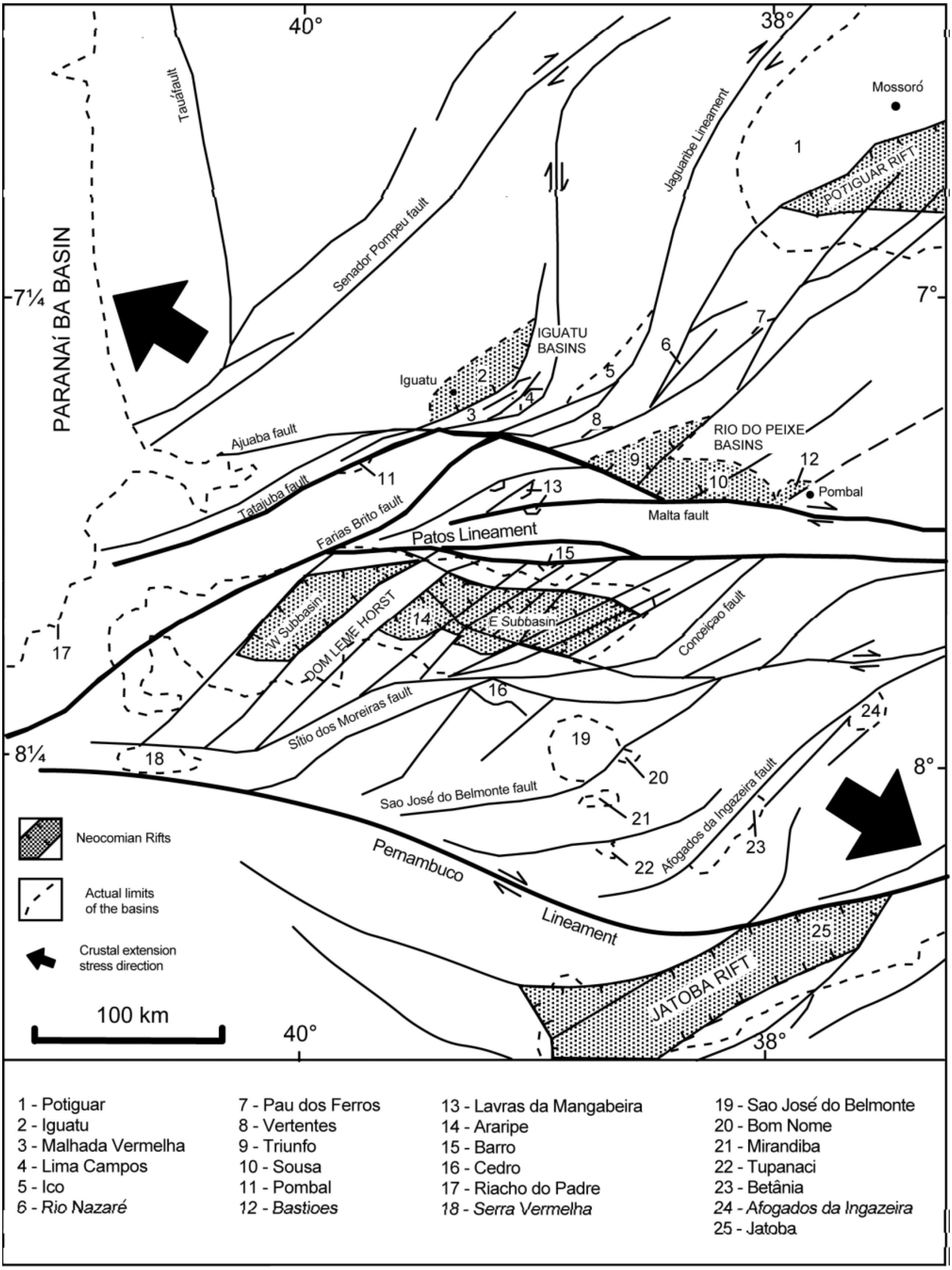

FIGURE 2 **Geologic sketch of the intracratonic basins of NE Brazil, including Araripe basin.**

A synthesis of the geological evolution of these intracontinental sedimentary basins is presented in this paper. It is the result of field observations made over the last tens of years, and the revision, integration and actualization of research carried out by the present and various other authors, as well as of unpublished reports (senior and "masters" theses of students of Brazilian universities and the Brazilian Petrobrás Oil Company) concerning the sedimentology, stratigraphy, tectonics and paleontology of Northeast Brazilian basins. Many of these studies have been performed on the fossil assemblages found in the basins of the depression, mainly in the Araripe basin, famous for its fossil fish and reptiles enclosed in calcareous concretions, and in the Rio do Peixe basin, well known for its dinosaur tracks (Viana et al., 1999). Besides, the occurrences of deposits of proven marine origin in the western part of the Araripe basin, constitutes an interesting record for the solution of the problem of the opening of the Atlantic seaway. The great wealth of information summarised in this paper provides an integrated view of the paleogeographic evolution of the intracontinental part of the region and its relation with the Atlantic Ocean history.

GEOLOGICAL SETTING AND BASIN DESCRIPTION

Precambrian basement

The earliest tectonic evolution of the Borborema tectonic province (Almeida et al., 1981) was characterised by thermal and tectonic-magmatic processes which took place during the Meso- and Neo-Proterozoic continuing into the Cambrian-Ordovician (Santos and Brito Neves, 1984). The province shows various zones of supracrustal rocks embedded among gneissic-migmatitic terrains with diverse structural trends. These zones are grouped into fold systems, resulting in the superposition of diverse tectonic, metamorphic and magmatic events upon the sedimentary and volcanic rocks accumulated since the Meso-Proterozoic (Almeida and Hasui, 1984).

Recent studies (Trompette et al., 1993) suggest that the Borborema province belonged to a larger Precambrian paleocontinent extending into Africa. The region was affected periodically by the formation of intracontinental rifts, for the last time from Callovian onwards (Fig. 3; Matos, 1987). As a consequence, several sedimentary basins resulted from the differential reactivated fault movements within the ancient Precambrian belt zone. The crustal extension gave rise to the generation, along the pre-existing Precambrian fault lines, of SW-NE oriented, tilted half-grabens (Ponte, 1992).

Araripe basin

This extensive basin (Fig. 2) is found in the south of Ceará state, continuing into Pernambuco and Piauí states, and has been the subject of many studies, mainly due to its exceptional fossil record (see summary by Ponte and Appi, 1990). The basin stands out as a flat tableland of elevated height (up to 900 m), limited by abrupt erosional scarps and occupying a surface of over 6000 km^2.

