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The transgressive-regressive cycle of the Romualdo Formation (Araripe Basin): Sedimentary archive of the Early Cretaceous marine ingression in the interior of Northeast Brazil

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ABSTRACT

Geologic events related to the opening of the South Atlantic Ocean deeply influenced the sedimentary record of the Araripe Basin. As consequence, upper stratigraphic units of the basin record a marine ingression in northeastern Brazil during the late Aptian. The timing and stratigraphic architecture of these units are crucial to understand the paleogeography of Gondwana and how the proto-Atlantic Ocean reached interior NE Brazil during the early Cretaceous. This marine ingression is recorded in the Araripe Basin as the Romualdo Formation, characterized by a transgressive-regressive cycle bounded by two regional unconformities. In the eastern part of the basin, the Romualdo depositional sequence comprises coastal alluvial and tide-dominated deposits followed by marine transgressive facies characterized by two fossil-rich intervals: a lower interval of black shales with fossil-rich carbonate concretions (*Konservat-Lagerstätten*) and an upper level with mollusk-dominated shell beds and shelly limestones. Following the marine ingression, an incomplete regressive succession of marginal-marine facies records the return of continental environments to the basin. The stratigraphic framework based on the correlation of several sections defines a transgressive-regressive cycle with depositional dip towards southeast, decreasing in thickness towards northwest, and with source areas located at the northern side of the basin. The facies-cycle wedge-geometry, together with paleocurrent data, indicates a coastal onlap towards NNW. Therefore, contrary to several paleogeographic scenarios previously proposed, the marine ingression would have reached the western parts of the Araripe Basin from the SSE.

1. Introduction

The Araripe Basin is an interior Mesozoic basin located in Northeast Brazil that experienced brittle reactivation during the Mesozoic. The genesis and sedimentary infill are closely tied to the late Cretaceous tectonic events that resulted in the break-up of Gondwana and the associated opening of the South Atlantic Ocean (Assine, 1992, 2007; Matos, 1992; Ponte and Ponte Filho, 1996; Maisey, 2000).

One of the earliest consequences of the South Atlantic evolution was a regional-scale marine transgression in the interior region of Northeast Brazil. This is recorded in the Araripe Basin as the late Aptian Romualdo Formation (Fig. 1). This unit encompasses one of the most important fossil *Konservat-Lagerstätten* of the world (Mabesoone and Tinoco, 1973; Maisey, 1991; Martill, 1997, 2007, 2011; Kellner and Campos, 1999; Kellner, 2002; Fara et al., 2005; Vila Nova et al., 2011; Martill et al., 2012), an impressive archive of the palaeobiota that lived and flourished in Gondwana during the early Cretaceous (Martill, 2007). Due to the high preservation quality of several fossil groups, especially 3D-preserved fishes (Martill, 1988; Maldanis et al., 2016), scientific studies have focused mainly on the systematic paleontology. The chronostratigraphy is based on biostratigraphic schemes using palynomorphs (Regali, 1974; Lima, 1978; Coimbra et al., 2002; Rios-Netto et al., 2012). In contrast, there are far fewer studies dealing with the stratigraphy and sedimentology of the sedimentary package, and those related to facies analysis and sequence stratigraphy are scarce (Assine, 1992, 2007; Assine et al., 2014).

The major debate on the marine nature of the Romualdo Formation concerns the Aptian paleogeography and the exact extent of the flooding of the interior sea. Contrasting paleogeographic reconstructions exist in the literature, some suggesting that the marine ingression occurred from various directions. In these scenarios, different

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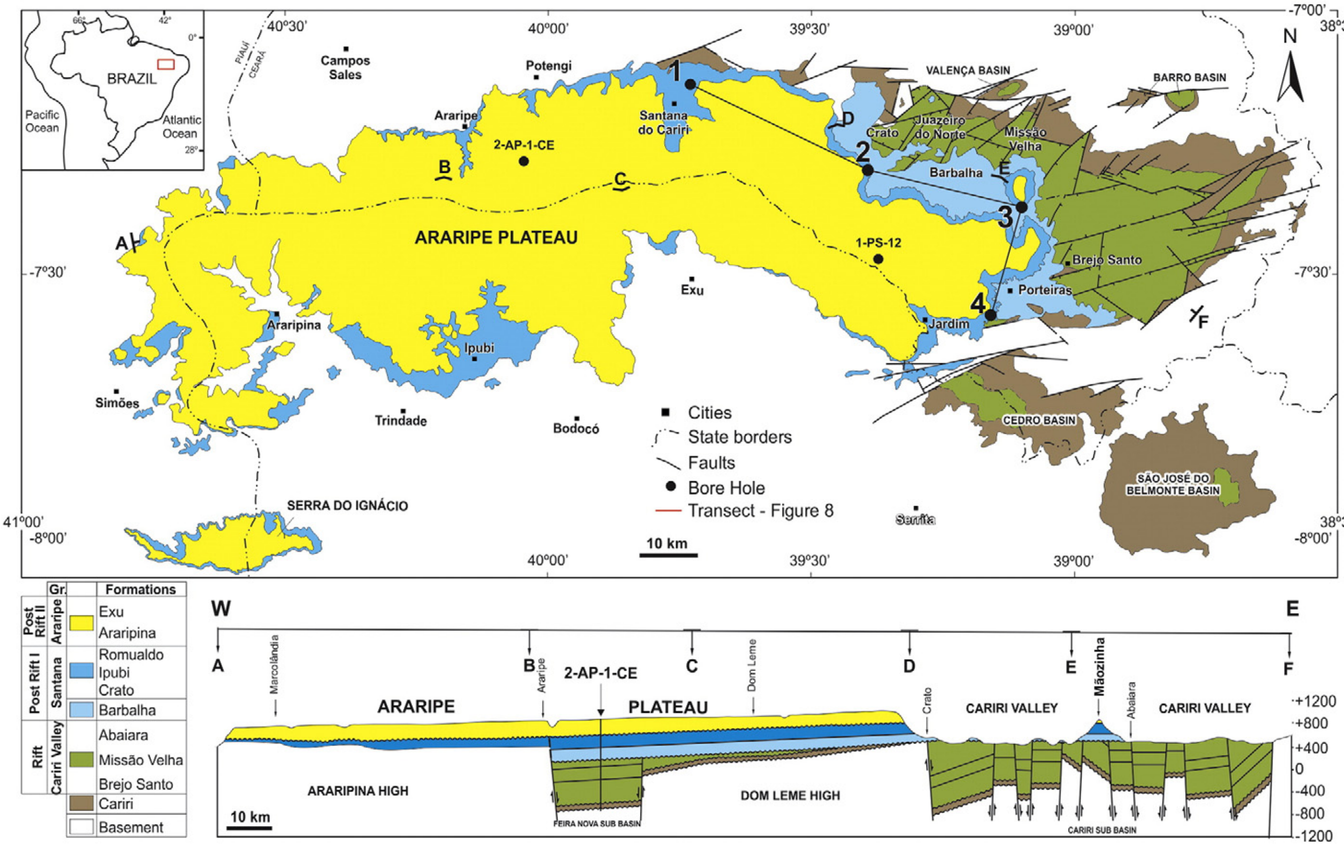

Fig. 1. Geologic map of the Araripe Basin, showing the stratigraphic record of the rift and post-rift stages (modified from Assine, 2007). Stratigraphic sections: (1) Pedra Branca; (2) Sitio Romualdo; (3) Serra do Mãozinha; and (4) Sobradinho.

connections of the Araripe Basin with surrounding basins and the Tethys are assumed (Beurlen, 1963, 1966, 1971a; Braun, 1966; Mabesoone and Tinoco, 1973; Arai, 2014). These proposals, however, were mainly based on paleontological data and, in most of the cases, lack an integrative approach combining stratigraphy and geometry of the deposits (Assine, 1994, 2007; Assine et al., 2016). Both vertical and lateral distribution of facies, the geometry of the depositional systems, and their sedimentary provenance are key elements in order to reconstruct the paleogeographic scenario of the interior NE Brazil during Romualdo times.

This contribution comprises the first detailed stratigraphic analysis of the Romualdo Formation, and focuses on surface data from the eastern part of the Araripe Basin. The stratigraphic analysis allowed us to interpret lateral facies changes and the stratigraphic sequence geometry. By using a sequence stratigraphy approach, we present key surfaces and facies associations of the unit. These and the correlation of measured sections resulted in a stratigraphic framework that displays a transgressive-regressive cycle composed by two depositional systems tracts. Our results support or refute available paleogeographic scenarios tied to the marine ingression in the interior NE Brazil during the latest early Cretaceous. Our data lead to accurate regional paleogeographic interpretations that have profound impact on the path of the marine ingression into interior of northeastern Brazil during Aptian times.

2. Background: stratigraphy of the Romualdo Formation

The Mesozoic sedimentary succession of the Araripe Basin comprises four unconformity-bounded stratigraphic megasequences (Fig. 2), which record distinct tectonic phases of a polygenetic basin (Assine, 1992, 2007; Ponte and Ponte Filho, 1996). These sequences encompass numerous different units, and many lithostratigraphic schemes have been proposed during the years (see Assine, 1992; Martill, 2007 for correlative tables of units).

The terms Santana and Romualdo have been employed in many distinct stratigraphic meanings. Most of the papers have ranked the Santana unit as formation, in accordance with the seminal proposal of Beurlen (1971a). In this context, the Santana Formation would include, from base to top, the Crato, Ipubi and Romualdo members (Mabesoone and Tinoco, 1973; Santos, 1982; Ponte and Appi, 1990; Assine, 1990, 1992; Castro et al., 2006; Prado et al., 2015).

Later on, Neumann and Cabrera (1999) elevated the Santana Formation in lithostratigraphic nomenclature to group rank, and its former members to formations. The lowermost Aptian Barbalha Formation (Assine, 1992) was included in the Santana Group by Assine et al. (2014) and Neumann and Assine (2015). In accordance with the latter authors, we consider that the Santana Group comprises the Barbalha, Crato, Ipubi and Romualdo formations. Also, the group represents the stratigraphic record of the local Alagoas Stage (Upper Aptian to basal lower Albian) and of the post-rift I sequence of the Araripe Basin (Assine, 2007).

