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ARTICLE

High resolution stratigraphy of initial stages of rifting, Sergipe-Alagoas Basin, Brazil

Estratigrafia de alta resolução dos estágios iniciais de rifteamento, Bacia de Sergipe-Alagoas, Brasil

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ABSTRACT: The present work aims to characterize the Neo-Jurassic to Neocomian succession of the Sergipe-Alagoas Basin, located in northeast region of Brazil, in order to discover the influence of tectonics on sedimentation in detailed scale and thus separating this sedimentary succession in tectono-stratigraphic units. Fieldwork observations and stratigraphic sections analysis allowed subdividing this rift succession into three depositional units that indicate different paleogeographic contexts. Unit I, equivalent to the top of Serraria Formation, is characterized by braided fluvial channel deposits, with paleocurrent direction to SE; unit II, corresponding to the base of Feliz Deserto Formation, is composed of anastomosed fluvial channel and floodplain facies associations; and unit III, equivalent to the major part of Feliz Deserto Formation, is characterized by delta deposits with polymodal paleocurrent pattern. The changes of depositional system, as well as paleocurrent direction, suggest that the previously described units were deposited in different evolutionary stages of rifting. Units I and II represent the record of a wide and shallow basin associated with the first stage of rifting. Unit I is characterized by incipient extensional stress generating a wide synclinal depression, associated to the low rate of accommodation and low tectonic activity. These two parameters progressively increase in unit II. The paleocurrent direction of unit I indicates that the depocenter of this wide basin was located at SE of the studied area. No conclusion could be done on paleocurrent from unit II because of the low amount of measurements. Unit III suggests a second stage marked by a deeper basin context, with a high rate of accommodation space associated with the lateral connection of faults and individualization of the half-graben. The scattering in the paleocurrent direction in this unit indicates sedimentary influx coming from several sectors of the half-graben. The boundary between these two stages is marked by a flooding surface that indicates an extremely fast transition and suggests a radical change in geometric characteristics of the basin due to the increase of tectonic activity.

KEYWORDS: Rift; Sergipe-Alagoas Basin; Serraria Formation; Feliz Deserto Formation; Sequence stratigraphy.

RESUMO: *O presente trabalho tem como objetivo caracterizar a sucessão Neo-Jurássica a Neocomiana da Bacia de Sergipe-Alagoas, localizada na região nordeste do Brasil, visando descobrir em escala de detalhes a influência da tectônica na sedimentação e separar essa sucessão sedimentar em unidades tectono-estratigráficas. As observações de campo e a análise de perfis estratigráficas permitiram subdividir essa sucessão de rifte em três unidades, que indicam diferentes contextos paleogeográficos. A unidade I, equivalente ao topo da Formação de Serraria, é caracterizada por depósitos de canais fluviais entrelaçados, com direção de paleocorrente para SE; a unidade II, correspondente à base da Formação Feliz Deserto, é composta das associações de fácies de canais fluviais anastomosados e planície de inundação; e a unidade III, equivalente à maior parte da Formação Feliz Deserto, é caracterizada por depósitos deltaicos com padrão de paleocorrente polimodal. As mudanças de sistema deposicional, bem como na direção de paleocorrente, sugerem que as unidades descritas anteriormente foram depositadas em diferentes estágios evolutivos de rifte. As unidades I e II representam o registro de uma bacia ampla e rasa associada ao primeiro estágio do rifte. A unidade I é caracterizada por tensão extensional incipiente resultando em uma ampla depressão sinclinal, associada a baixas taxas de acomodação e baixa atividade tectônica. Pode-se inferir que esses parâmetros aumentam levemente na unidade II pela preservação de sedimentos finos externos ao canal. A direção de paleocorrente da unidade I indica que o depocentro dessa ampla bacia estava localizado no SE da área estudada. Nenhuma conclusão pode ser feita com base nas paleocorrentes da unidade II por causa da baixa quantidade de medidas. A unidade III sugere um segundo estágio marcado por um contexto de bacia mais profunda, com alta taxa de espaço de acomodação associada à conexão lateral de falhas e individualização dos meio-grabens. A dispersão na direção de paleocorrente nessa unidade aponta influxo sedimentar proveniente de vários setores do meio-graben. O limite entre os dois estágios é marcado por uma superfície de inundação caracterizada por sedimentos de prodelta sobre os de canais fluviais anastomosados. Esse contato abrupto indica uma transição extremamente rápida e sugere uma mudança radical nas características geométricas da bacia por conta do aumento da atividade tectônica.*

PALAVRAS-CHAVE: *Rifte; Bacia de Sergipe-Alagoas; Formação Serraria; Formação Feliz Deserto; Estratigrafia de sequências.*

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INTRODUCTION

The recent studies on rift basins focus on the influence of tectonic on basin geometry, on distribution and connection of faults and on the ratio between accommodation and sediment supply (A/S) during the stages of rifting (Prosser 1993, Bosence 1998, Gawthorpe and Leeder 2000, Morley 2002, Kuchle and Scherer 2010). Nevertheless, there is a lack of detailed studies on characterization of depositional systems and stacking patterns of the basin for each evolutionary stage, even more in the early stages in which the identification of depocenters, the depositional systems and their distributions in basins are poorly understood (Kinabo *et al.* 2007, Morley 2002, Kuchle *et al.* 2011, Scherer *et al.* 2014).

The Sergipe-Alagoas basin is located on the northeast Brazilian margin, has an elongated shape in N45ºE direction and an onshore area of approximately 13,000 km^2 and offshore area of 40,000 km^2. The origins of Sergipe-Alagoas basin are linked to the rifting and opening processes of the South Atlantic (Schaller 1969, Assine 2007, Campos Neto *et al.* 2007). Unlike most of the Brazilian marginal basins, the Sergipe-Alagoas basin is the only one that shows the complete Jurassic-Cretaceous stratigraphic succession of rift initiation. Due to the excellent exposition of these rocks, the Sergipe-Alagoas Basin consists of an excellent case study to observe, in a detailed scale, the sedimentation in rift excavation. In submerged basins, the lack of outcrop only allows indirect methods such as seismic and well log from wildcat wells.

This paper aims to apply the concepts of sequence stratigraphy to analyze depositional architecture and the stacking patterns of the initial phases of the rift, which in Sergipe-Alagoas corresponds to the Serraria and Feliz Deserto formations. Some specific goals can be highlighted:

- To analyze the facies architecture and paleocurrent pattern of the top of the Serraria Formation and the base of Feliz Deserto Formation through the construction of high-resolution sedimentary logs.
- To propose a stratigraphic framework of the initial stages of rifting by correlation of key surfaces throughout the basin.
- To discuss the tectonic control on sedimentation and drainage system.

The results of this study are exposed in the Lithofacies, Facies association and Stratigraphic context chapters. The facies described in outcrops allowed the characterization of the depositional system and thus the creation of a paleogeographic model to understand the Tectonic-stratigraphic evolution.

METHODS

To contemplate this work, three areas were selected in the Sergipe sub-basin, where the widening of BR-101 highway has provided new outcrops with good lateral extension (Fig.1). The names assigned to these three areas represent the nearest towns: Malhada dos Bois, Japoatã and São Miguel.

At the fieldwork, the Serraria and Feliz Deserto formations were mapped allowing the construction of high-resolution stratigraphic logs. As the three studied areas are bordered by faults of uncertain displacement, for each area an individual composed stratigraphic section was elaborated build of the most representative high-resolution sections described at the fieldwork: the Malhada dos Bois compound stratigraphic section is made of the sedimentary logs measured in the points 1 and 2, which were correlated without covered interval, while the Japoatã section is built of the points 3 and 4 with a calculated covered interval of 360 m, and the São Miguel section shows the points 5 and 6 with a calculated covered interval of 400 m. In the Alagoas sub-basin no outcrops sufficiently thick to be correlated were found.