The Araripe basin evolved through different tectonic phases (Brito Neves, 1990). The first phase started with the beginning of lithospheric extension when continental separation began (Middle Jurassic). The influence of the reactivated discontinuities of the basement was very significant, reopening along ancient lines of weakness and causing relief rejuvenation and later destruction. Fault displacement has been estimated as 2000-3000 m (Petri and Campanha, 1981). Important strike-slip movement succeded extensional tectonics, enabling important transgression to be transferred to the whole sedimentary successions, before the beginning of the last evolutionary phase. During this last phase (Albian), the basin had obtained new limits.

Regional gravity, aeromagnetic and seismic surveys show the presence of two sub-basins in the Araripe basin, with NE-trending normal faults (Fig. 2). NW-trending transfer faults and/or accomodation zones bound the eastern graben (Feitoria sub-basin) and the western one (Cariri sub-basin; Ponte and Ponte Filho, 1996). These two sub-basins show normal SW-NE faults and basement highs as blocks locally tilted in opposite directions. Based upon the continuity of the shear zones in the Cariri sub-basin, it appears that the bounding faults reactivated pre-existing shear zones (Fig. 3).

The Araripe basin is surrounded by a number of sedimentary erosional remnants which testify its former greater paleogeographic extent during the middle Cretaceous (Alagoas stage; Ponte, 1994). These remnants correspond to the small basins of Barro (15 in Fig. 2), São José do Belmonte, Bom Nome and Mirandiba (19, 20 and 21 in Fig. 2) in the southeast, Serra Vermelha (18 in Fig. 2) in the southwest, and Riacho do Padre or Padre Marcos, (17 in Fig. 2) in the west, commonly occurring in fault-bounded basement depressions.

Rio do Peixe basin

The Rio do Peixe basin is subdivided into four sub-basins (Pombal, Sousa, Triunfo and Vertentes; Fig. 2), which present similar sedimentary sequences. The basin occurs at about 100 km NE of the Araripe basin, in Paraíba and Ceará states. The origin of the basin is mainly related to the reactivation of the Patos (or Paraíba) lineament shear zone which enabled the generation of the sub-basins associated with inflection points of the Precambrian faults (Matos, 1992).

The basin includes two major sub-basins (Sousa to the SE, and Triunfo to the NW) with similar but not identical evolutionary histories. The Sousa sub-basin seems to be deeper as is recorded by the presence of an up to 800 m thick mudstone-dominated sequence. Another two minor basins also outcrop, the Pombal and Vertentes basins, which occur as isolated areas bound by minor local faults and show a poor stratigraphic record. Because of the abundance of vertebrate tracks, the basin has also been the subject of detailed studies (Carvalho and Leonardi, 1992).

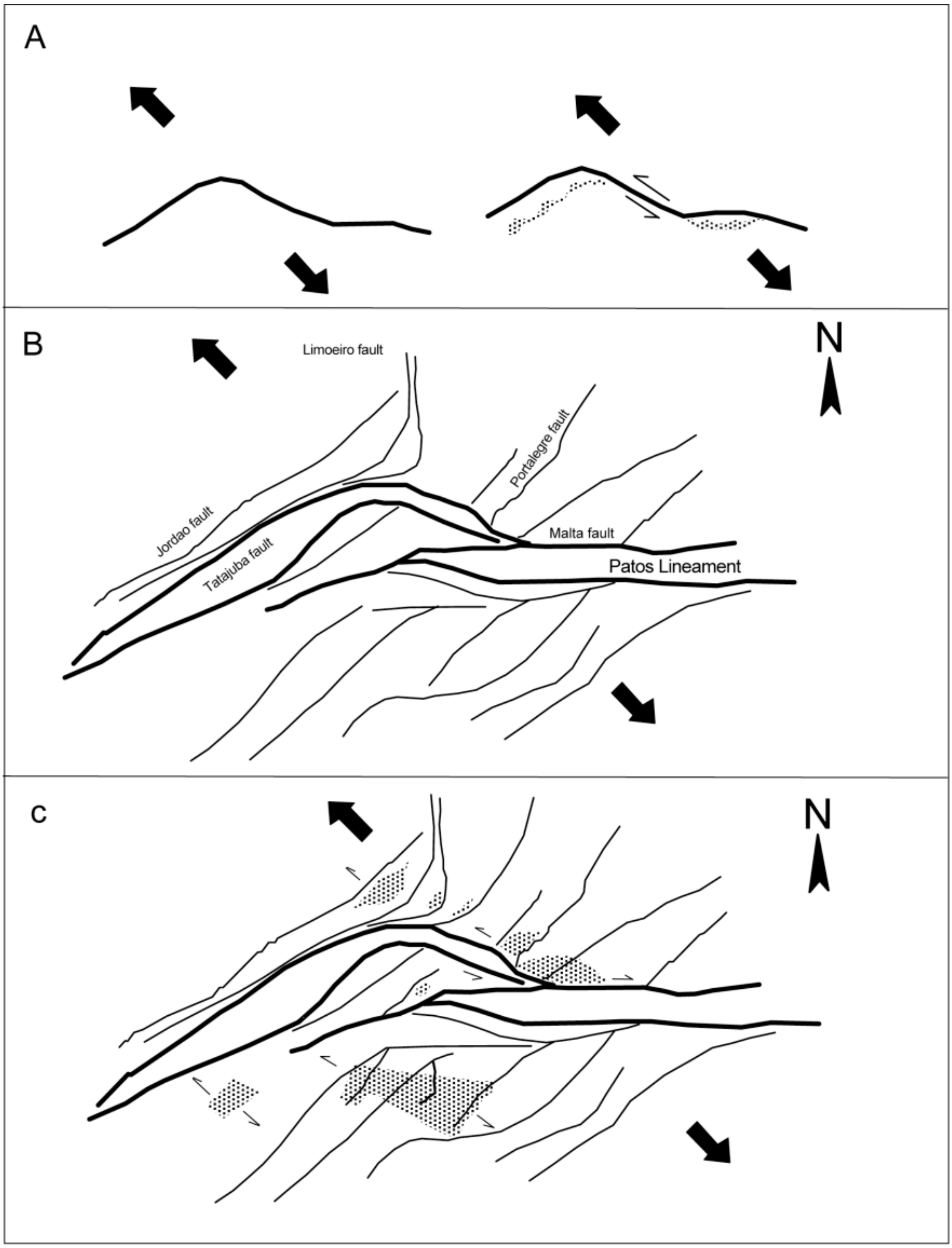

FIGURE 3 **Tectonic evolution of the rift intracratonic basins, NE Brazil: A) NW-SE extension model along of the sigmoidal pre-existing lineament. B) Pre-rift tectonic situation. C) Tectonic situation and distribution of the rifts into the intracratonic basins (Matos, 1987).**

Iguatú–Icó basins

Four small basins of rather reduced size (from W to E: Iguatú, Malhada Vermelha, Lima Campos and Icó; Fig. 2) are related to small rift faults developed within Precambrian metamorphic rocks (Ghignone et al., 1986). The trends of these bounding faults coincide with the basement features that are considered to be reactivated stricke-slip structures evidenced by horizontal drag folds which affect the lower sedimentary sequence.