The Romualdo Formation comprises all Santana Group strata that succeed the evaporite sequence of the Ipubi Formation, which was recently restudied by Nascimento et al. (2016). At the top, the unit is disconformably overlain by alluvial sequences of the Araripina and Exu formations of the Exu Group (Assine et al., 2014; Fig. 2). The unit is very fossiliferous with abundant macrofossils (e.g., Beurlen, 1971b; Mabesoone and Tinoco, 1973; Martill, 2007), and microfossils (Lima, 1978; Arai and Coimbra, 1990; Coimbra et al., 2002; Antonietto, 2010; Antonietto et al., 2012).

The Romualdo Formation embraces a ~3- to 5-m-thick, concretion-rich black shale unit that is world-wide known for its well-preserved macrofossils, including fishes (e.g. Santos and Valença, 1968; Martill, 1988; Maisey, 1991; Fara et al., 2005), pterosaurs (e.g. Vila Nova et al.,

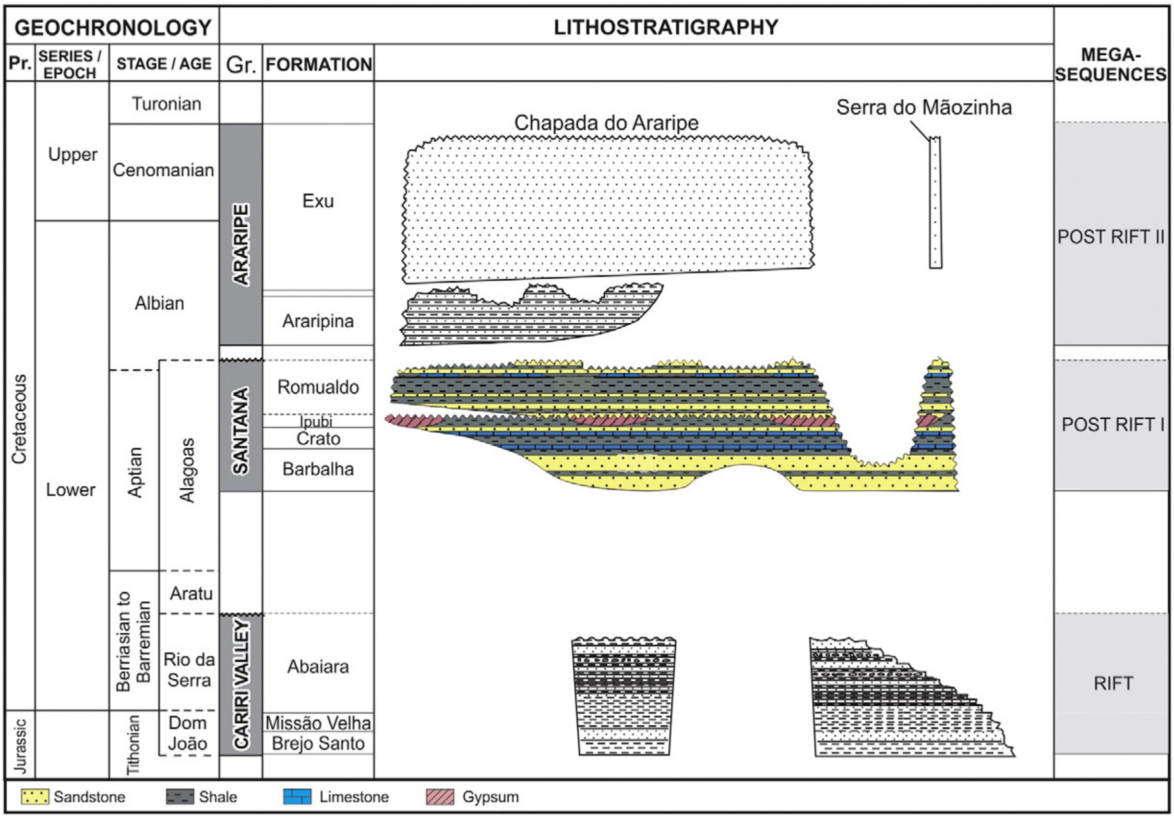

Fig. 2. Post-rift I megasequence (stratigraphic chart of the Araripe Basin modified from Assine, 2007).

2011; Martill, 2011; Aires et al., 2014), turtles (e.g. Meylan, 1996; Hirayama, 1998; Kellner and Campos, 1999; Romano et al., 2013), dinosaurs (Kellner, 1997; Kellner and Campos, 2000), and crustaceans (Santana et al., 2013; Pinheiro et al., 2014).

Various paleoenvironmental scenarios of the Romualdo Formation have so far been proposed for the level of fossil-bearing concretions. For example, based on a diverse and very well-preserved fossil fish fauna, Santos and Valença (1968) hypothesized an estuary as the depositional environment of the concretion-bearing black shales. Subsequently, a large gulf or embayment connected with the open sea, but influenced by high seasonal freshwater influx was envisaged by Mabesoone and Tinoco (1973). In contrast, a predominantly non-marine setting was suggested by Maisey (1991) and Martill (2007).

Marine incursions are documented by microfossils recorded in cores of the well 2-AP-1-CE (for location see Fig. 1), which include dinoflagellate cysts, ostracodes and foraminifers typical of coastal environments (i.e., lagoons and estuaries; Arai and Coimbra, 1990; Coimbra et al., 2002). According to Heimhofer and Hochuli (2010), the low diversity of dinoflagellate cysts suggests a restricted marine environment during the deposition of the Romualdo Formation.

The other key fossil-bearing interval occurs near the top of the Romualdo Formation and is characterized by 5- to 30-cm-thick shell beds rich in gastropods and bivalves (Beurlen, 1962, 1963, 1964, 1966, 1971a, 1971b; Mabesoone and Tinoco, 1973; Santos, 1982; Prado et al., 2015; Pereira et al., 2016), and echinoids (Beurlen, 1966; Manso and Hessel, 2007, 2012; Prado et al., 2016). The occurrence of echinoids is undisputable evidence of the Cretaceous marine transgression in the Araripe Basin.

The age of the Romualdo Formation is not precisely constrained (see Martill, 2007). Based on microfossils, an Early to Middle Albian age was proposed by Coimbra et al. (2002), whereas Heimhofer and Hochuli (2010) restricted the age to the Early Albian. Palynological data from various shallow wells drilled in the basin, including the 1-PS-12 (for location see Fig. 1) indicate that all the sedimentary succession is late Aptian and lacks any Albian taxa (Rios-Netto, 2011; Rios-Netto et al., 2012).

3. Dataset and methods

Subsurface data of the Romualdo Formation is quite scarce, which makes it essential to measure vertical stratigraphic sections in outcrops to better understand the stratigraphic architecture of the unit. This can be done along slopes of the Araripe plateau, but the task is hampered due to gravity flow deposits associated with the scarp retreat that commonly cover rock exposures. This fact explains why there are no detailed measured sections available in the geological literature.

We visited and described several available surface exposures along the outcrop belt of the Romualdo Formation on the eastern side of the Araripe plateau. Fortunately, we found good and continuous sections in small streams that cut the debris deposits so exposing the Cretaceous succession. We measured in detail many stratigraphic sections and described sedimentary facies in terms of lithology, sedimentary structures and fossil occurrences.

We also collected paleocurrent information from cross-bedded sandstones in order to incorporate it, for the first time, into the stratigraphic analysis of the Romualdo Formation. Alluvial facies provided important information on the sediment source-area and on the depositional dip of the basin.

In this study, we present four stratigraphic sections aligned approximately along the direction of the paleodepositional dip of the basin (Fig. 1), as well as description and analyses of five facies associations. Because the Sobradinho is the thickest and most complete section in terms of facies, a systematic sampling was done to investigate the total carbon content (TOC), the organic facies and the microfossil content. These analyses were performed in the Laboratório de Palinofácies e Fácies Orgânica (LAFO) at the Federal University of Rio de Janeiro (UFRJ), Brazil.

We analyzed the stratigraphic correlation of all sections to identify the bounding surfaces and the maximum flooding zone and, thus, to compose the sequence framework of the unit. The stratigraphic succession of facies associations and the lateral facies changes allowed definition of depositional systems tracts.

4. Facies associations

4.1. Alluvial coastal plain facies (FA-1)

4.1.1. Description

Pebbly, trough cross-bedded sandstones with abundant quartz, feldspar and rock fragments characterize this facies association. Centimeter-thick layers of polymictic conglomerates with granite and gneiss gravels are also recorded. This highly immature coarse-grained facies commonly occur as scour fill deposits that incorporate intraclasts eroded from the underlying mudstone deposits. Facies changes are common and fine-grained deposits occur laterally and interbedded with the coarse-grained facies. Meter-scale heterolithic facies composed of finely interbedded black shales with abundant ostracodes and carbonate laminites (ostracod-rich wackestones and packstones) locally occur interbedded with coarse-grained facies (Fig. 3).

4.1.2. Interpretation

The coarse-grained sandstones and conglomerates are alluvial facies deposited by ephemeral streams, the occurrence of which is strictly associated with a mountainous source-area on the northern border of the basin. Since this facies association laterally changes to tide-dominated facies, its deposition may have occurred on coastal plains. The heterolithic facies are deposits of shallow bodies of water (lagoons) present along the coast, separated from the sea but with variable salinity due to fresh and/or salt water inflow.

4.2. Tide-dominated coastal facies (FA-2)

4.2.1. Description

This facies association is made up of interbedded sandstones and green/gray shales of variable thickness. The cross-bedded sandstones are fine- to medium-grained, varying from dm-thick to 2- to 3-m-thick bedsets, locally with current ripples and flaser bedding (Fig. 4). The recurrence of mudstone and sandstone layers is very common in some intervals resulting in a heterolithic facies, with flaser, wavy and lenticular bedding. Concentrations of marine gastropod and bivalve shells on the foresets of sandstone bedsets occur in the upper part of the Sobradinho section, along with well-preserved fossil plant remains. Paleocurrents measured in these facies display unimodal or bimodal patterns and some beds exhibit a sigmoidal geometry and occasionally mud-drapes on foresets of cross-beds (Fig. 4).