The main stratigraphic log is the Outcrop 1 (Fig.1), a135 m thick log along 650 m and the only one in which direct contact between Serraria and Feliz Deserto formations was identified.

Facies were defined mainly on the basis of grain-size and sedimentary structures, according to the Miall's (1978) code, adding the letter *i* at the end when the lamination was incipient or diffuse. Gamma Ray logs were run every 50 cm for measured sections and correlated with subsurface logs. In addition, 24 architectural panels were constructed from photo-mosaics of sedimentary section no. 1, allowing the determination of the two-dimensional (2D) geometries of the deposits and the bounding surface hierarchy (Miall 1988). Here only the most representative facies associations photo-mosaics are shown. Paleocurrent orientations were measured from cross-stratified beds and were corrected to the horizontal surface based on the S0 depositional surface (Tucker 1996). The subsurface data of this paper are from Caioba Oilfield, in the offshore area of the Sergipe sub-basin, and the Furado Oilfield located in the Alagoas onshore area. These subsurface data were extracted from Borba *et al.* (2011) and are added to give a regional support to the interpretations.

STRATIGRAPHIC FRAMEWORK

The Sergipe-Alagoas basin, similar to the other Brazilian marginal basins, is associated with the Neocomian rift event that resulted in the separation of the South American and

African continents, specially in the opening of the East Brazilian continental margin (Schaller 1969, Assine 2007, Campos Neto *et al.* 2007). The extension area of this basin comprises part of the states of Sergipe and Alagoas. There are no features dividing the basin in emerged area, as well as deep water, but, as the tectonic style and the stacking pattern in Sergipe state are different from Alagoas, two stratigraphic charts were elaborated for the basin (Campos Neto *et al.* 2007, Schaller 1969). The Mesozoic stratigraphic record of the Sergipe-Alagoas basin reflects different stages of subsidence related to three main phases (Campos Neto *et al.* 2007):

- The Pre-Rift phase, characterized by viscoelastic intra-continental lithospheric stretching taking to a regional subsidence which extended to most northeastern Brazilian basins.
- The Rift phase, with accentuated mechanical subsidence, forming graben and/or half-graben systems.
- The Post-Rift phase, characterized by the predominance of thermal subsidence.

While the Recôncavo-Tucano-Jatobá graben systems represent aulacogen basins, the Sergipe-Alagoas basin has evolved as a passive margin. Thus, the stratigraphic record of

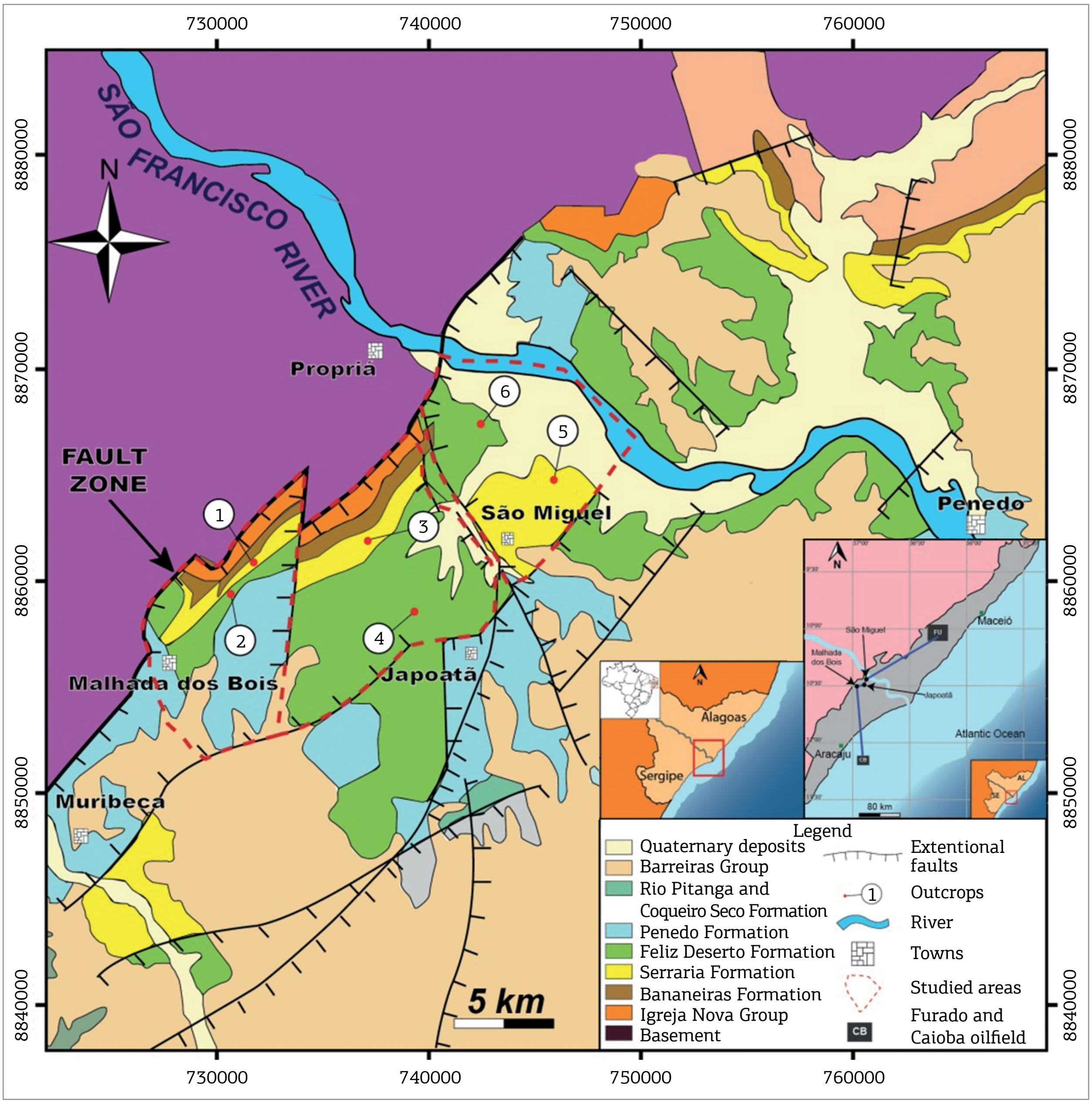

Figure 1. Simplified geological map of the eastern part of the Sergipe-Alagoas Basin, showing three fault bordered study areas where the six sedimentary logs discussed in this paper are located.

this basin comprises not only the intra-continental pre-rift succession, but the entire record of the rift evolution until those ones related to the passive margin phase.

The basement is composed of Archean to Paleozoic rocks, with different compositions being reflected in the composition of the sediments filling the basin (Souza-Lima 2006). In the northern part of the state of Alagoas, the basement is composed of granites, gneisses and migmatites, while the southern part of the state and the entire state of Sergipe are composed of folded metasediments with metamorphism ranging green shale facies to amphibolite (Souza-Lima 2006). The basement of the southern part of Sergipe is formed by Archean rocks of the São Francisco Craton and its superimposed Lagarto and Estância sedimentary formations. The Sergipe belt occurs from the Vaza Barris Fault to the north and enters a bit in Alagoas state (Almeida 1977).

Upon the basement, Carboniferous and Permian Igreja Nova Group and later the Perucaba and Coruripe groups were deposited, to which belong respectively to the Serraria and Feliz Deserto formations (Garcia 1991).