These basins are considered to be genetically related to the great NE-trending lineaments in Ceará state (Fig. 2). The subsidence of structural blocks in the inflexions of the tectonic lines resulted in the basement depressions in which these basins developed, separating them by basement horsts. All four basins are half-grabens with flexural limits in the NW, dipping towards the SE, against large border faults.

It is supposed that the tectonism of the rifting phase was responsible for the formation of a large, extensive paleo-Iguatú basin. A later reactivation fragmented this paleobasin into the present four smaller sub-basins.

Other small intracratonic basins

Other small basins occuring in the NE Brazilian crystalline area (5, 6, 11, 12, 21, 22 and 23 in Fig. 2) are chiefly isolated outcrops to the north, as well as to the southeast of the central Araripe basin. They are generally half-grabens which developed within the metamorphic basement as a consequence of the activity of extensional faults. They are all linked by a relay pattern along fault lines, with a general SW-NE orientation. Their rectilinear borders are due to combined processes of erosion and slow subsidence.

These small intracratonic basins appear to be erosional remants of one or more larger basins. They do not exhibit a unique stratigraphy or proper border faults, with only a few exceptions. Their extension and depth are linked to reactivation of transcurrent faults in the basement. Very few new faults have been created during sedimentation, and syntectonic stratigraphic units are rare.

Pendência graben of Potiguar basin

This graben is located towards the NE (Fig. 1), and belongs actually to the Potiguar basin of the equatorial Atlantic margin. The graben also constituted a rather extensive intracratonic basin before the continental break-up. Before the final continental Brazilian-African separation, the Araripe-Potiguar depression extended well into Africa, and other sedimentary basins belonging to this depression are found in this latter continent (Benkhelil, 1988).

The Pendência graben that also occurs in the Araripe-Potiguar depression originated along NE trending, probably ancient, fault lines and has been filled in with clastic sediments. Only in the Albian the graben was invaded by the ocean and became a part of the equatorial Atlantic coastal Potiguar basin.

This area is not as well known because its stratigraphic fill does not crop out. The graben itself is known only in subsurface data. Nevertheless, available data about tectonics and sedimentary infill have been obtained exclusively from wells drilled by Petrobrás. The graben appears to be divided into higher and lower parts by secondary faults (Françolin and Szatmari, 1987), with their corresponding consequences for the basin infill.

TECTONIC-SEDIMENTARY BASIN EVOLUTION

Tectonic stages

In the intracratonic basins of northeastern Brazil, four major tectonic-sedimentary evolutionary stages may be distinguished between the Middle Jurassic and the middle Cretaceous (Ponte and Ponte Filho, 1996; Mabesoone, 1998), which are:

1) Pre-rift stage, Callovian-Berriasian (Dom João age, after local Brazilian time scale; Fig. 4) with minor faulting episodes and beginning of basin formation.

2) Syn-rift stage, Berriasian (Rio da Serra-Aratu) with tectonic reactivation alternated with more quiet phases, and its consequent sediment deposition.

3) Erosional (transitional) stage, late Barremian-Early Aptian (Buracica-Jiquiá-Lower Alagoas) with a shift of main rifting from the southern to the equatorial Atlantic region, causing erosion in the Araripe-Potiguar depression.

4) Post-rift stage, late Aptian-Albian (upper Alagoas-Albian) with beginning of drift, subsidence of the area permitting invasion of the sea, and finishing with regression turning the area continental.

5) Uplift stage, from the end of the Albian and the beginning of the Cenomanian onwards, when the area underwent a tectonically rather quiet stage, with a slow uplift, so that the area now became one of denudation and erosion.

The sedimentary sequences that record these tectonic events are not present in all the intracontinental basins. Only in the Araripe area is the succession is almost complete. The tectonic stages can be easily recognised in the