4.2.2. Interpretation

Heterolithic facies with wavy and linsen bedding, sigmoidal sandstones with mud drapes on the foresets and in between the sandstone bodies, and paleocurrents indicating opposite directions point to an environment influenced by tidal currents. The presence of plant debris and concentrations of reworked shells of marine gastropods and

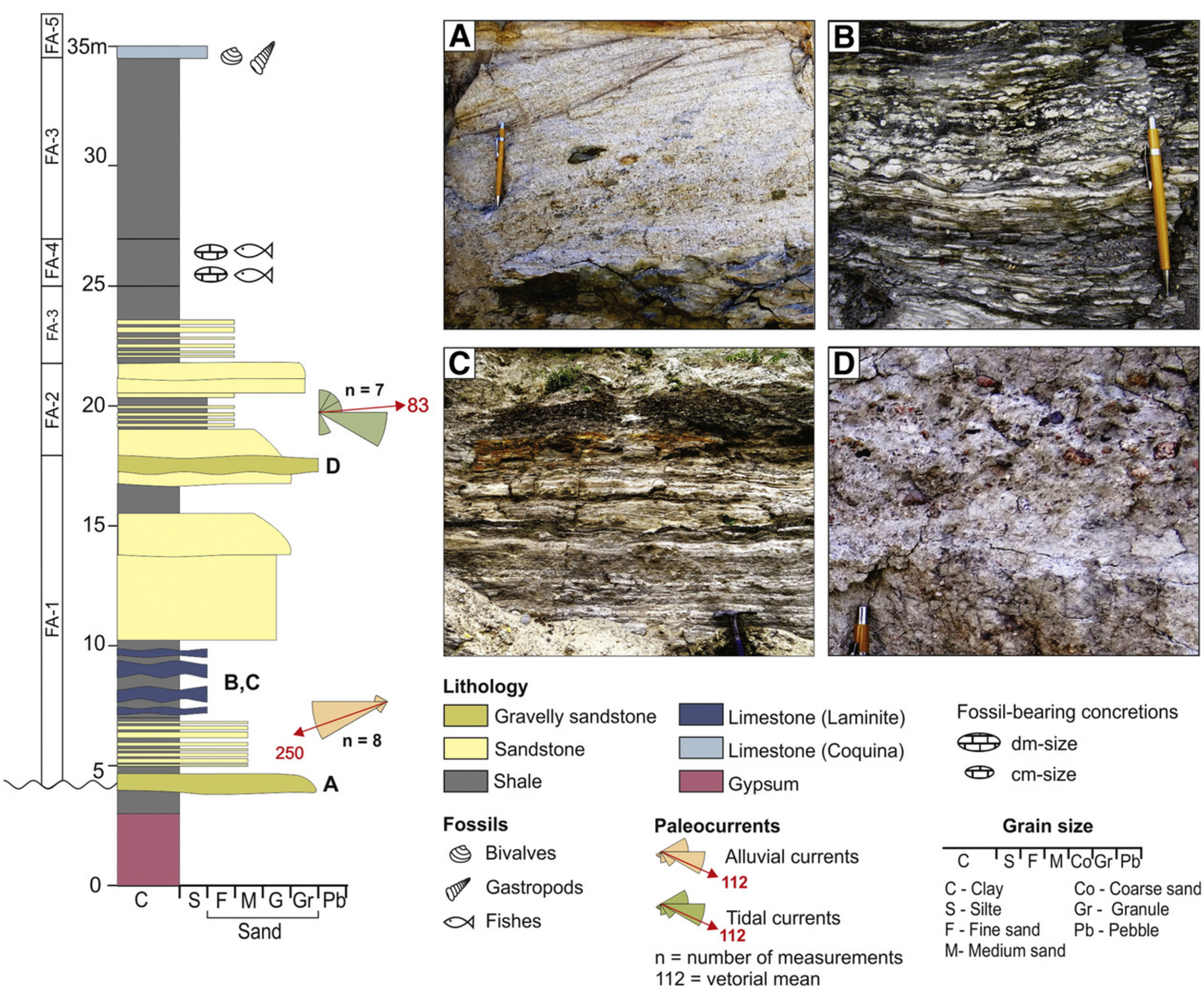

Fig. 3. Facies associations FA-1 in the Pedra Branca Section. (A) Pebbly, trough cross-bedded, coarse-grained sandstone; note the presence of rip-up mud clasts in the foresets; (B and C) heterolithic facies composed of dark shales interbedded with carbonate laminites; and (D) polymictic conglomerate interbedded with coarse-grained sandstones.

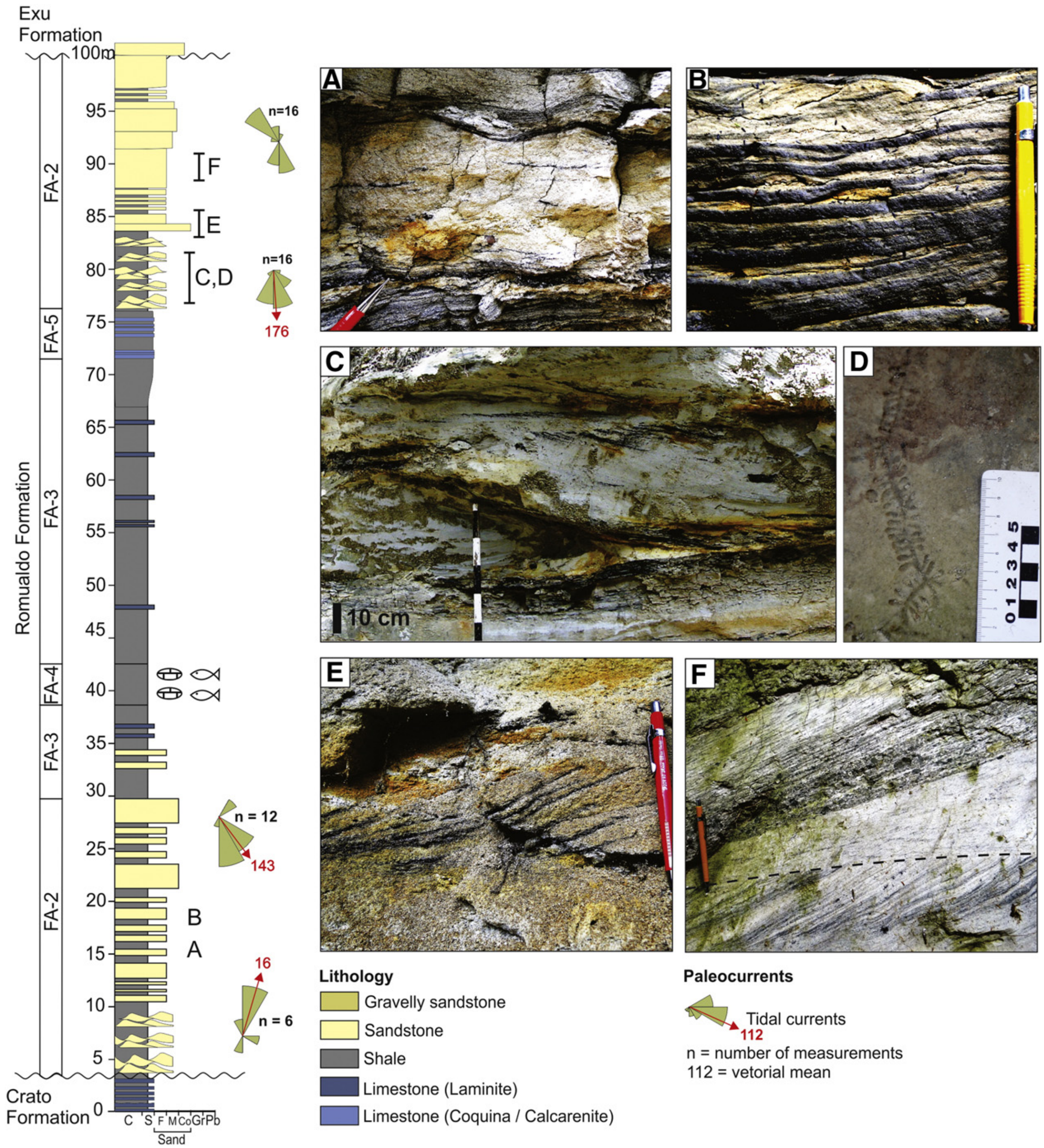

Fig. 4. Facies associations FA-2 in the Sobradinho Section. (A, B) Heterolithic facies with flaser, wavy and lenticular bedding; (C) Sigmoidal cross-bedded sandstones with mud drapes in the foresets; (D) carbonized plant imprint in interbedded massive silty sandstones: (E) gastropod shells on the foresets of cross-bedded sandstones; and (F) mud drapes on foresets of cross-bedded fine-grained sandstones.

bivalves suggest that this facies association was formed in coastal depositional environments.

4.3. Inner shelf marine facies (FA-3)

4.3.1. Description

Medium to dark gray, fossil-rich (bivalves, gastropods, shrimps) shales constitute this facies association. The percentage of organic matter is variable and phytoclasts are common in silty-shale intervals. Decimeter-thick bioclastic limestone beds occur interbedded within the shale section, occasionally showing hummocky cross-stratification, or developed as bivalve and gastropod shell beds. Fine- to medium-grained cross-bedded and rippled sandstones can be present, particularly in proximal settings (Fig. 4).