The Perucaba group corresponds to the pre-rift sequence and was deposited in intra-continental conditions between Neo-Jurassic and Eo-Cretaceous. During this period, the Sergipe-Alagoas basin represented a segment of the Afro-Brazilian Depression (Ponte & Asmus 1976) that covered the actual Namibia, Brazil and Gabon territories (Kuchle & Scherer 2010). This depression is a wide and shallow basin with small faults, and the deposits are characterized by the great lateral continuity. The Serraria Formation was deposited during the Neocomian and it is described as a succession of medium to coarse sandstones, white, greyish to reddish, poorly to moderately sorted with frequently subrounded feldspar and kaolinitic grains and locally conglomerate (Schaller 1969). These sediments represent deposits of braided fluvial channels systems with aeolian reworking (Campos Neto *et al.* 2007, Chagas 1996). The subsequent Eo-Cretaceous Coruripe Group, where the Feliz Deserto Formation is inserted, corresponds to the rift sequence and is characterized by mechanical subsidence (Campos Neto *et al.* 2007). Lithologically, the base of Feliz Deserto Formation is marked by the Caioba Sandstone, fine- to medium-grained tabular fluvial deposits up to 10 m thick (Borba *et al.* 2011), and follows a thick succession of greenish mudstones interlayered with thin sandstones beds deposited in deltaic-lacustrine environment (Campos Neto *et al.* 2007).

LITHOFACIES

Based on the fieldwork observation, the Serraria Formation is composed of quartz sandstones, mudstones and subordinate conglomerates. Texturally, the sandstones are medium- to very coarse-grained (predominantly medium), moderated- to poorly-sorted and subangular to rounded. Quartz pebbles are common mainly at the base of sets and along stratifications. Mudstones are red, with granular and blocky peds and root traces. The conglomerates have a sandy matrix and are massive or stratified, with quartz pebbles and intraformational mudstones clasts. Fragments of fossilized tree trunk are common, and bioturbations can occur.

The Feliz Deserto Formation, in turn, is composed of grey to greenish mudstones massive or laminated interlayered with fine- to medium-grained quartz sandstones moderately- to well-sorted. Based on the sedimentary logs, it was possible to recognize 12 facies (Table 1).

FACIES ASSOCIATION

The Serraria Formation is composed of one facies association: braided fluvial channel; and the Feliz Deserto Formation has four facies associations: anastomosed fluvial channel, floodplain, prodelta/distal delta front and proximal delta front.

Braided fluvial channel facies association

Description

This facies association is characterized by several sandstone bodies up to 8 m thick, composed mainly by fine- to coarse-grained sandstones moderately- to poorly-sorted and subordinate conglomerates with tabular and lenticular geometry. These sandstone bodies show sheet geometry, overlain each other and extend over 200 m, but due to the dipping of beds the lateral extension of individual beds couldn't be determinate. The sandstone bodies are amalgamated and bounded at the base by erosive surface, which in some case are marked by concentrations of granules and pebbles (Fig. 2B). Internally, the sandstone bodies exhibit weakly developed fining-upward pattern cycles. These cycles are formed at the base by massive conglomerates (Gm), with trough cross-stratification (Gt) or centimeter thick lags of coarse-grained to conglomeratic massive sandstone (Sm). Upon these basal sandstone and conglomerates occur predominantly medium-grained sandstone with trough cross-stratification (St), and may also occur in a subordinate quantity planar cross-stratification (Sp), low angle cross-stratification (Sl) and horizontal lamination (Sh). Commonly alternation between horizontal lamination and low angle cross-stratification (Sh/Sl) is observed, or between low angle cross-stratification and trough cross-stratification (Sl/St). Fine-grained sandstones with ripple cross-stratification (Sr) are found at the top of some cycles. Fragments of fossilized tree trunks up to 45 cm diameter thick were also found (Fig. 2A and 3A) at the base of sandstone bodies and numerous intraformational mudstone clasts dispersed in sandstone bodies (Fig. 2C).

Table 1. Summary of lithofacies observed in the Serraria and Feliz Deserto formations.

Facies	Description	Interpretation
Gm	Massive or stratified conglomerates and sandy conglomerates, clast supported or with medium- to coarse-grained sandstone matrix; intraformational clasts of mudstone (up to 25 cm in size); 0.2 to 1.5 m thick beds. Normal gradation and erosional base surface.	Bedload deposition as diffuse gravel sheets (Hein & Walker 1977) or lags deposits by high-magnitude flood flows (Miall 1977, Nemec & Postma 1993).
Gt	Sandy conglomerate, clast supported, granule to pebble quartz clasts; trough cross-stratified sets, 10 to 20 cm thick; normal gradation and erosional base surface.	3-D gravel dunes (Rust 1978, Todd1996).
Sh	Medium- to coarse-grained sandstone, moderated- to poorly-sorted; horizontal lamination, granules and pebbles quartz clasts dispersed, at the base of sets or along lamination. 30 cm to 4 m thick bed; rare burrows on top and normal gradation, common fluidizations and erosional base surface.	Planar-bedded deposits originated via upper flow regime (Miall 1977, Best & Bridge 1992) later modified by bioturbation (Allen 1963).
Sl	Medium- to coarse-grained sandstone, poorly-sorted; low angle cross-lamination. Common intraformational mudstones clasts (up to 7 cm in size) and quartz clasts.	Washed-out dunes and humbpack dunes (transition between subcritical and supercritical flows) (Harms *et al.* 1982, Bridge & Best 1988).
Ssg	Medium-grained sandstone; moderately-sorted; sigmoidal cross-bedding; 20 cm to 1.2, thick sets.	Lower- to upper-flow regime transitional bedform (Wizevich 1992).
St	Medium- to very coarse-grained sandstone, badly-sorted, granule and pebble quartz clasts, dispersed or at the base of sets; trough cross-stratification; 10 cm to 3.7 m thick sets; common intraformational mudstones clasts (up to 20 cm in size); normal gradation.	3-D subaqueous sandy dunes (lower flow regime) (Miall 1996,Todd 1996).
Sp	Medium- to coarse-grained sandstone, poorly-sorted; planar cross-stratification. Dispersed granule and pebble clasts, well-rounded and subangular grains. 20 cm to 1.5 m thick sets; normal gradation.	2-D subaqueous sandy dunes (lower flow regime) (Miall 1996) and folded because of fluid escape simultaneous with the flow (Todd 1996).
Sr	Very fine- to medium-grained sandstone; well-sorted; ripple cross-lamination, supercritical and rare subcritical climbing angle. 1 to 10 cm thick sets.	2D- or 3D-ripples (lower flow regime) with variation of traction/suspension ratio (Allen 1963, Miall 1977).
Sm	Fine-grained to conglomeratic sandstone; massive. 20 cm to 2.7 m thick beds; granules quartz clasts and intraformational mudstones clasts dispersed or at the base.	Rapid deposition of hyperconcentrated flows, fluidization or intensive bioturbation (Miall 1978, 1996).
Fm	Red mudstones and siltstones; massive; granular to blocky peds, root traces. 80 cm to 6.4 m thick beds	Suspension settling from weak currents or standing water; lack of lamination due to (i) flocculation of clay suspension or (ii) loss of lamination associated intensive bioturbation; post-depositional redness under oxidant conditions (Miall 1977, Foix *et al.* 2013).
Fl	Mudstones and siltstones gray and greenish gray; thin parallel lamination; with bivalve fossils; 20 cm to 8 m thick beds.	Suspension settling dominantly from standing water; post-depositional graying under reducing conditions, post-depositional greenish under reducing conditions (Turner 1980, Jo & Chough 2001).
P	Mudstone and muddy sandstone, white to gray; massive or with incipient lamination.	Subaerial exposition of sediments and obliteration of primary structures (Todd 1996)

Gm: massive conglomerates; Gt: trough cross-stratification; Sh: horizontal lamination; Sl: low angle cross-stratification; Ssg: sigmoidal cross-stratification; St: trough cross-stratification; Sp: sandstone with planar stratification; Sr: ripple cross-stratification; Sm: massive sandstone; Fm: massive mudstone; Fl: laminated mudstone; P: paleosol.

Measurements of the cross-strata dip direction display a unimodal pattern with a main vector toward SE.

Sometimes, it is possible to identify compound cross-strata, 1.6 to 4 m thick, which internally displays sets of planar and trough cross-bedding bounded by low angle (<10º) surface with well-developed slipfaces dipping in the same direction of the cross strata. Simple, large-scale planar cross-strata, up to 1.5 m thick are also present (Fig. 2E).