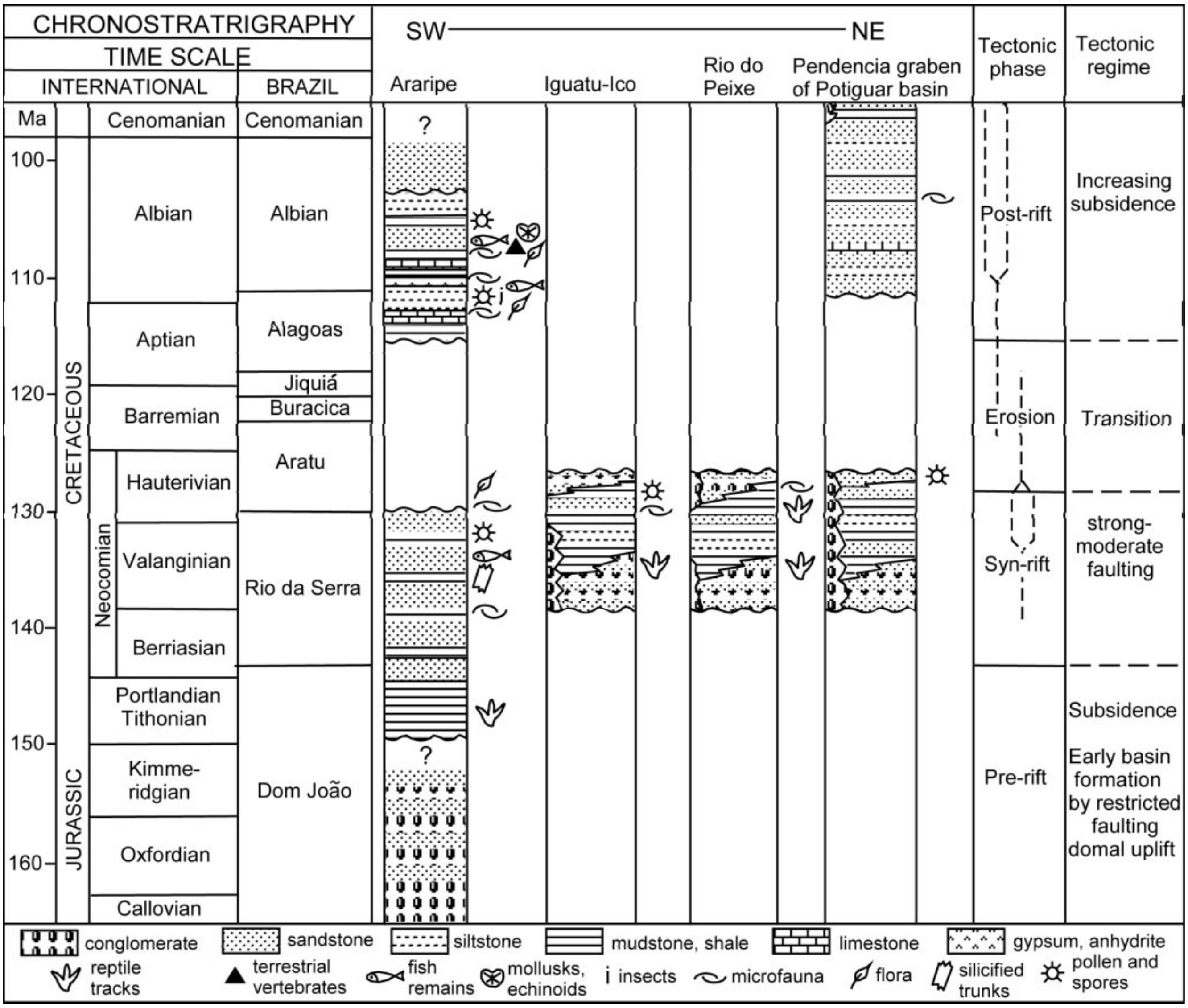

FIGURE 4 | **Time scales (international after Harland et al., 1982; local Brazilian after Arai et al., 1989), lithologic columns of the principal basin groups, and tectonic phases and regimes in sedimentary basins of Araripe-Potiguar depression (extension of Araripe-Potiguar depression and its continuation into Africa after Berthou, 1990).**

sedimentary record of the basins in the Araripe-Potiguar depression.

Pre-rift stage

This first stage corresponds to regional subsidence, accompanied by the beginning of reactivation of Precambrian faults on the both sides of the Borborema dome (Fig. 1). To the east, the downwarped area is called the Afro-Brazilian depression, to the west the equivalent is called the Araripe-Potiguar depression (Mabesoone, 1994) which included the Pendência graben of the Potiguar basin. During this early tectonic reactivation phase the slow subsidence in the Afro-Brazilian depression was more constant, whereas in the Araripe-Potiguar depression, from about Callovian onwards, the tectonic reactivation occurred more irregularly, due to the nature of the Precambrian crystalline basement.

The lithostratigraphic record of the early phase of this evolutionary stage was influenced by the activity of normal faults, and presents a thick succession of polymictic matrix supported conglomerates and immature conglomeratic sandstones (Mauriti Fm. in the Araripe basin; Ponte and Ponte Filho, 1996) that accumulated in proximal and medial zones of alluvial fans along the fault lines in the newly formed basins (Fig. 5A). The medial alluvial-fan deposits pass basinward into distal braided river systems, with N-NW paleocurrent directions (Assine, 1992), possibly embouching into an aqueous body (Feitosa, 1987).

The sediments show some eolian reworking. In the coarse clastics only a few dinosaur foot prints and rare trace fossils have been found (Carvalho et al., 1995), although these are poorly preserved because of the coarseness of the sediments. The tracks seem to belong to theropods and ornithopods. This phase lasted until about the end of the Kimmeridgian. The sediments were also affected with silicification in various places during temporary exposure.

Until recently this Mauriti Fm. was correlated with the Tacaratu Fm. of the Jatobá basin and the Serra Grande Group of the Parnaíba basin, both of Silurian age, an attribution based only on lithologic similarity. This has proven to be wrong due to the finding of the dinosaur tracks, making a Mesozoic age more certain (Carvalho et al., 1994).

Towards the end of the stage, in Tithonian/Portlandian times, fault activity slowed down considerably. Subsidence continued, however, and the infilling of the sedimentary basins proceeded under more quiet circumstances. In the Araripe basin deposition took place in lacustrine environments (Brejo Santo Fm.), represented by shales, claystones and siltstones, with intercalations of fine to medium-grained sandstones (Fig. 5B). The sequence lies unconfomably upon the lower clastic sequence. The formation yielded a rather abundant ostracod fauna, belonging to the *Bisulcocypris pricei* zone of the Jurassic (Dom João age; Fig. 6), as well as some conchostracans. The Jurassic-Cretaceous boundary is supposed to occur within this lithostratigraphic unit, although no precise data exist on the subject (Da Rosa and Garcia, 1994).

Rift stage

The rift stage is characterised by vigorous faulting in the Afro-Brazilian depression from the end of the Jurassic-beginning Cretaceous onwards (Matos, 1992). This rifting resulted in the opening of the southern Atlantic rift. This