4.3.2. Interpretation

A shallow marine environment is attested by marine mollusks occurring along the section and by dinocysts recovered from many shale samples. Petrographic analyses of intercalated limestones revealed the presence of miliolid foraminifers, indicative of marginal-marine protected environments (Dias-Brito et al., 2015b). The total organic carbon percentage, the types of organic matter and the presence/absence of marine palynomorphs are suggestive of fluctuating ecological conditions, from periods of high sea level, low sediment input

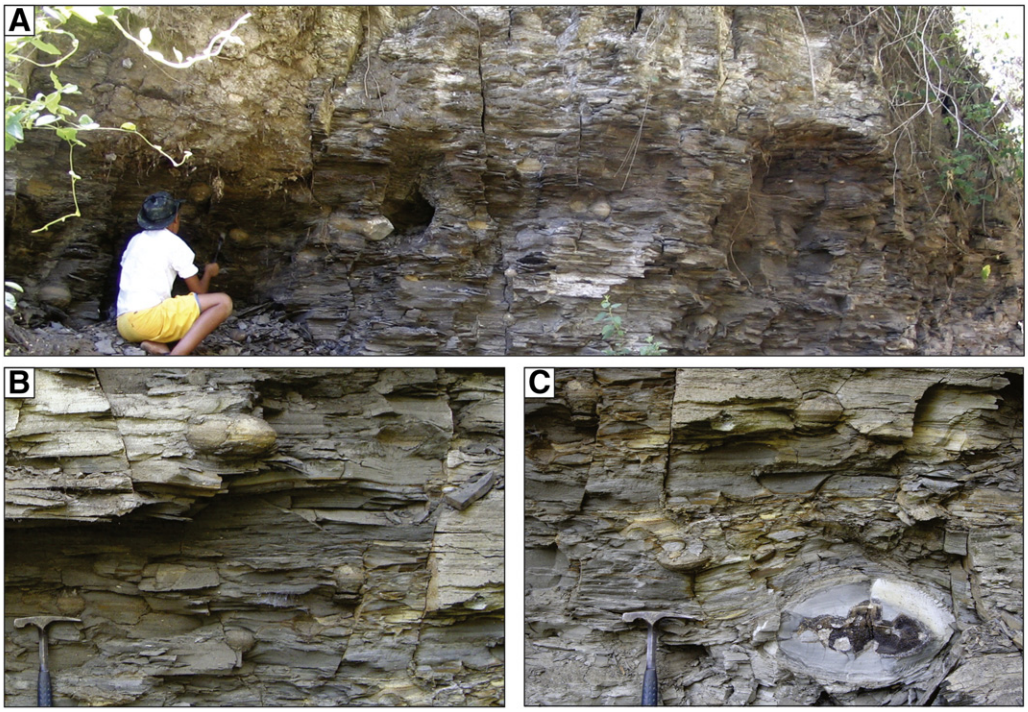

Fig. 5. Marine shales of the inner to outer shelf with discoidal and ellipsoidal fossil-bearing carbonate concretions (Facies association FA-4). Note that the shale lamination is slightly deformed by the discoidal concretion indicating its pre-compactional growth.

and dysoxic bottom waters, to periods of higher sediment supply and phytoclasts input in nearshore settings.

4.4. Inner to outer shelf facies (FA-4)

4.4.1. Description

The homogenous interval of organic-rich black shales bears fossiliferous carbonate ellipsoid concretions with very well-preserved fishes, turtles, pterosaurs, dinosaurs, and crustaceans (Fig. 5). Centimeter-thick layers of ostracod-rich limestones with hummocky cross-stratification are interspersed in the lower part of the black shales.

4.4.2. Interpretation

Fishes, turtles, and palynomorphs attest a marine setting. The high content of organic carbon (up to 12%) and the dominance of amorphous organic matter are compatible with a stratified, comparatively deep-water column and dysoxic to anoxic bottom conditions. Thin layers of limestones with hummocky cross-stratification record episodic reworking by storm-derived bottom currents.

4.5. Storm-dominated marine facies (FA-5)

4.5.1. Description

The facies association is characterized by cm-to-dm-thick beds of shelly limestones composed of dispersed to densely packed mollusk shells (mainly gastropod and bivalve shells) and occasionally with echinoids. Some beds are hybrid sandstones composed of quartz grains, shells and other bioclasts. The shell beds are internally complex, may have an erosional base, and are interbedded with gray shales rich in marine palynomorphs (Fig. 6).

4.5.2. Interpretation

A facies association generated by storm-derived currents during high energy events, which produced different types of shell concentrations depending on the shelfal topography and coastal paleogeography. Graded shell concentrations and hybrid sandstones correspond to storm deposits (tempestites) generated at variable water depths.

5. Sequence stratigraphy

The post-rift I megasequence (Santana Group) corresponds to the stratigraphic record of the local Alagoas Stage (late Aptian to very early Albian) of the Brazilian marginal basins (Assine, 2007). In the Araripe Basin, an angular unconformity separates the Aptian strata from the underlying rift succession, and the stratigraphic architecture indicate diminishing tectonic activity through time. The Romualdo Formation corresponds to the younger (third) depositional sequence of the post-rift I megasequence delineated by Assine et al. (2014), and stratigraphic relations indicate a period of tectonic quiescence. Onlap of thin layers of marine black shales in a vast expanse of the Precambrian basement (crystalline rocks) strongly suggest eustatic control on sedimentation.

An important tectonic reactivation took place after the deposition of Romualdo sequence, generating the regional unconformity that separates the megasequences post-rift I and II (Assine, 2007). This unconformity is commonly a disconformity that changes laterally to a slightly angular unconformity, especially in the western part of the basin, where tectonic activity caused block-tilting before the deposition of the Araripe Group. The Romualdo Formation is overlain by alluvial deposits of the Araripe Group. Paleocurrents towards west in the latter, measured in fluvial facies of the Exu Formation, contrast with paleocurrents towards southeast in fluvial facies of the Santana Group (Barbalha Formation). This tectonic event and the associated uplift of Northeast Brazil rearranged the continental drainage, changing the sedimentary source areas (Assine, 1994, 2007).

5.1. The unconformity-bounded transgressive-regressive cycle

The Sobradinho section reaches ~100 m in thickness and records the most complete stratigraphic profile, and can be assigned as the lithostratigraphic type section of the Romualdo Formation (Fig. 4). The formation corresponds to a depositional sequence, the top of which being the above mentioned regional unconformity between the post-rift I and II megasequences, respectively.

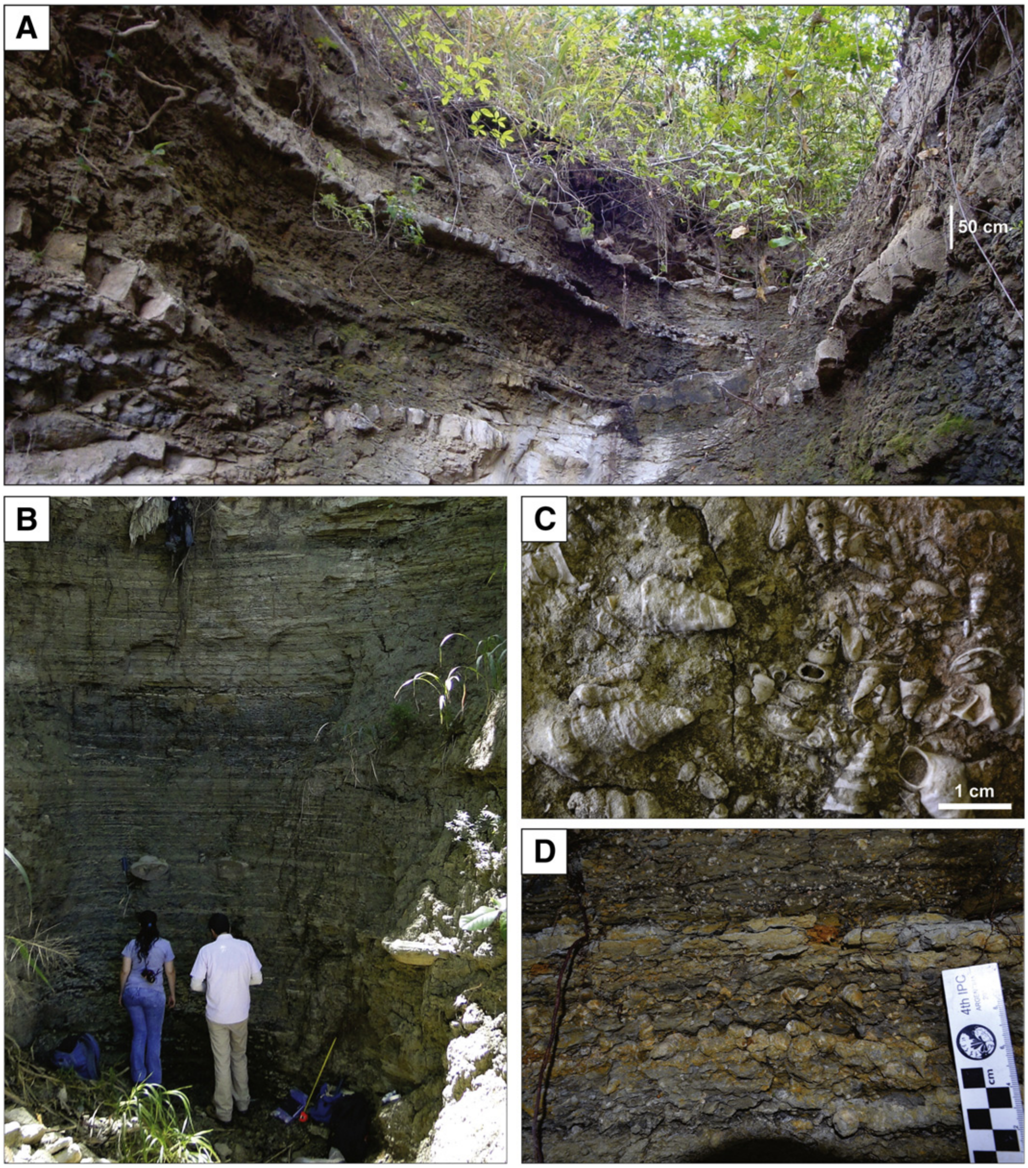

Fig. 6. Storm-dominated marine facies (FA-5). (A) Outcrop view of tabular dm-thick gastropod-rich shell beds interbedded with gray-colored shales in the Sobradinho section; (B) thin shell beds interbedded with silty shales and discoidal concretions in the Mãozinha section; (C) detail of bioclast-supported concentration of partially fragmented gastropod shells; and (D) several shell beds with thin shale interbeds containing dispersed bioclasts.