Interpretation

The occurrence of sandstone bodies bounded by erosive surfaces, characterized by medium- to coarse-grained sandstones, moderately- to poorly-sorted, organized in stacked sets of unidirecionally-oriented, decimeter-scale trough and planar cross-strata forming fining upward cycles, suggests deposition in fluvial channels (Chagas *et al.* 2007, Miall 1996). The simple, large-scale cross-strata are interpreted as formed by downstream migration of sand bars with well-developed slipfaces, such as transverse bars, alternate bars or tributary mouth bars (Wizevich 1992). Downstream-dipping, inclined compound cross-strata represent the downstream accretion of compound sand bars with superimposed dunes (Fig.3). This element is similar in internal architecture and facies assemblage with mid-channel bars (Wizevich 1992, Miall 1996). The maximum thickness of architectural elements is 4 m and it implies that the maximum bankfull channel depth was 8 m, according the assumption that the architectural element height is at least half the depth of the channel during floods (Bristow 1987). The abundance of cross-strata suggests a relatively constant discharge,

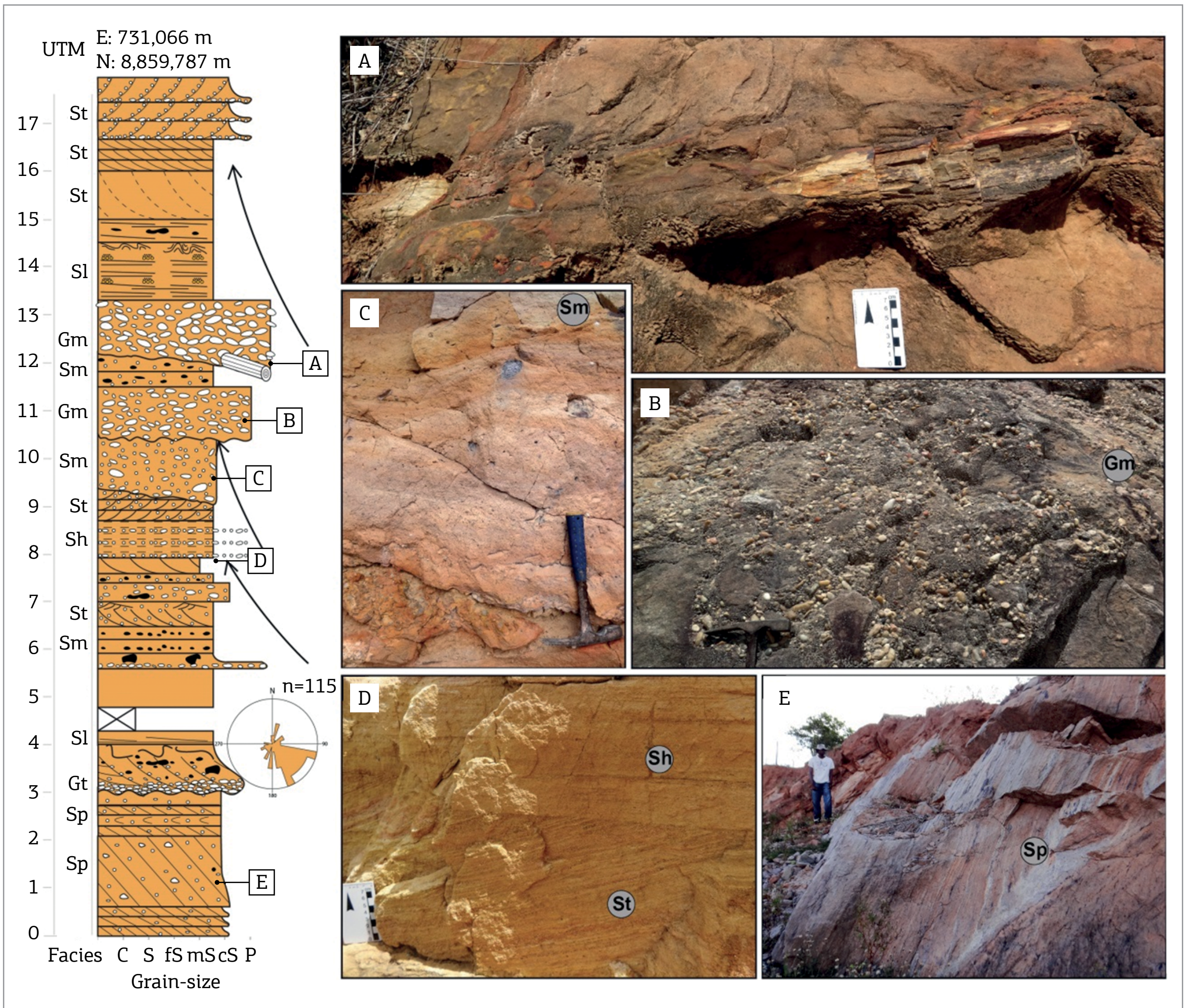

Figure 2. Vertical log of braided fluvial channel facies association with paleocurrent direction to SE. (A) Fossilized tree trunk at the base of a cycle; (B) massive conglomerate showing quartz granules and pebbles; (C) massive sandstone with intraformational mudstone clasts; (D) sand bodies with trough cross-stratification (St) and horizontal lamination (Sh); (E) simple, large-scale planar cross-strata (Sp).

indicating perennial fluvial channels (Miall 1996). The frequent occurrence of intraformational mudstone clasts indicates that rare records of floodplain may have deposited, but they were later eroded by fluvial channel avulsions (Kumar *et al.* 2004). The alternation between horizontal lamination and low angle cross-stratification (Sh/Sl), as well as between low angle cross-stratification and trough cross-stratification (Sl/St), suggests variation of discharge energy. The abundance of fossilized tree trunk founded suggests a relatively humid climate. The multistory stratified sand bodies with thick macroforms, low dispersion of paleocurrents, lack of well-defined fining-upward cycles and the high occurrence of simple to compound downstream accretion architectural element collectively suggest a low-sinuosity, deep perennial braided river.

Anastomosed fluvial channel facies association

Description

This facies association extends over more than 50 m in outcrop and consists of sandstone bodies up to 4 m thick, composed of medium-grained white to gray sandstones, well-sorted with tabular geometry. These sandstone bodies are isolated from each other and separated by an extensive succession of red mudstones (Fig.4 and Fig.5), internally exhibit weakly developed fining-upward pattern with a predominant aggradational trend and are bounded at the base by erosive or diffuse surface. These bodies are formed by 20 to 30 cm thick sets of trough cross-stratification (St) (Fig. 4C), planar cross-stratification (Sp) low angle cross-stratification