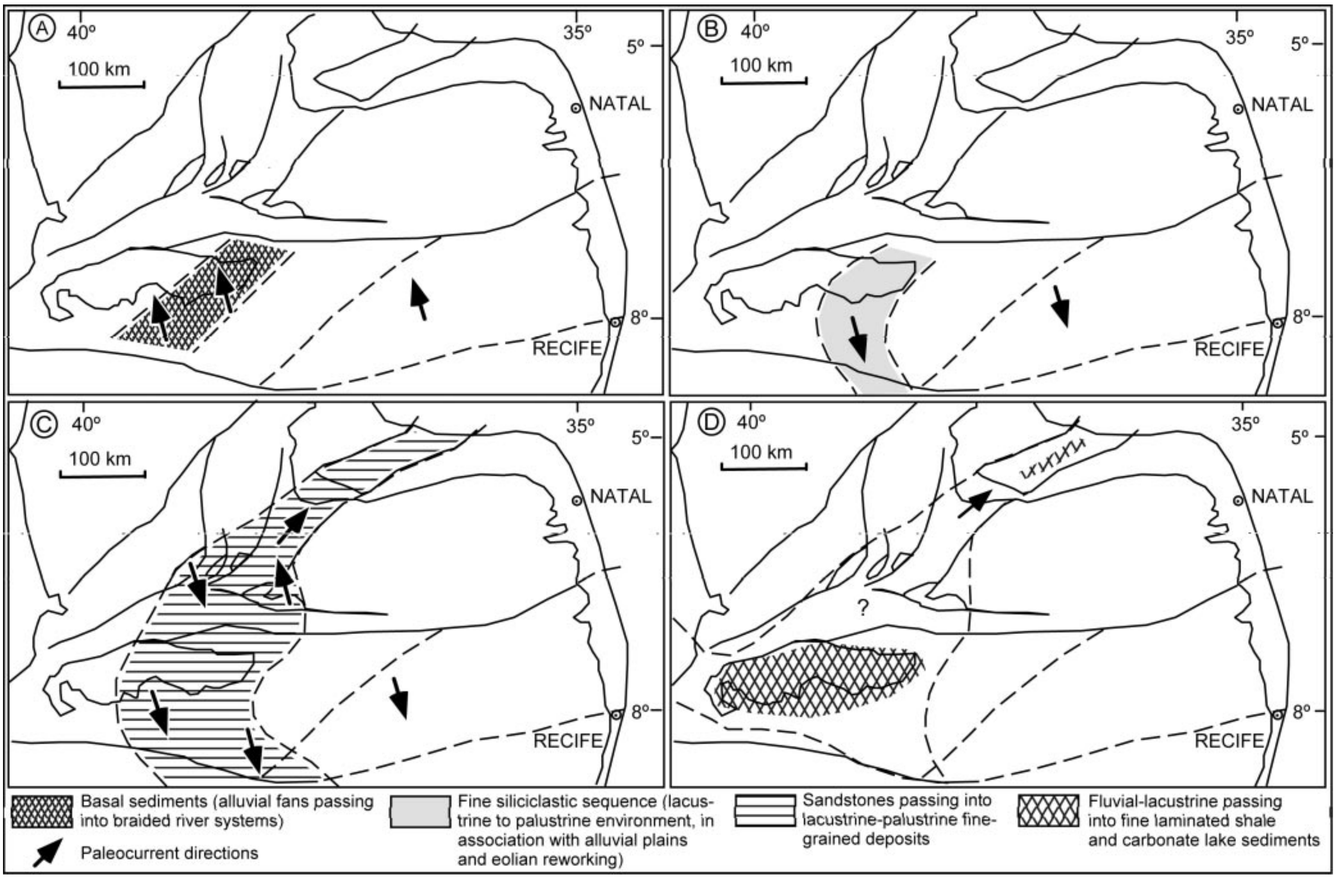

FIGURE 5 **Evolutionary stages of NE Brazilian intracratonic basins: A) Callovian and Tithonian ocurrence of fault scarp conglomerates and distal equivalents of Mauriti Fm., deposited during the first evolutionary stage. B) Tithonian-Berriasian lakes filled upward in river deposits of Brejo Santo and Missão Velha Fms. during second phase of first stage. C) Valanginian-Barremian rift stage sedimentary areas in the basins of Araripe-Potiguar depression, deposited in fluvial and lacustrine environments. D) Late Aptian-Albian extension of marine, lacustrine and fluvial environments during post-rift stage in Araripe-Potiguar depression.**

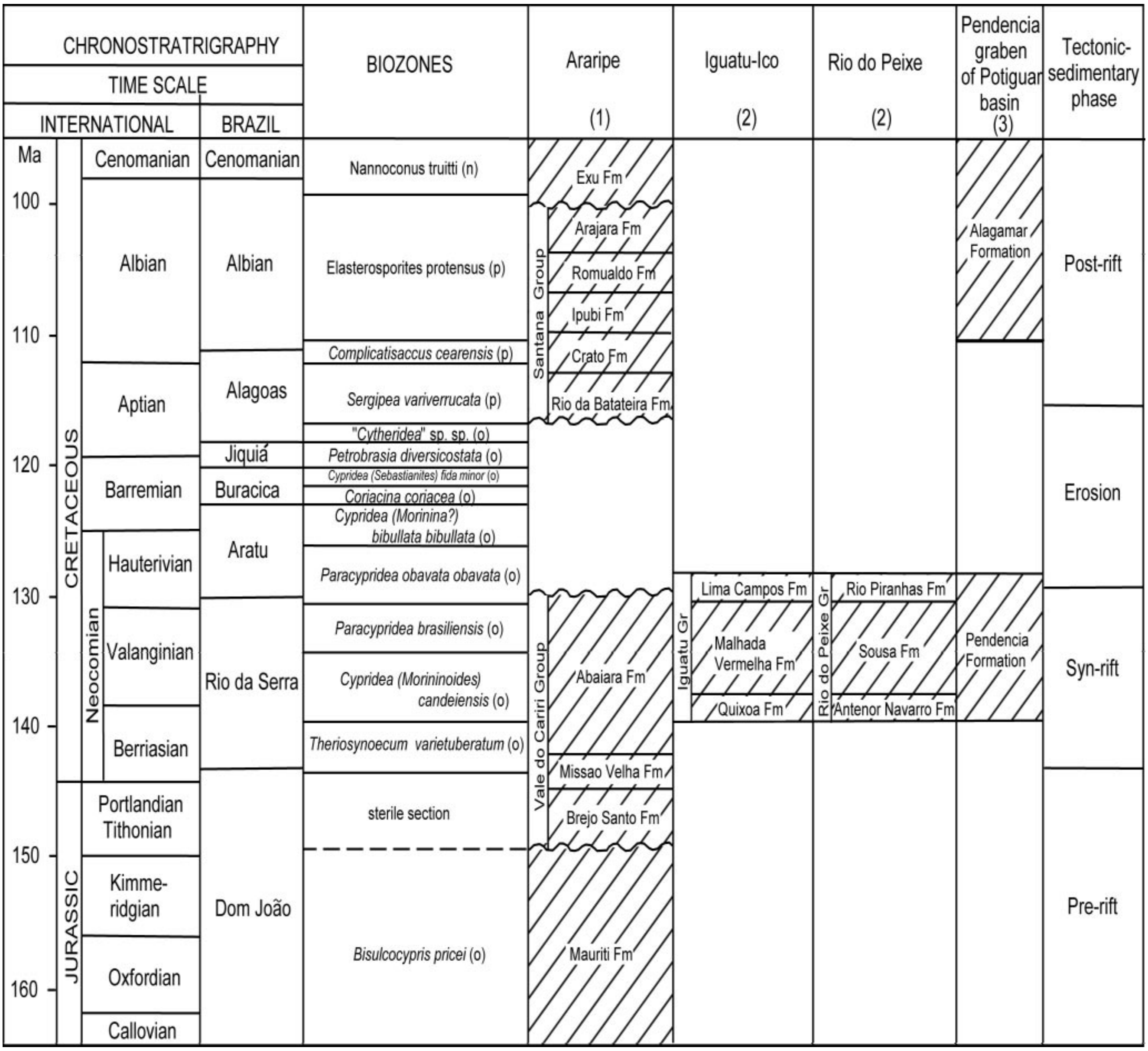

FIGURE 6 | **Chronostratigraphy of the study area and respective tectonic stages. Microfossil biozones after Arai et al., 1989 (o – ostracod, n – nannofossil, p – palynomorph). Lithologic formation names (Rio da Batateira, Crato, Ipubi, Romualdo and Ararjara): 1: after Ponte and Appi (1990); 2: after Mabesoone and Campanha (1974); 3: after Souza (1982).**

also had consequences in the Araripe-Potiguar depression where rifting continued even more intensively, and became very active to the north of the Paraíba or Patos lineament, where the basins of Iguatú-Icó and Rio do Peixe developed (1 to 10 in Fig. 2).