The lower sequence boundary (LSB) is an unconformity overlying diverse substrates (Assine et al., 2014). In proximal settings of the basin the lower boundary is a disconformity, where coastal-plain sediments of the lower part of the Romualdo Formation are in erosional contact with the underlying evaporite (gypsum) facies association of the Ipubi Formation (Fig. 3). Laterally it passes into a nonconformity towards the northern margin of the basin, where deposits of the Romualdo Formation directly rest on metamorphic or igneous rocks. The lower boundary tends to flatten down-dip where the sequence begins with nearshore facies. Transgressive lags interpreted as representing an early transgressive event are represented by thin flat-pebble carbonate conglomerates capping Ipubi gypsum beds and by tidal-influenced sandstones at the base in the Sítio Romualdo section (Fig. 7). Towards the basin depocenter, as in the Sobradinho section on the eastern side of the basin, evaporites of the Ipubi Formation are commonly lacking and nearshore deposits rest unconformably on the carbonate-siliciclastic facies of the Crato Formation (Fig. 4).

The LSB is a regional stratigraphic surface that changes its expression throughout the basin and corresponds to the unconformity previously recognized by Silva (1986) on the top of gypsum beds, characterized by paleokarst features. Notably, the LSB is an erosional transgressive surface at the western margin of the basin, where in many places the marine shales with fossil-rich concretions rest directly on Precambrian metamorphic rocks (Assine et al., 2014, 2016).

The maximum flooding zone (MFZ) is represented by a 3- to 5-m-thick interval of fossil-rich, concretion-bearing black shales, as already suggested by Assine (1992). This fossiliferous concretionary interval is regionally recorded across the basin and can be found resting on the Precambrian basement along the northern margin of the basin, and even far west, such as near the small city of Simões, State of Piauí (see Fig. 1 for location). Marine palynomorphs, mainly dinoflagellates (dinocysts) and palynoforaminifera, were found in this black shale interval.

The stratigraphic sections shown on Fig. 8 are aligned along the paleodepositional dip of the basin and depict a transgressive-regressive cycle, composed by transgressive and highstand systems tracts (Fig. 9). The stratigraphic framework reveals a facies-cycle wedge with coastal onlap towards north/northwest, in the opposite

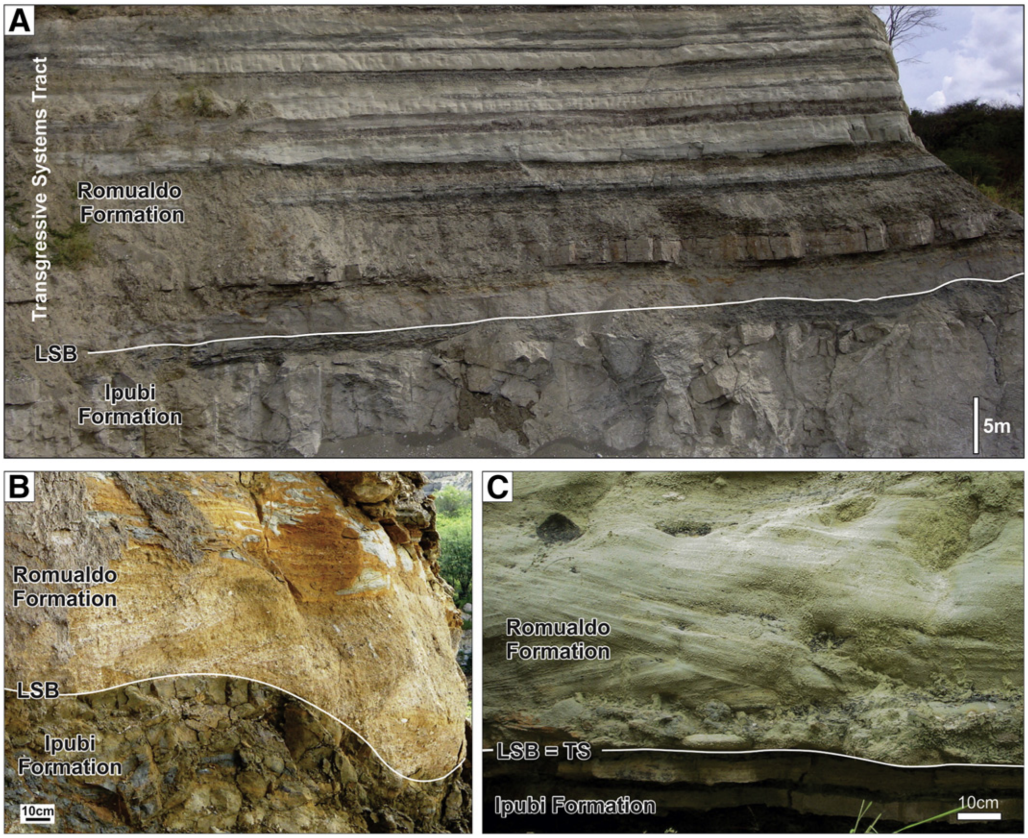

Fig. 7. The lower sequence boundary (LSB). (A) Unconformity between the Romualdo and Ipubi formations at the Pedra Branca Section; (B) detail showing the alluvial cross-bedded pebbly sandstones on the erosional basal contact; and (C) flat-pebble conglomerate resting on a transgressive surface (TS) coincident with the LSB at the Sítio Cercado section.

direction of the fluvial paleocurrents of the Barbalha Formation, the basal unit of the Santana Group (Assine, 1994, 2007; Chagas et al., 2007; Scherer et al., 2015). A depositional dip towards south/southeast is compatible with paleocurrents measured in alluvial and tidal sandstone facies (FA-1 and FA-2) of the Romualdo sequence.

5.2. Transgressive systems tract (TST)

Alluvial coastal plain deposits (FA-1) dominate the vertical profile of the TST in proximal settings. The sequence begins with pebbly trough cross-bedded sandstones with abundant feldspar and rock fragments (granites and gneisses). This very immature facies commonly occur as scour fill deposits that are associated to fine-grained deposits.

Meter-scale heterolithic facies composed of finely interbedded black shales with abundant ostracodes and carbonate laminites (ostracod-rich wackestones and packstones) locally occur, as in the Pedra Branca section (Fig. 3). According to Dias-Brito et al. (2015a), the microfossils are indicative of freshwater environment, whereas carbonate nodules occur mainly in organic-rich laminated sediments and contain agglomerates of spherulites and microbial spheres. Many packstones are composed of ostracod shells (so-called ostracodites) interpreted as having been concentrated by episodic bottom currents.

Tide-dominated facies (FA-2) progressively dominate the sedimentary succession down-dip towards southeast. The alluvial conglomerates do not occur in the Sítio Romualdo section, where the sequence begins with a cm-thick layer of flat pebble carbonate conglomerate interpreted as a transgressive lag resting unconformably on the Ipubi evaporite facies association (Fig. 7). The transgressive lag is capped by fine-grained trough cross-bedded sandstones, with thin mud layers and aligned mud balls in-between cross-bedded sets, which originated in tidally-influenced coastal environments (Fig. 8).

The stratigraphic succession in the southeastern outcrop area reveals more distal facies associations in the Araripe Basin. In the Sobradinho section (Fig. 8), the lower portion of the TST is mainly composed of mudstones with intercalations of dm-thick lenticular beds of fine- to medium-grained sandstones, with sets showing sigmoidal geometry and occasionally mud-drapes on the foresets of cross-beds (FA-2). Tabular dm-thick sets of cross-bedded medium-grained sandstones progressively increase in percentage towards the top of the section, and are replaced by 2- to 3-m-thick sandstone bedsets. Interestingly, paleocurrents measured in these facies are southward-directed, opposite to the northward-directed paleocurrents of the underlying sigmoidal and climbing-ripples sandstones, suggesting local dominance of flood or ebb tidal currents.

Despite differences in facies associations, the stratigraphic succession of the lower part of the TST exhibits an aggradational pattern, characterized by recurrence of alluvial coarse-grained sandstones in all sections, except the Sobradinho section that records distal facies composed exclusively of tide-dominated facies association (Figs. 8 and 9).

The overall occurrence of gray-green silty shales with rare cm-thick layers of fine- to medium-grained sandstones (FA-3) marks an important transgressive surface on the top of tide-dominated sandstones of FA-2 (Figs. 8 and 9). Decimeter-thick limestone beds may occasionally occur, occasionally showing hummocky cross-stratification, in which miliolid foraminifers indicate marginal-marine protected environments (Dias-Brito et al., 2015b).