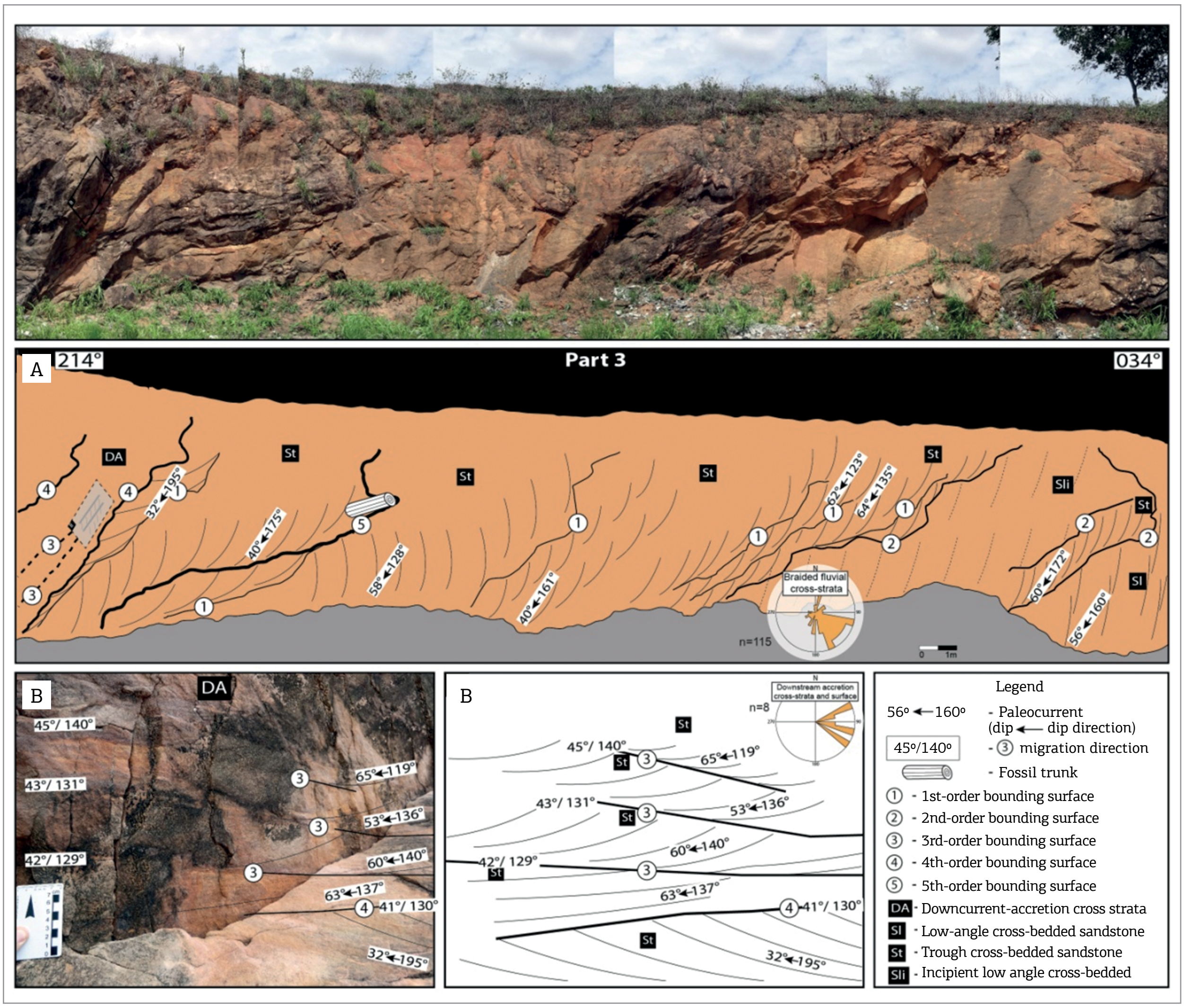

Figure 3. Photo-mosaic with (A) interpreted outcrop panel showing cross-strata paleocurrents and bounding surfaces; (B) detailed downstream accretion architectural element interpreted. Note the downstream accretion composed cross-strata and surface dipping toward the same direction that braided fluvial cross-strata.

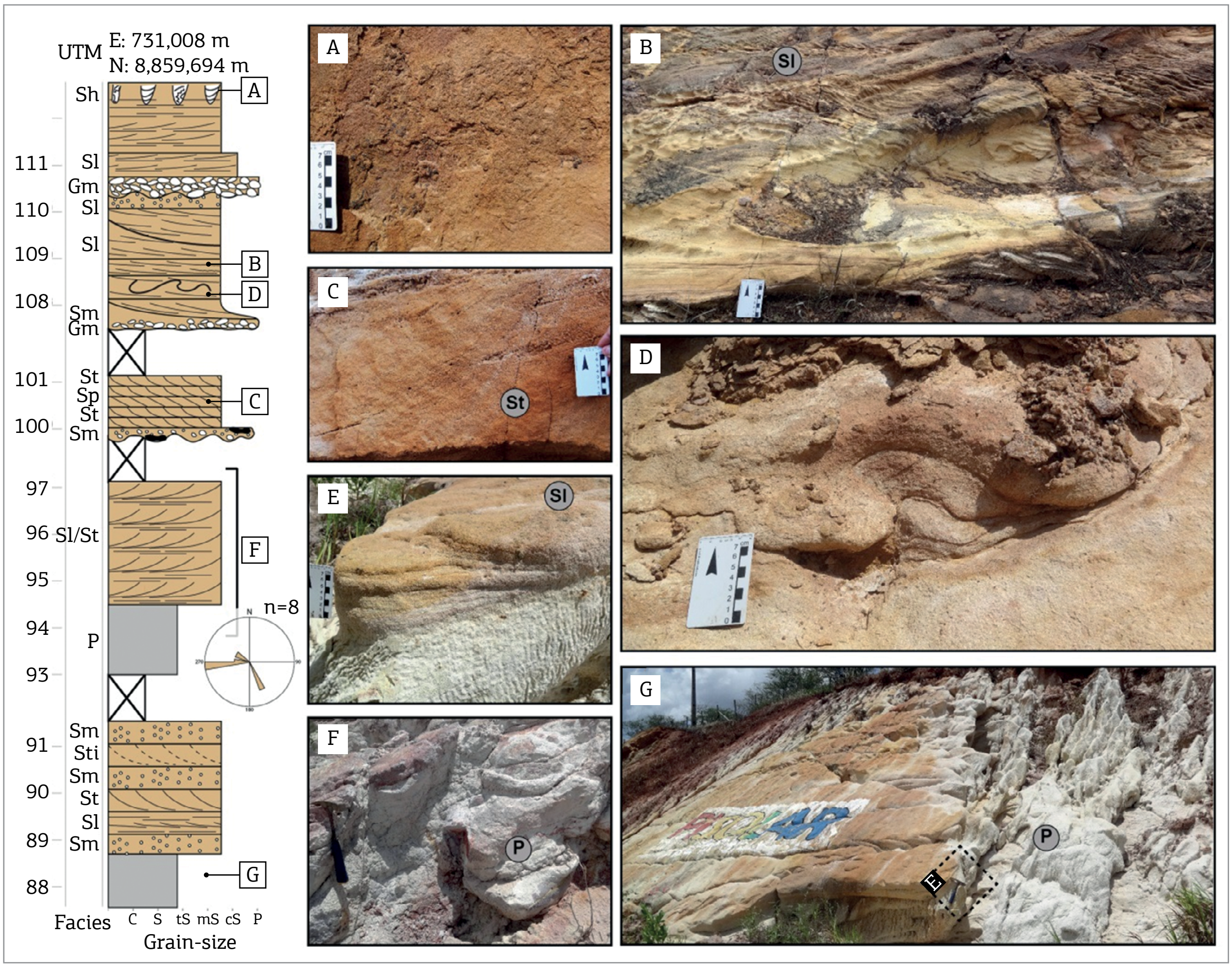

Figure 4. Vertical log of anastomosed fluvial channel facies association showing: (A) sandstone with bioturbation on top; (B) intense fluidization on sandstone obstructing structure identification; (C) fine-grained moderately-sorted sandstone with trough cross-stratification; (D) flame structure; (E) low-angle cross-stratification on well-sorted fine-grained sandstone; (F) muddy sandstone with incipient lamination; (G) general view of sandstone bodies laterally interlayed with mudstones.