When the first manifestation of this rifting became more developed, the depositional environment changed into a more fluvial realm (Missão Velha Fm.) composed of intercalations of well-bedded, clayey sandstones with variegated siltstones and shales. At the base of the unit, coarse to medium-grained sandstones are cross-bedded showing a fining upward sequence, suggestive of braided river deposits. Upward, the sandstones become gradually finer, indicating the environment had changed into low-sinuosity and even meandering rivers (Cavalcanti and Viana, 1992). Paleocurrent measurements indicate drainage directions towards the south, where a possible connection with the southern Atlantic realm coud have existed (Rolim and Mabesoone, 1982). The Missão Velha sandstones are unfossiliferous except for a great number of silicified trunks of the conifer *Dadoxylon benderi*, which means a growth of luxurious forests in the river plains.

The proper rift stage is recorded in the Araripe basin by the Abaiara Fm. This unit is composed of fine to medium-grained clayey sandstones with interbedded fine-grained deposits which conformably overlies the lower coarse deposits (Fig. 5C). In the area of ocurrence the statigraphic record sequence is not very thick (up to 125 m). In the Abaiara Fm. the fossil assemblages are rather rich. Besides some reworked fragments of the silicified trunks, coprolites, algal structures, ostracods, conchostracans and pollen have been found, chiefly in the finer clastic intercalations. Recently, a rather rich fauna of fish has been discovered, although more work is need on this find.

North of the Paraíba or Patos lineament, active faulting lead to basin infill in the Iguatú, Malhada Vermelha, Lima Campos, Icó, Lavras de Mangabeira, Pau dos Ferros, Rio Nazaré, Vertentes and Rio do Peixe (1 to 10 and 12 in Fig. 2) basins**.** During the early stage of rifting proximal alluvial coarse sandy to conglomeratic sequences were deposited, mainly along the active fault lines. These passed basinward into finer distal alluvial facies (Fig. 4), sometimes alternating with meandering river stream influxes. The drainage was directed from the sides to the basin centre and from there towards NE where the Pendência graben is found. After this early faulting, the tectonic activity slowed, although subsidence continued. The lower sandstones pass gradually into lacustrine-palustrine fine siliciclastic sediments (Fig. 5C) that are up to 800 m thick. This phase is represented in the Rio do Peixe basin by the Sousa Fm., and in that of Iguatú by the Malhada Vermelha Fm. in which most of the dinosaur footprints occur (Carvalho and Leonardi, 1992). The occurrences point to shallow waters and fairly dry climates. As noted previously, the fossil content consists mainly of vertebrate tracks (Fig. 7A). In the coarse clastic deposits of the lowermost Antenor Navarro Fm. of the Rio do Peixe Group, few fossils are found. These include ostracods, fish and bivalves. The Iguatú and Lavras de Mangabeira basins have yielded very few fossils. These consist of nonmarine ostracods, conchostracans, fish remains, pollen, spores and plant fragments, mostly of the same types as those in the middle Sousa Fm. of the Rio do Peixe area, which makes a correlation possible. In the smaller basins and that of Lavras de Mangabeira, the fauna assemblages are composed of not yet determined conchostracans and association of trace fossils (*Skolithos*) and insect dwelling burrows (Carvalho and Fernandes, 1992). Reactivation of faults resulted in the deposition of the upper sandstone sequences in these basins, again in alluvial fan and braided to low-sinuosity river environments.

A similar sequence appears to be present in the Pendência graben of the Potiguar basin (Pendência Fm.), although its occurrence exclusive in the subsurface prevented a more detailed study. The syn-rift stage lasted between end Berriasian and beginning of Barremian.

Erosional (transitional) stage

When the shift of main rifting changed from the southern Atlantic realm towards the equatorial Atlantic (Matos, 1992) in the late Barremian, an erosional period started in the basins of the Araripe-Potiguar depression. This is recorded by an important erosional unconformity that is very well represented in the Araripe basin, being mappable in the surface at many places, and which can be readily identified in seismic reflection lines. It can also be identified by an absence of certain ages in the biostratigraphical record (Ponte and Ponte Filho, 1996). In the basins north of the Paraíba lineament, sedimentation ceased completely and no younger sequences have been found. In the Pendência graben, deposition occured when the ocean inundated it in Albian times (Fig. 6).

Post-rift (drift) stage

The fouth, so-called post-rift stage, when drifting started, is represented in the Afro-Brazilian depression as a proto-oceanic gulf environment. In the Araripe-Potiguar depression a thermal-mechanical flexural subsidence took place (Ponte and Ponte Filho, 1996). During the Aptian-Albian worldwide transgression the sea invaded the southern and equatorial Atlantic branches and reached the intracratonic depression as is recorded by the marine deposits in the area.

This stage has been subdivided into three phases: transgression, inundation, and regression, respectively. Sedimentation started again in the late Aptian, but record of it only exists in the Araripe area (Fig. 6). In the other basins, if some deposition did take place later erosion has removed all evidence. Only the occurrence of a small oyster bank in the Malhada Vermelha basin has been reported (Beurlen, 1970). In the Araripe area the sequence is represented by the so-called Santana Group, composed of the Rio Batateira, Crato, Ipubi, Romualdo and Arajara Fm., and the uppermost Exú Formation, recording the transgression-regression cycle (Fig. 6).

The transgression phase is represented by the lowermost lithostratigraphical unit of the Rio Batateira Fm. that is composed of lower medium to coarse-grained, cross-bedded, lenticular sandstones which consist of fining upward sequences and show S-SE oriented paleocurrents (Assine, 1992) in a river environment (Fig. 5D). These lower, coarse sandstones pass upward into green and black bituminous and fossiliferous shales. Such lithologic succession illustrates a lacustrine depositional system, with subaquatic lobes of river deposits into shallow lakes that fill in the shal-