The upper part of the TST is defined by an almost ubiquitous 3- to 5-m-thick interval of greenish to black shales with cm- to-dm-thick carbonate concretions (FA-4), suggesting an increase of water depth throughout the basin. The black shales bear fossiliferous ellipsoid carbonate concretions (cm to dm in size), which contain very well-preserved fossils including fishes, pterosaurs, dinosaurs, crustaceans and plant remains. The fauna preserved in the concretions

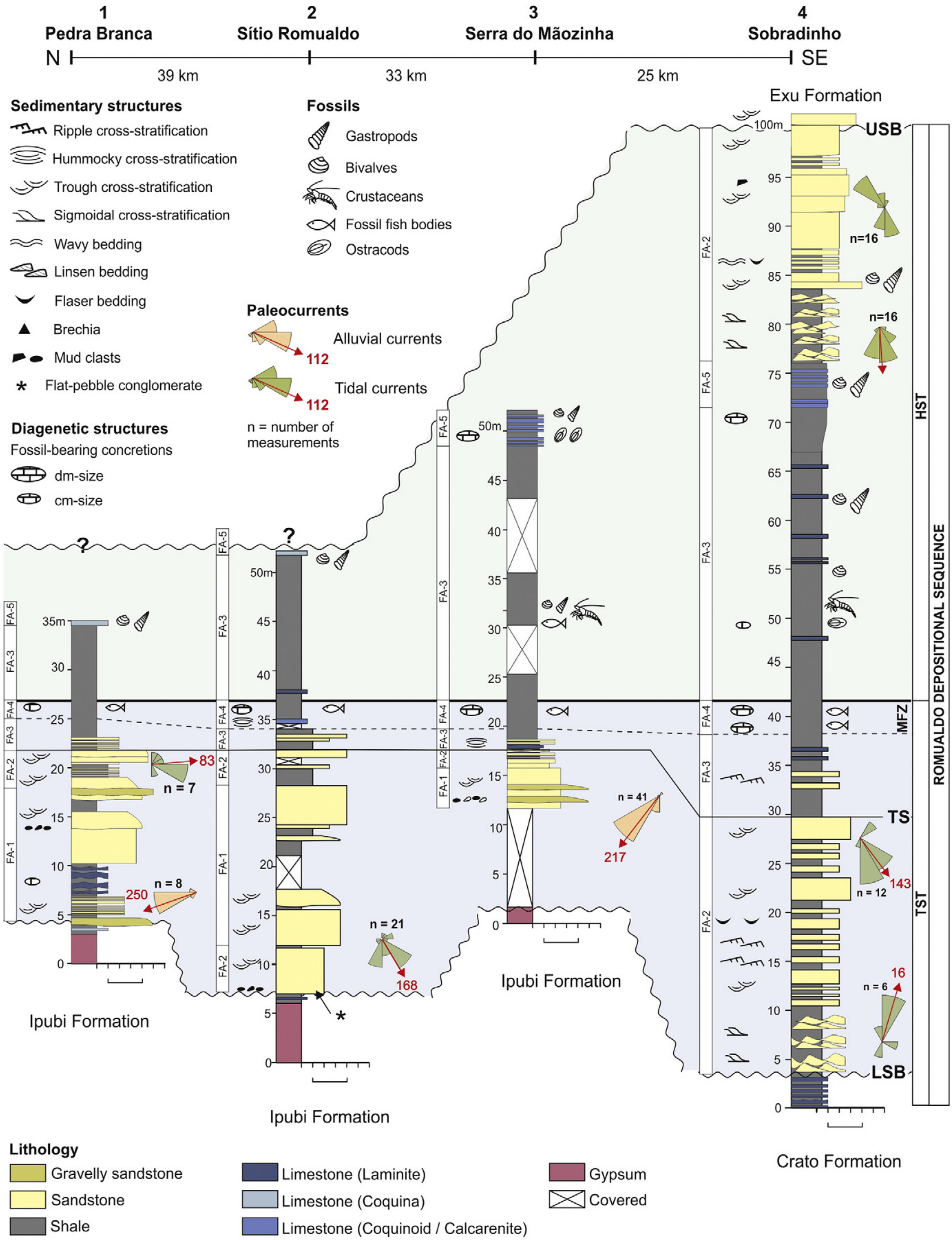

Fig. 8. Transect of the measured sections and their interpreted stratigraphic sequences. LSB = lower sequence boundary; USB = upper sequence boundary; TST = transgressive systems tract: HST = highstand systems tract; TS = transgressive surface; MFZ = maximum flooding zone. For localities see Fig. 1.

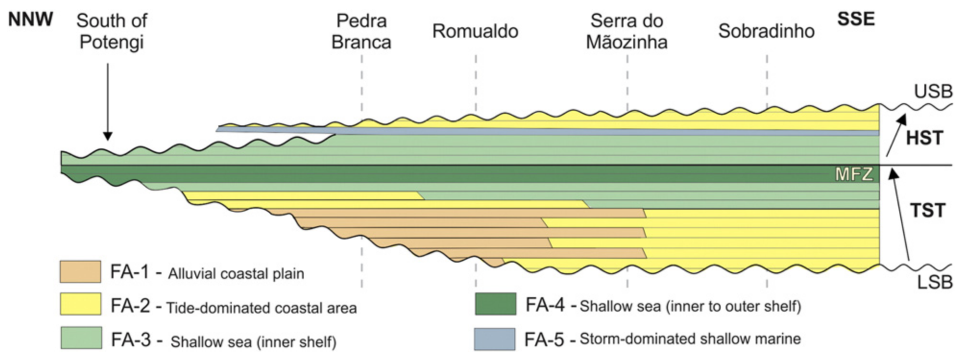

Fig. 9. Idealized diagram showing the unconformity-bounded limits and the depositional systems tracts (acronyms are the same as in Fig. 8). The transgressive-regressive wedge shows coastal onlap from SSE to NNW.

include species of marine fishes, such as *Lepidotes* (Semionotidae), *Aspidorhynchus* [=*Vinctifer*] (Aspidorhynchiformes), *Microdon* (Pycnodontiformes), *Cladocyclus* (Ichthyodectiformes), and *Rhinobatos* (Rhinobatidae), as well as fishes of brackish waters, including elopiforms of the genera *Brannerion*, *Paraelops*, and *Notelops* (Santos and Valença, 1968).

A very detailed and inspiring investigation, based on controlled excavations at the level of shales containing these early diagenetic carbonate concretions, was conducted by Fara et al. (2005), near the town of Santana do Cariri. At a place called "Parque dos Pterossauros", located ~6 km south of the Pedra Branca section, these authors recognized seven concretion-bearing horizons, four of them fossiliferous. In ascending order, the following taxa dominate the fish assemblages: (a) *Tharrhias*, (b) *Tharrhias* and *Cladocyclus* and (c) *Aspidorhynchus*. Moreover, a barren 60-cm-thick limestone bed, locally named "Matracão", separates the youngest assemblage (*Aspidorhynchus*) from the two older ones. The same basic sedimentary succession and concretion types were also recorded by Vila Nova et al. (2011) in another controlled excavation near the Sítio Romualdo (locality 2 of this study; Fig. 8). However, the regional significance of this stratigraphic control remains to be proven.

Analysis of the organic facies at the Sobradinho section confirms the transgressive pattern (Fig. 10). The abundance of marine palynomorphs (dinocysts) varies up-section, including the fossil-rich carbonate concretion-bearing interval. Black shales with very high total organic carbon values (i.e., up to 12%) and predominantly amorphous organic

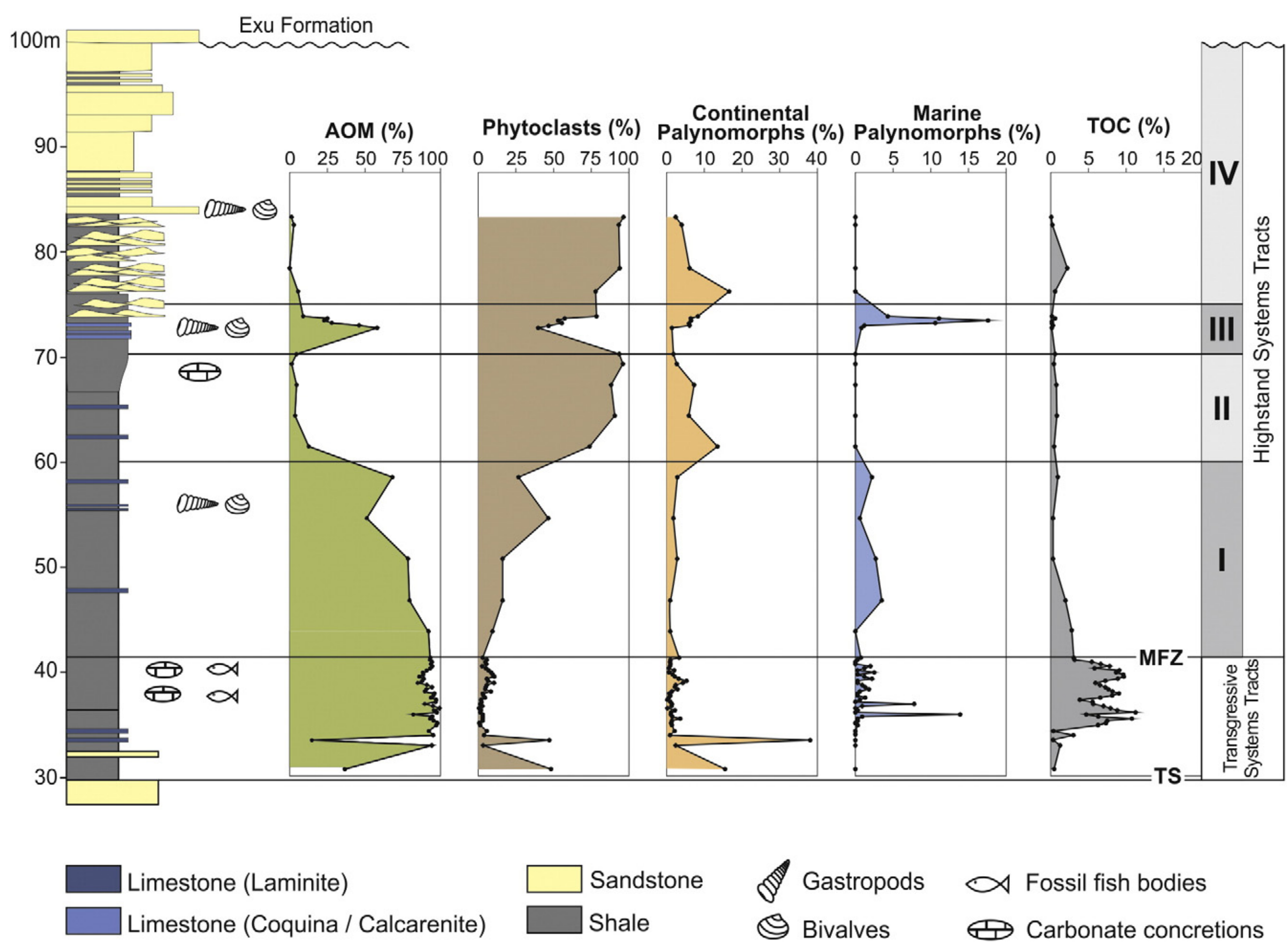

Fig. 10. Transgressive and highstand systems tracts recorded in the Sobradinho section. The four highstand phases are identified by Roman numbers. AOM, amorphous organic matter; TOC, total organic carbon; TS, transgressive surface; MFZ, maximum flooding zone.

matter, as well as a low content of phytoclasts and continental palynomorphs, are good indicators of hypoxia/anoxia during a phase of low sediment supply and reduced input of terrestrial plant remains. Similar results were also obtained in the Pedra Branca area by Heimhofer et al. (2008).