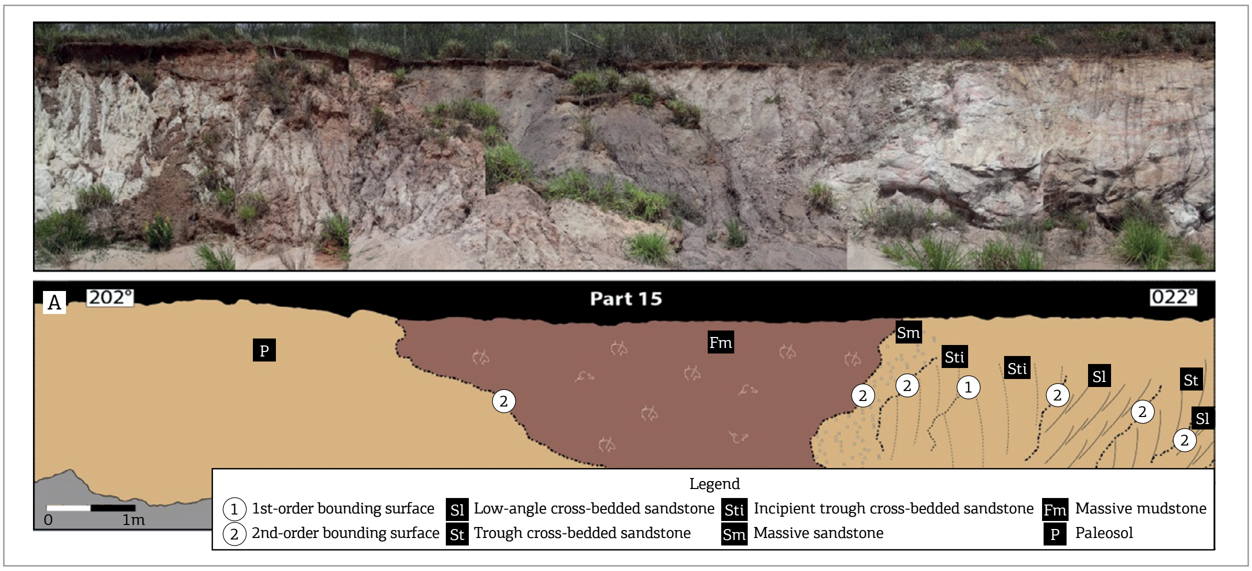

Figure 5. Photo-mosaic of anastomosed fluvial channel. Note the association with fine sediments and (A) interpreted outcrop panel showing facies, cross-strata paleocurrents and bounding surfaces.

sandstones (Sl) (Fig. 4E), massive sandstone (Sm) with dispersed granule and intraformational mudstone clasts and rare beds of white, massive, very-fine sandstones to siltstone or with incipient lamination (P)(Fig. 4F and G). Sometimes bioturbation on top of beds (Fig. 4A) occurs, and the sand bodies can be intensely fluidized, displaying flame structures (Fig. 4B and D). Due to the low quality of preservation of these sandstone and intense fluidization, only eight measures of paleocurrent were collected.

Interpretation

The occurrence of sandstone bodies bounded by erosive surfaces, characterized by sandstones with decimeter-scale unidirecionally-oriented sets of trough and planar cross-strata forming fining upward pattern, suggests deposition in fluvial channels (Chagas *et al.* 2007, Miall 1996).The lack of macroforms indicates that the channel filling occurs by migration and climbing of subaqueous dunes (SB element of Miall 1985). The predominant aggradational stacking trend of channels and low amount of mudstones clasts indicate channel stability and rare lateral migrations, suggesting the presence of cohesive banks rarely eroded. Aggradational channel sandstone bodies, rare lateral migrations, stable banks and intercalation with fine deposits indicate a network of interconnected fluvial channels separated by constantly flooded parts and suggest anastomosed fluvial channel deposits (Smith &Smith 1980).

Floodplain facies association

Description

This facies association has a variable thickness, from 0.8 to 6.4 m, and laterally extensive for up to 15 m. These deposits are composed of red to gray massive mudstones and siltstones (Fm) (Fig. 6A). The reddish mudstones display gray slickensides along fracture planes, root traces and granular and blocky peds. This facies association occurs interlayered with anastomosed fluvial channel facies association sandstone bodies.

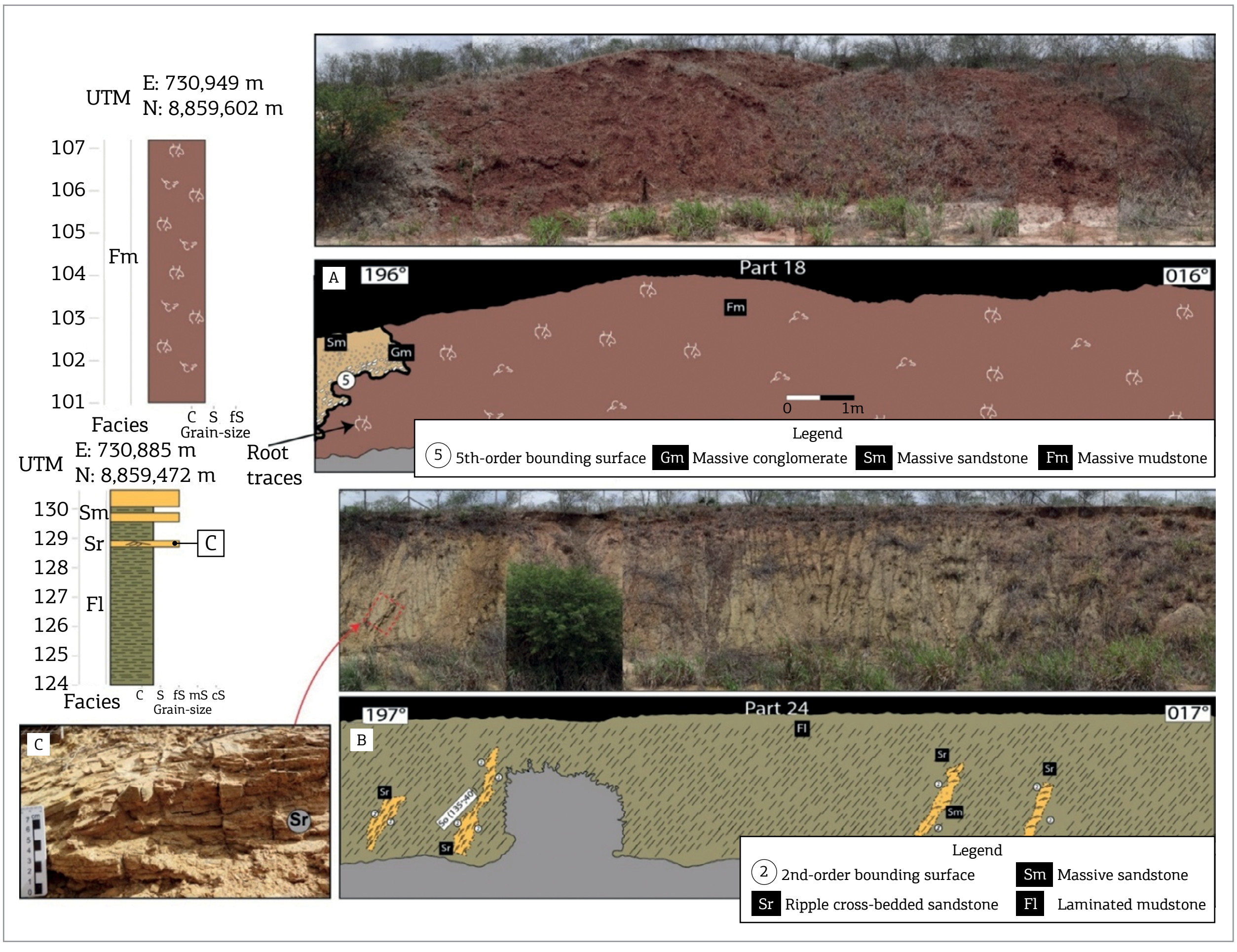

Figure 6. Schematic floodplain and prodelta/distal delta front log with related photomosaic. (A) Interpreted outcrop panel of prodelta; (B) prodelta/distal front. Note the reddish tone of floodplain fine sediments different from the greenish tone of prodelta/distal delta front where fine sediments are interlayered with progressively thicker sandstone beds. (C) Detail picture of ripples cross-lamination within distal delta front sandstones.