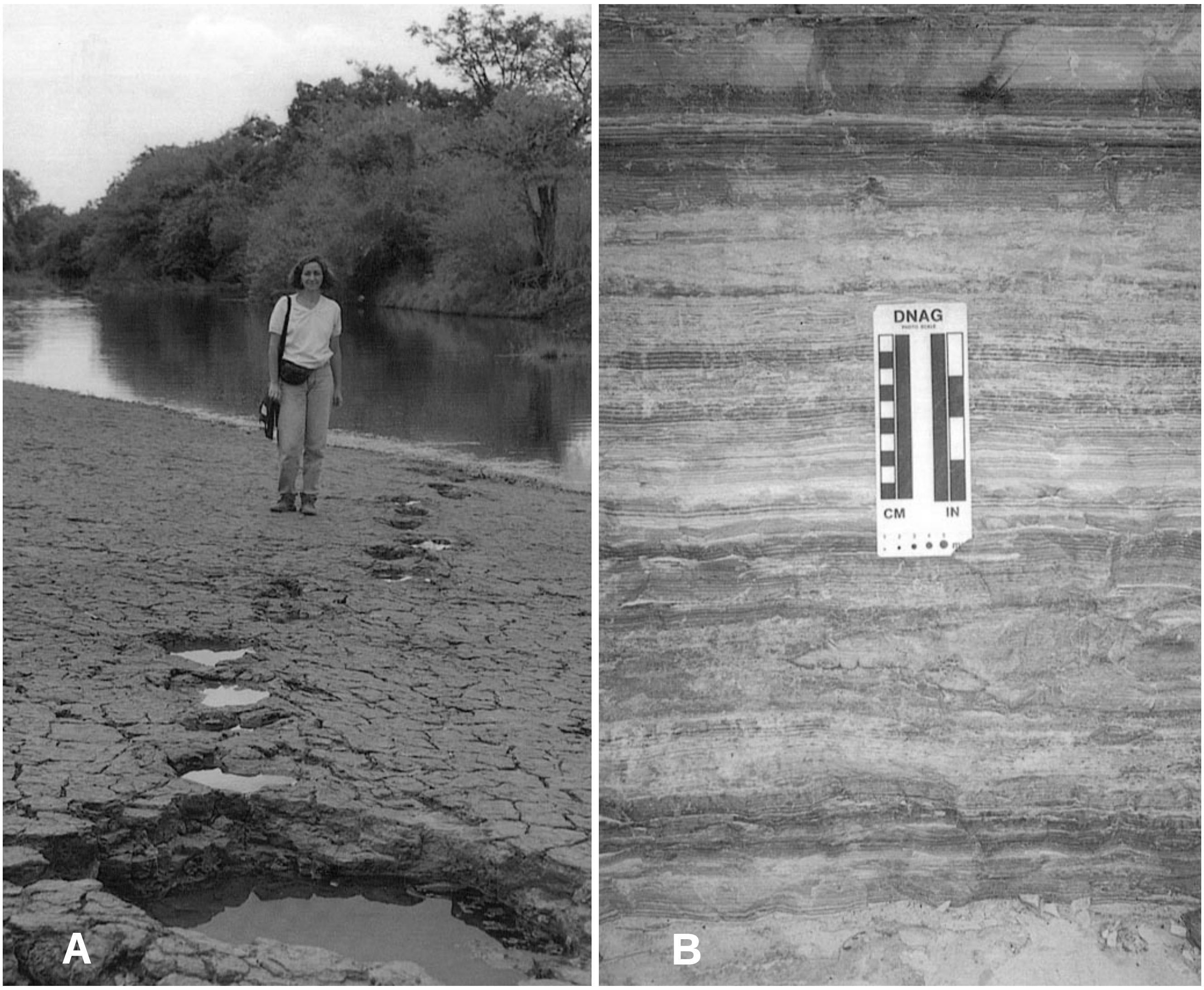

FIGURE 7 | **A) Sousa Fm., laminated clayey siltstones with ripple marks, mud cracks, and track of biped dinosaur. Passagem do Pedro, Sousa municipality, Rio do Peixe basin (Paraíba). Photo Alcina M. F. Barreto. B) Crato Fm. finely laminated clay carbonate rhythmites (detail). Andre quarry, Nova Olinda–Ceará State.**

low depressions still existing in the erosional surface of the former stage. On top of this sequence another similar cycle is found, in which the uppermost shales contain a calcareous component (Ponte and Appi, 1990).

Near the end of the Aptian, the inundation phase started with the deposition of the Crato Fm. This unit is composed of an alternation of dark-coloured, calciferous shale laminae, and grey-coloured micritic limestone laminae, with variable clay content (Fig. 7B). This complex is interpreted as a lake paleoenvironment with strong seasonal cycles, under fairly dry climatic circumstances, with their marginal and central parts distinguished through facies differences. This lake was very extensive and surpassed the limits of the above-mentioned depression. The fossil content of this formation is very rich, while recent discoveries have expanded the paleontologic database. In this case the reader is referred to the papers of Mabesoone and Tinoco (1973), Martill (1993), Broin (1994), Berthou et al. (1994), Martill and Filgueira (1994), Viana and Agostinho (1995), and Neumann et al. (1998). In the laminated deposits abundant fossil insects occur (belonging to 21 orders and 10 families). In addition, ostracods, conchostracans, fish, possible remains of amphibians and birds, as well as a rich flora of pollen, spores and plant fragments are present. Most of the species are endemic and many of them have not yet been determined with certainty.

The lacustrine system turned saline under dry climate conditions, enabling the deposition of evaporites, chiefly gypsum and anhydrite with an average thickness of 30 m, and thin intercalations of dark-coloured clay (Ipubi Fm.). The depositional environments are considered to be inland sabkhas or lakes which became gradually more saline due to an increasing rate of evaporation (Menor and Amaral, 1991). An erosional unconformity tops this sequence.

The upper unit of the Santana Group (Romualdo Fm.) is made up by interbedded shales, marls and limestones with abundant concretions containing fossil fish and reptile bones, of crocodiles, turtles, pterosaurians and a few dinosaurs (Broin, 1994; Hirayama, 1998). Ostracods, conchostracans, copepods, gastropods, bivalves, shrimp-like crustaceans (chiefly in the stomachs of fish), and a macroflora of gymnosperms and a few angiosperms have also been identified (Viana et al., 1999), as well as occurrences of amber. This sequence is interpreted as a lake or gulf cycle.

These limestones are associated with some marls, limestones and shales in which fossils of marine gastropods, bivalves and a few echinoids have been determined. Gastropods are extremely common at some sites, where they constitute true gastropod limestones. The lower section of these limestones gives evidence for a short marine transgression. Later in the Albian the area experienced a more important and somewhat longer lasting marine invasion, recorded by other marine deposits. The paleoenvironment was complex, with a shelf system undergoing transgression and later regression, accompanied by shallow marine, lagoonal sabkha and even some coastal lake systems. The whole Albian appears to have been a subsided low-lying area in the Araripe-Potiguar depression (Petri, 1987) in which the sea could enter during the Aptian-Albian worldwide transgression epoch.

At the end of the Albian, a regression occurred, returning the area to the lagoonal and coastal plain system. This section is represented by a sequence of siltstones, shales and clayey fine sandstones, brightly-coloured, well bedded and interbedded, and with structures such as cross lamination, ripple marks and fluidisation phenomena (Arajara Fm.). Because of this gradual transition from the underlying limestones, the section is considered to still belong to the same depositio-nal cycles as its regression. The fine clastics have been interpreted as rhythmites (Fig. 6) from the shallow coastal environment with increasing terrigenous supply.