Although freshening events by runoff (Beurlen, 1971a) and associated anoxia have been suggested as the main causative factors for the high fish mortality and the genesis of the fossil-rich concretions (Martill, 1988, 1997), the intrusion of sulphide-containing waters and photic-zone euxinia are more likely (Heimhofer et al., 2008). The genesis of the concretions was also considered to result from microbially mediated processes, and controlled by fermentation and methanogenesis, generating a zone of sulphate reduction around the decaying carcasses (Heimhofer et al., 2017).

Despite the growing body of knowledge about the formation of the fossil-rich concretions, many details about the depositional environment are still obscure. For example, the presence of bottom currents must be taken into consideration, because the carbonate rocks that are interbedded with the concretion-bearing shales, as in the Sítio Romualdo section (Fig. 4), are ostracod-rich limestones with hummocky cross-stratification. These are wave- or current-induced structures, recording episodic storm events during the marine flooding. During these high-energy events, anoxic bottom waters and organic-rich sediments have been reworked and this may be associated with fish mass-mortality events (Martill et al., 2008).

We did not establish a maximum flooding surface because of the lack of reliable criteria to precisely define it. Instead, we defined a maximum flooding zone (MFZ) that is represented by the black shale interval (AF-4), thought to be a “condensation” interval formed during a period of high sea level. The origin of black shales in shelfal environments is constrained by rapid transgression and expansion of the basin, which favor starvation in deep water settings because of the rising sea-level and sediment entrapment in coastal systems (Wignall, 1991; Wignall and Maynard, 1993).

A retrogradational stacking pattern is confirmed in all sections by the stratigraphic packing, from inner shelf (FA-3) to outer shelf (FA-4) marine facies associations. The top of the MFZ is the upper limit of the TST, whose thickness decreases slightly from southeast (15 m) to northwest (10 m), whereas sandstones gradually become more and more common towards the basin margin (Fig. 8). The systems tract thins abruptly towards the basin margin south of the town Potengi, where transgressive, fossil-rich, concretion-bearing shales rest directly on the Precambrian basement (Fig. 9).

5.3. Highstand systems tract (HST)

Following the level of fossil-rich carbonate concretions, the base of HST is dominated by marine inner shelf facies (FA-3), mostly marine fossil-rich (i.e., ostracods, bivalves, gastropods, shrimps, and fish remains) shales, with thin interbedded limestones (Fig. 8). The shale interval thickens down-dip and is commonly capped by cm- to dm-thick tabular beds of shelly limestones that comprise a diversity of facies commonly made up of dispersed to densely packed mollusk shell concentrations (mainly gastropods and bivalves, Fig. 6).

The sequence shows a progradational pattern, but the upper facies are commonly not preserved because of erosion that preceded the deposition of the overlying alluvial facies of the Exu Formation. This process generated an unconformity on the top of the sequence. Unfortunately, these progradational facies are not well-exposed, since the rocks are usually covered by recent debris flows and talus deposits that are associated with the escarpment retreat of the Araripe plateau.

As outlined above, the Sobradinho section is the most complete one of the Romualdo Formation. Based on a detailed facies description combined with a systematic sampling of rocks and fossils and on an analysis of the organic facies, four distinct depositional phases were recognized and the environmental changes during the highstand traced (Fig. 10).

Accommodation space created during transgression was progressively filled up during a period of slow sea-level rise and aggradation (phase I). The fossil content (i.e., dinocysts, bivalves and gastropods) suggest sedimentation in marine settings. However, the increase of phytoclasts up-section indicates increasing continental sediment supply and freshwater influx from the surrounding land areas. Ostracod species recovered from a coeval interval in the well 1-PS-12 (well location on Fig. 1) corroborate the existence of a water body with fluctuating salinity (Antonietto et al., 2012). Terrestrial organic debris composed of fusain (i.e., charcoal) recovered from the carbonate concretions is interpreted to be the result of wildfires in an arid hinterland (Martill et al., 2012).

The aggradational phase is followed by the beginning of progradation before sea-level stillstand (phase II). In distal settings (Sobradinho – Fig. 10), abrupt disappearance of marine and enhanced appearance of continental palynomorphs, low AOM and TOC percentages, and high content of phytoclasts, also observed macroscopically in the field, associated with elevated silt content, indicate an important environmental change due to renewed sediment supply and much freshwater influx, probably leading to an important drop in salinity. The stratigraphic succession is regressive, and changes in shelf deposits are interpreted as a result of shoreline progradation and increased input of continental sediments and plant debris from nearby land areas.

Accommodation space is not created in coastal settings during stillstand phase. Instead, previous deposited sediments may be eroded and redistributed by marine processes (phase III). Recurrent high-energy events induced by tidal currents and storms reworked the bottom sediments of the shallow sea. Resedimentation produced distinct shell concentrations depending on the depth, bottom characteristics and shoreline morphology, although invariably mollusks (gastropods and bivalves) dominate. Shales interbedded with the shell beds are rich in marine palynomorphs and in AOM (Fig. 10), confirming this interval as an important stratigraphic marker during stillstand, an easily recognizable facies association (FA-5) that can be traced regionally across the basin.

The shell beds are internally complex, cm-thick dense concentrations of gastropods and bivalves, some showing discontinuous grading and erosional base (sensu Fürsich and Oschmann, 1993). These features indicate that the shell beds were generated by high energy events and may correspond to storm-induced concentrations (i.e., tempestites; e.g., Sales, 2005; Prado et al., 2016). Tabular dm-thick shell beds are present in the sedimentary succession of the Romualdo Formation at Sobradinho (Fig. 4), some are shell-rich limestones or true shell beds, but at least one of them is a hybrid sandstone composed of scattered shells in a matrix of quartz and bioclastic sand.

From the shell beds towards to the top, the stratigraphic succession is highly progradational (phase IV). This late HST is only partially preserved because its deposits were commonly removed by erosion before sedimentation of overlying alluvial deposits of the Exu Formation (Assine et al., 2014). Where present, the upper progradational facies are commonly covered by recent gravity-flow deposits produced during the escarpment retreat of the Araripe plateau (Morales and Assine, 2015). The only section where the late HST was measured is Sobradinho, the stratigraphic pattern of which shows a typical progradational coarsening-upward sequence (Fig. 8), with no marine palynomorphs and abundant continental palynomorphs and phytoclasts (Fig. 10).

The late HST deposits are tide-dominated facies (FA-2) composed of sandstones and heterolithic facies. Bedding in heterolithic facies varies from wavy to flaser types depending on the clay content, whose color can be black (TOC $<2\%$) or vivid green. Linsen sandstones locally dominate and reveal southward-directed paleocurrents (ebb-tidal flow). Sigmoidal fine-grained sandstones occur interbedded with the heterolithic facies and commonly exhibit mud drapes on the foresets of cross-beds and mud clasts scattered or concentrated between sets. Sigmoidal foresets tend to flatten down-dip passing laterally into heterolithic facies. Sandstones predominate up-section and record a bimodal paleocurrent pattern oriented NNW-SSE. Locally, turritellid gastropod shells occur on foreset planes of the regressive sandstones.

6. Implications for paleogeographic reconstructions

During latest Aptian times, the marine ingression extended far inland, reaching the Araripe Basin in the interior of Northeast Brazil and forming a vast epeiric sea. These seas are complex land-locked water masses over continental crust, whose history is usually marked by short-lived sea-level changes, followed by abrupt fluctuations in salinity, temperature, and oxygenation. The sedimentation pattern is also complex, since sediment influx from different directions and source areas are recorded, resulting in frequent mixture and coexistence of marine, brackish and non-marine settings. In our opinion, this is the main reason for the distinct and conflicting paleoenvironmental interpretations already proposed for the Romualdo Formation.

Contrasting paleogeographic reconstructions suggest that the marine ingression occurred through different pathways, i.e. (1) from the north, through the São Luís and Parnaíba basins (Beurlen, 1963, 1966; Braun, 1966; Arai et al., 1994; Arai, 2014; Prado et al., 2015); (2) from the northeast, through the Potiguar Basin (Lima, 1978), and (3) from the southeast, crossing the limits of the Sergipe-Alagoas Basin (Mabesoone and Tinoco, 1973; Assine, 1994).

These different possibilities were discussed in detail by Assine et al. (2016). The Tethyan faunal affinity has been used as argument to propose a marine ingression from the north (Arai, 2014), but the fossil content alone is not sufficient evidence to postulate a particular seaway ingression into the interior of the continent. Connection through the Parnaiba Basin is not supported by stratigraphic architecture and paleoenvironments of the Codó Formation (Rossetti et al., 2000; Paz and Rossetti, 2006). A similar situation is observed with respect to the Potiguar Basin, in which the Aptian Alagamar Formation shows a proximal to distal transition towards northeast, indicating a distinctly different continental paleo-drainage than that observed in the Araripe Basin (Assine, 1994). In other words, the stratigraphic and sedimentologic information suggest a drainage divide between the Araripe and Potiguar basins roughly following the Patos Lineament (Assine et al., 2016).