Interpretation

Fine sediments settle by decantation in low energy environments. The occurrence of red mudstones associated with root traces, slickensides, granular and blocky peds indicates well-drained vegetated floodplains that were subjected to periods of non-deposition and subsequent oxidation and development of paleosol (Bown & Krause 1987, Kraus 1999, Therrien 2006, Cleveland *et al.* 2007, Retallack 2008). Surfaces with slickensides are interpreted as being formed by shrinking and swelling of clays, associated with episodic water infiltration and evaporation (Retallack 1994). The granular and blocky peds are interpreted as types of argilans formed in clay-rich paleosols (Sigleo and Reinhardt 1988).

Prodelta/distal delta front facies association

Description

This facies association is characterized by up to 8 m thick deposits and internally form cycles with coarsening-upward pattern. These cycles are composed, at the base, by 1 to 7 m thick beds of gray to greenish parallel laminated (Fl) and massive mudstone (Fm). Sometimes these mudstone interlayers with thin beds of very fine- to fine-grained sandstone forming flaser, wavy and linsen heterolitic bedding. Towards the top the mudstones interlayer with progressively thicker sandstone beds (10 cm to 1 m thick), fine- to medium-grained, moderated-sorted, gray to yellow, massive (Sm), with ripple cross-lamination (Sr) (Fig. 6C) or trough cross-stratification (St). Bivalve fossils can be found. This facies association has an abrupt basal contact with anastomosed fluvial channel sandstone bodies.

Interpretation

The abundance of mudstones interlayered with thin sandstones is indicative of deposition in a quiet-water environment with periodic input of sand. The laminated mudstones at the base of cycles are generated by gravitational settling of suspended particles below the level of wave performance, being interpreted as prodelta deposits. Massive and unidirectionally-oriented sandstone intercalated with mudstones suggests that these sediment beds represent respectively hyperconcentrated flows in which the current density is higher than that one of the receiving body-water and low density turbidity currents, caused by periodic increases in the discharge of the river (Bhattacharya 2006). These progressively thicker sandstones beds represent progradation of delta front facies association upon prodelta.

Proximal delta front facies association

Description

This facies association is characterized by intensely fluidized sandstone beds up to 10 m thick, composed by moderated- to well-sorted fine- and medium-grained sandstones with sigmoidal cross-stratification (Ssg), trough cross-stratification (St), ripple cross-stratification (Sr) and massive sandstone (Sm). The sandstone beds become progressively thicker and more frequent characterizing coarsening-upward cycles. This facies association shows a gradual transition with prodelta/delta front deposits below. The paleocurrent measurement displays a wide spreading. This facies association was found at the point 2 (), which stratigraphic position is above point 1. The limited extension of the outcrop and abundant vegetation limit the construction of photo-mosaic and good photography.

Interpretation

The facies succession characterized by sandstone beds with intense fluidization, coarsening-upward cycles and associated with prodelta deposits suggests delta front deposits (Bhattacharya 2006). The abundance of unidirecionally-oriented cross-stratification sets indicates a constant discharge current and suggests a river dominated delta front facies association. According to Bhattacharya (2006), intense fluidization is common in river dominated deltas and indicates a high sedimentation rate over water-saturated sediments resulting in fluid expulsion and causing bed deformations in the overlapping sandstones. A predominantly sandy delta front facies association indicates rapid deceleration of unidirectional flow (Bhattacharya 2006). Sigmoidal cross-stratifications are generated by a transitional bed forms between dunes and flat beds strata (Wizevich 1992). The sigmoidal shape of this structure is a result of the relation between traction and particle settling.

STRATIGRAPHIC CONTEXT

In the studied area, the Neo-Jurassic-Neocomian succession of the Sergipe-Alagoas Basin consists of three depositional intervals (Fig. 7 and Fig. 8).The unit I corresponds litho-stratigraphically to the top of Serraria Formation and is characterized by multi-storey and multi-lateral, amalgamated, sandstone bodies with paleocurrent unimodal to SE toward the depocenter of the Afro-Brazilian Depression, that was located outside the borderlines of the present federal states of Sergipe and Alagoas as suggest the extension of this basin. The unit I, in this study, corresponds to the already documented as sequence II of Serraria Formation by Kuchle *et al.* (2011) and suggests deposits of a wide perennial braided channel system

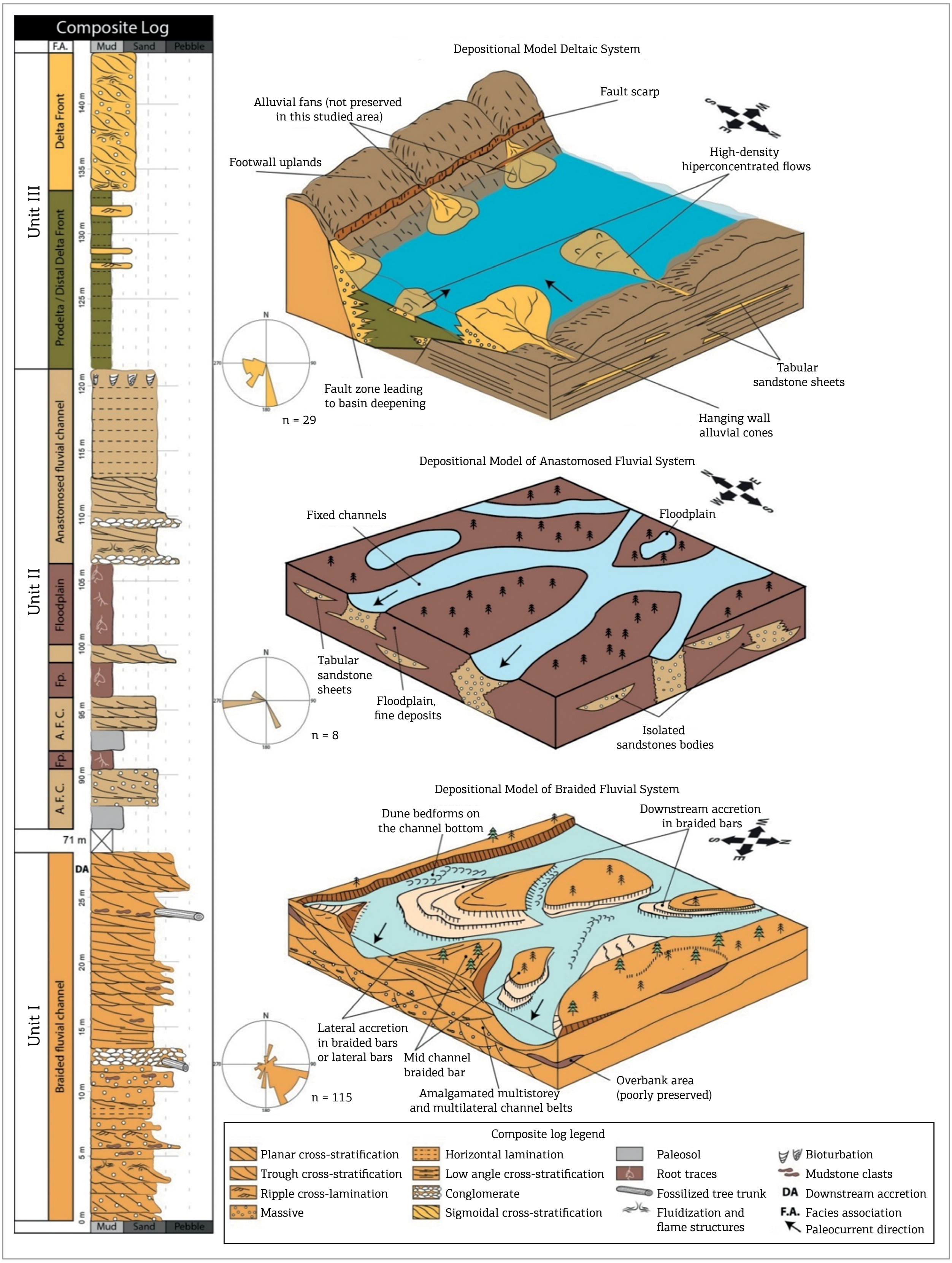

Figure 7. Composite log of the sedimentary succession showing depositional model of each unit (modified from Scherer *et al.* 2014). Unit I represents braided fluvial channels with downstream accretion bars. Unit II shows anastomosed fluvial channels separated by floodplain deposits. Unit III represents a half-graben geometry with delta systems on the flexural margin and some hyperconcentrated sediments.

established in humid climatic conditions during the initial moments of rifting and with similar deposits preserved in all territories that belonged to this depression.