Unconformably upon these marine and lacustrine cycles is a 150-200 m thick sandstone sequence that covers the present Araripe tableland. It is represented by a monotonous succession of red, clayey, friable sandstone of various grain sizes and with cross-bedding. This so-called Exú Fm. exhibits four facies types within a fluvial environment of braided to low-sinuosity character (Valença, 1987). The drainage direction had turned towards the west, where the Parnaíba basin exists (Assine, 1992). Because the unit is non-fossiliferous, it is postulated to be Albian to beginning of Cenomanian in age due to its stratigraphic position.

Probably in the Cenomanian, the sedimentation of the fluvial Exú Fm. ends, thus finishing the Late Mesozoic depositional history of the NE Brazilian Araripe-Potiguar depression. Only in the Pendência graben of the Potiguar basin sedimentation continued, but now as forming part of an equatorial Atlantic marginal basin in which the sea entered since the Albian.

Development since Cenomanian

From the end of the Albian-Cenomanian sedimentation phase onwards, the area became subject to uplift and erosion. This uplift seems to be due to the reactivation of the Borborema province to the separation of South America and Africa. This Late Mesozoic and Cenozoic history falls beyond the scope of this paper.

OPENING ATLANTIC OCEAN

A problem that has still not been completely solved is the timing and location of the final separation of South America and Africa and the opening of the Atlantic Ocean between its equatorial and southern parts. The site is thought to occur in the area of the actual Paraíba sedimentary basin in northeastern Brazil (Françolin and Szatmari, 1987; Mabesoone, 2000).

More controversial remains the age when the definitive open ocean connection was established. There is a record of marine fauna exchange between the two oceans in the Albian, and this is generally considered to mark the timing of the open ocean link. However, tectonic and geophysical research in the area concluded that the continental break-up happened only in the Campanian (Figueiredo Filho and Petta, 1998).

The suggested solution to the problem seems to be present in the above-considered intracontinental basins of NE Brazil. The record of Albian marine deposits in the Araripe basin proves that the sea had invaded the area then. The possible places where this sea entered the area are: 1) through the Parnaíba sedimentary basin in the west; 2) through the Pendência graben of the Potiguar basin in the northeast; or 3) through the Sergipe-Alagoas southern Atlantic margin basin in the southeast. Between the Araripe area and the sea there still exist remainders of marine deposits along all three ways. This lead Lima Filho et al. (1996) to suggest that the sea could have entered the Araripe basin from all three sides, separating two large islands formed by structural rises in between (Fig. 8). Viana (1998) and Arai (1999) confirmed this suggestion through an investigation of the faunal affinities, with species from the equatorial Atlantic Ocean with Tethyan affinities, into the southern Atlantic. This means that the sea invaded the northern part of this South Atlantic rift through the intracontinental seaway from the equatorial side, and through the Sergipe-Alagoas basin.

Thus, the existence of such a temporary seaway enables us to propose an alternative Atlantic Ocean connection with more precision through the interior of NE Brazil. The Albian marine fauna exchange between the equatorial and southern Atlantic through this alternative seaway was temporary, lasting only for the period of the Aptian-Albian worldwide sea level high stand. The definitive open ocean connection was established during the next worldwide high sea level stand during the Cenomanian-Turonian transition (Bengtson, 1998; Mabesoone, 2000) when the last link of continental crust between Brazil and Africa had subsided.

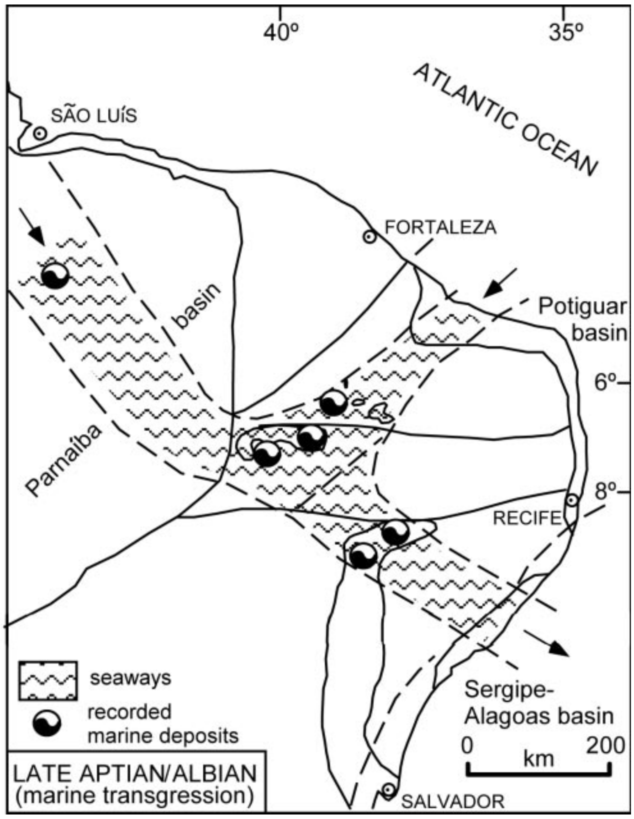

FIGURE 8 **Proposed Late Aptian-Albian marine transgression and saway conections with the Atlantic Osean.**

CONCLUDING REMARKS

The sedimentary development and the tectonic history of the study area, located within the Northeast Brazilian Borborema tectonic province, contributes to the knowledge of the processes that occurred before the final breakup between South America and Africa. Reinterpretation and integration of available data about tectonics (mainly rifting evolution) basin formation, and stratigraphic record, together with the results of recent new research make the Araripe-Potiguar depression a crucial area for the solution of the still existing uncertainties.

The area underwent alternating uplift and subsidence phases. Its tectonic and sedimentary development can be divided into four principal stages (proto-rift, syn-rift, erosional –transitional- and post-rift –drift-), with their coeval stratigraphic record showing that faulting started as early as in the Callovian (Middle Jurassic) and continued until Albian (middle Cretaceous). These movements weakened the strength of the area against the reactivation processes that affected the crystalline basement rocks split by numerous faults.

When the Atlantic Ocean was established in the late Aptian, although still without a constant connection between its southern and equatorial parts, a temporary seaway appeared to have existed twice through the study area, at the latest Aptian and in the early Albian. Marine deposits that are recognised mainly in the central Araripe basin record this seaway connection. The synthesis of so much dispersed information enabled us to propose the existence of such an alternative Atlantic Ocean connection with more precision. It also enabled us to constrain the timing of the existence of some continental crust linking between South America and Africa, and the age when the definitive open ocean connection established at its present site.

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