Our data suggests that the stratigraphic architecture of the Romualdo Formation portrays a facies-cycle wedge with coastal onlap towards north and a thickening of the whole sequence towards the SE quadrant (Fig. 11). Paleocurrents, measured in alluvial coarse-grained sandstones and shallow, tidal-influenced fine-grained sandstones of the TST, are consistent with the interpretation of sediment source-areas in the north of the basin and a depositional dip towards south. Sandstone facies, as those observed in the distal Sobradinho section, are tidally influenced and show bimodal paleocurrents towards north

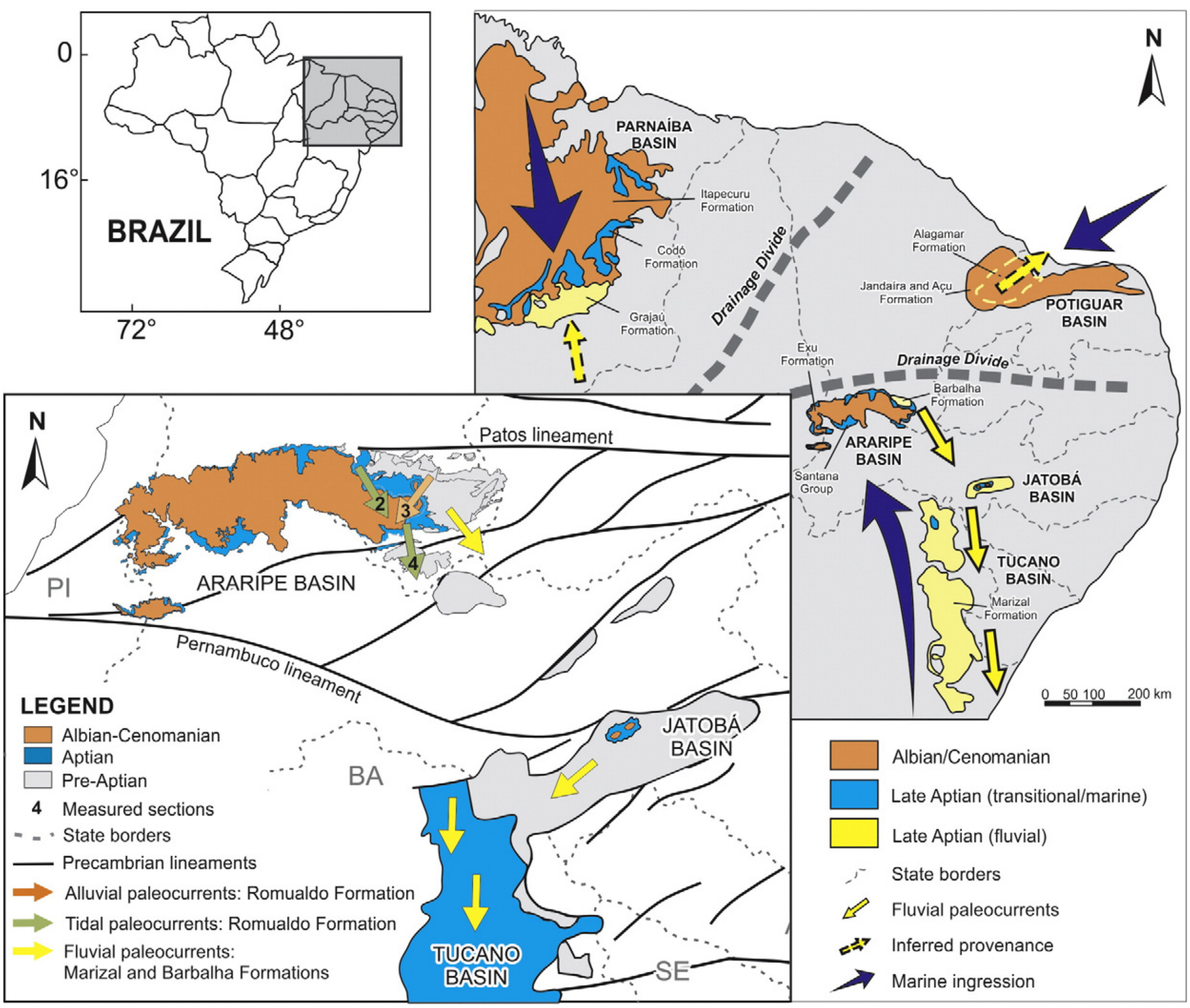

Fig. 11. Paleogeographic reconstruction of northeastern Brazil during Aptian times. The yellow, green and red arrows represent the main sediment routes based on paleocurrent data. Note the presence of paleo-highs that divides the Potiguar and Parnaíba basins from the Araripe and Tucano basins. Sediment input was consistently to the south from the Araripe Basin. Consequently, the marine ingression (blue arrow) is assumed to have taken place towards the north, upstream along the fluvial valleys. Based on Assine et al. (2016) and Varejão et al. (2016).

and south (Fig. 8). Remarkably, fossil-rich carbonate concretions recorded in the "Parque dos Dinossauros" locality are elongated and their longest axes show a NNW-SSE orientation (Fara et al., 2005). This is interpreted as result of constant low-energy bottom currents (Fara et al., 2005), roughly oriented perpendicularly to the coastline, up and down the depositional dip.

Our data also fits very well the available information on fluvial paleocurrents of the Barbalha Formation, at the base of the Santana Group, which consistently indicate a continental paleo-drainage towards southeast, in the direction of the Tucano Basin. Fluvial paleocurrents towards south have also been established for the Aptian Marizal Formation of this basin (Varejão et al., 2016), supporting the interpretation that both basins belonged to the same continental drainage basin. Considering this paleogeographic scenario, the marine ingression reached the southernmost areas of the Araripe Basin via the Tucano Basin, following upstream river valleys (Assine, 1994, 2007), in an opposite direction of that proposed by Arai (2014). The stratigraphic architecture and paleocurrents of the Romualdo Formation reinforce the paleogeographic reconstruction (Fig. 11) suggested by Assine et al. (2016).

In addition, remnants of Aptian deposits are not found in the Cretaceous Rio do Peixe and Iguatu basins, located between the Araripe and Potiguar basins. It is noteworthy that the Santana Group occurs south of the Patos Lineament, in the Tucano (Serra do Tonã) and Jatobá (Serrra Negra) basins, with the same stratigraphic succession as in the Araripe Basin (Varejão et al., 2016). This strongly supports the existence of an epeiric sea connected to the ocean via the Reconcavo/Tucano/Jatobá rift system. In the Brazilian Northeast Interior, regional uplift and denudation events took place in the Campanian to Miocene time interval (Magnavita et al., 1994; Japsen et al., 2012) and were responsible for the relict preservation of the Aptian megasequence, the sedimentary record of which is now found scattered across the area.

7. Final remarks

The stratigraphic record of the Romualdo Formation is a key to unravel the paleogeographic and paleoenvironmental setting of the Araripe Basin, in response to the fragmentation of Gondwana and the opening of the South Atlantic Ocean. By providing a stratigraphic framework of the Romualdo sequence, together with data on facies, paleocurrents and paleontology, we found that the Romualdo Formation marks a key late Aptian marine ingression across a broad area of interior NE Brazil. This scenario is supported by several novel interpretations and data, such as:

(1) The architectural framework of the Romualdo Formation is a depositional sequence bounded by unconformities. The Romualdo Formation rests disconformably on the underlying Ipubi and Crato formations, or as non-conformity on Precambrian basement. The upper sequence boundary is a remarkable regional unconformity with the overlying alluvial sequences of the Araripe Group (Exu and Araripina formations).

(2) The depositional sequence comprises transgressive and highstand systems tracts. The transgressive systems tract includes coastal alluvial and tide-dominated facies, and marine black shales that encompass the maximum flooding zone. Theses black shales represent anoxic to dysoxic facies, with high total organic carbon contents (up to 13%) and an interval including fossil-rich carbonate concretions. Together with fishes and turtles found in the concretions, the marine nature of the sediments is confirmed by the presence of palynomorphs (dinocysts and palynofacies).

(3) The highstand systems tract is a progradational package that records gradual continentalization at the end of the Romualdo sequence. Tidal-influenced sandstones and heterolithic facies predominate, but the most remarkable deposits are those associated with processes such as wave-induced erosion and re-sedimentation of shelf sediments. These resulted in cm-thick, internally complex shell beds, recording brief transgressive events during stillstand phases.

(4) Facies and consequently systems tracts are arranged in a transgressive-regressive facies-cycle wedge, with coastal onlap towards the north and northwest, where marine facies overstep the basin margin, resting directly on basement rocks. A NNW-SSE oriented paleo-depositional dip is also supported by paleocurrents of tidal-influenced sandstones and heterolithic facies of the transgressive and highstand systems tracts.

(5) The stratigraphic record of the Romualdo Formation implies the existence of an epicontinental sea in the interior of northeastern Brazil, the original size of which was much larger than the Present-day area of the Araripe Basin. A remaining key question, namely the direction of the marine ingression, can be answered by our data on basin architecture and paleocurrents. Together with the available geological and paleontological data, they support the interpretation that the sea reached the Araripe Basin from the southeast.

Finally, despite of our progress on the Cretaceous stratigraphy and paleogeography of the Araripe Basin during deposition of the Romualdo Formation, various key details of the paleoenvironmental evolution of this interval are still missing but deserve to be investigated. Although beyond the main scope of the present study, they are briefly stressed here, since they could constitute future research avenues for the Cretaceous of the Araripe Basin. First, our detailed sampling strategy of the fossil-rich, concretion-bearing shales and associated facies show that the mudstones are richer in fossils than previously realized. Fossils of the benthic invertebrates are not randomly distributed in these facies and high-resolution study of these apparently barren rocks could provide details on oxygen bottom variations (i.e., periods of ventilation versus anoxia), phases of substrate colonization and mass mortality. Second, most studies on the carbonate concretion level are based on the fossils found within the concretions, but little is known about the geochemistry of these diagenetic structures. A multiproxy study of the concretions, including detailed data on their fossil content, sedimentology, geochemistry, and stratigraphy can provide valuable information on the triggering genetic mechanisms and time of concretion genesis. Third, many different types of shell-rich concentrations rest on ravinement surfaces (Assine, 2007). However, these have not yet been precisely described or interpreted, and may be an important tool for basin analysis (see Fürsich and Oschmann, 1993). Fourth, despite the progress on our knowledge about the taphonomy and stratigraphy of some shell beds of the Romualdo Formation, a detailed analysis is still missing. For example, little is known about the taxonomic composition of the bioclastic-rich deposits, and their taphonomic and sedimentologic attributes. Moreover, the broad stratigraphic meaning of these shell-rich deposits deserves to be investigated in detail.

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