The unit II, which corresponds to the base of Feliz Deserto Formation, is characterized by a network of anastomosed fluvial channels separated by vegetated floodplains. The change of fluvial system from braided to anastomosed between these two units reflects an increase in the rate of accommodation allowing preservation of mudstone beds progressively thicker and the aggradation of fluvial channel sandstone bodies known as Caioba Sandstone sometimes exposed to sub-aerial conditions. The low number of paleocurrent measures does not allow further interpretations, but units I and II have the same detrital composition suggesting that the source area is probably the same.

The unit III corresponds litho-stratigraphically to the Feliz Deserto Formation and is characterized by coarsening- and thickening- upward cycles, composed by prodelta/distal delta front facies association at the base and progressively evolving to proximal delta front facies association indicating progradational deltaic lobes (Fig. 7 and). The paleocurrent direction displays a high dispersion (8 measures toward W, 11 toward SW and S and 3 toward E and SE), suggesting that sedimentation occurred in restricted basins with sedimentary influx from several flanks. The contact between units II and III is marked by prodelta mudstone superimposed on anastomosed fluvial channel sandstones and indicates a rapid flooding. The change on paleocurrent direction added to the rapid flooding suggests that the basin underwent a significant rearrangement associated with tectonic movements. The change of depositional system confirms the restructuring of the basin and suggests that the increasing rate of accommodation creation already observed in unit II becomes more intense.

TECTONIC-STRATIGRAPHIC EVOLUTION

The sedimentary succession studied exhibits three distinct stratigraphic intervals that allow the identification of different evolutionary stages of rifting. The paleocurrent and depositional systems distribution of units I and II indicate that these units occupied a depositional area larger than the Sergipe-Alagoas Basin itself. Data collected in outcrops and

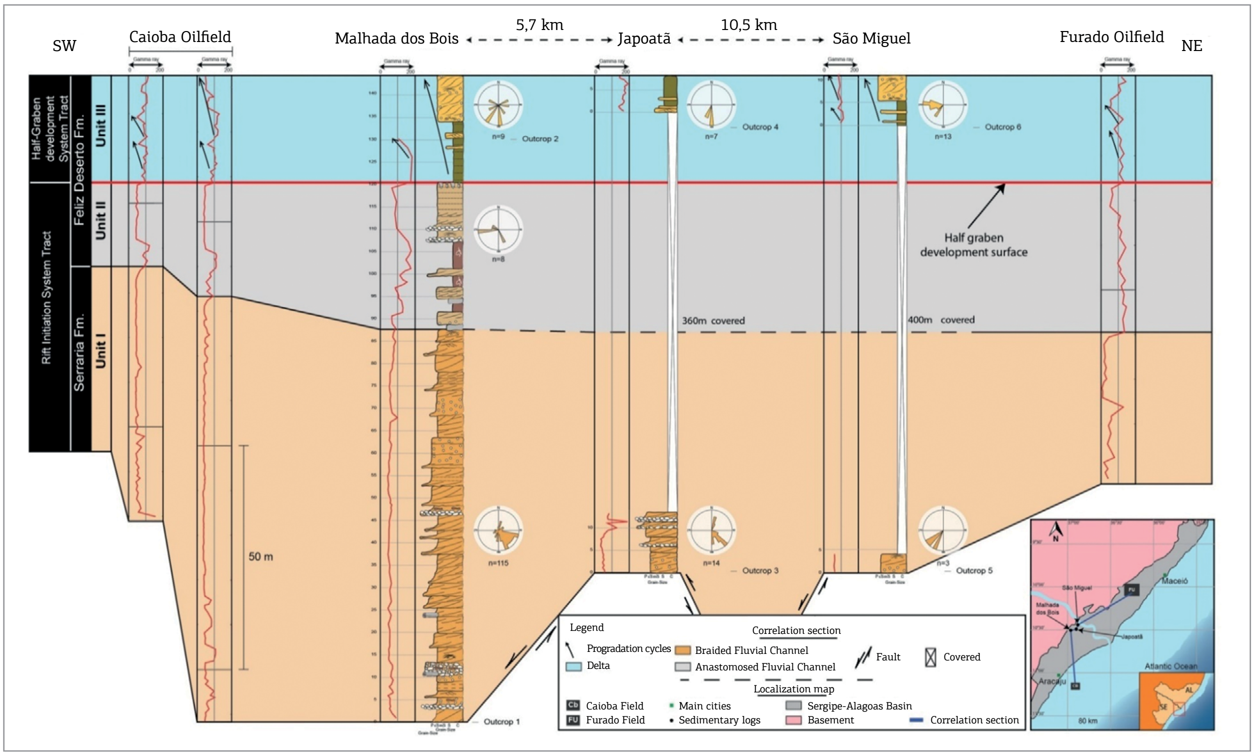

Figure 8. Correlation section along Sergipe-Alagoas Basin. Each compound stratigraphic section shows the sedimentary logs as described during fieldwork and the calculated covered interval. Note the similarity between gamma ray of sedimentary logs and subsurface data that allowed correlation: low and uniform values in unit I, then high values, indicating floodplain deposits, and a small interval of regular and low values, which suggests Caioba anastomosed fluvial sandstones (unit II) and on the top several cycles of progressive reducing of gamma values, suggesting progradations stacking pattern typical of Feliz Deserto.

available in previous studies suggest that these units were deposited in a large sedimentary basin related to the initial stage of Neocomian rifting (Campos Neto *et al.* 2007, Kuchle *et al.* 2011). The Serraria Formation was deposited in the north flank of this large and shallow basin whose depocenter was located at the SE of Sergipe-Alagoas Basin (Kuchle *et al.* 2011).This accumulation phase has been called Rift Initiation Tectonic System Tract by Kuchle and Scherer (2010), instead of the term Pre-Rift attributed by Campos Neto *et al.* (2007), that is restricted to rocks that are completely unrelated to the rifting process, consisting of sedimentary basement upon which taphrogenic processes will act (Prosser 1993, Bosence 1998, Scherer *et al* .2014).

The unit I has sedimentological-stratigraphical characteristics and paleocurrent patterns suggesting that the Rift Initiation Tectonic System Tract is characterized by incipient extensional stress generating a wide synclinal depression, associated to the low rate, continuous and uniformly distributed tectonic activity (Morley 2002, Kinabo *et al.* 2007, Kuchle *et al.* 2011). The predominance of multi-storey amalgamated sandstone bodies without deposits from outside channel along this unit indicates low accommodation creation rate and is related to a uniform A/S ratio with positive- close to 0 values (Martinsen *et al.* 1999, Scherer *et al.*2014).

The unit II represents a transition interval between the rift initiation and the individualization of half-grabens. Amalgamated sandstone bodies are replaced by isolated sandstone bodies allowing preservation of floodplain fine deposits. The character aggradational of fluvial channel sandstones and the substantial thickness of mudstones indicate a progressive increase of the accommodation creation rate and A/S ratio less than 1 (Martinsen *et al.* 1999, Scherer *et al.* 2014). This unit still belongs to the Rift Initiation Tectonic System Tract suggesting the shallow character of the basin, interpreted from the oxidation of mudstones, but the increase of A/S ratio indicates that the tectonic activity becomes more and more intense, however without individualization of half-grabens.

The unit III is characterized by a thick deltaic succession indicative of a deeper basin and high A/S ratio above 1 (Martinsen *et al.* 1999, Scherer *et al.* 2014). Besides, the scattering in paleocurrent direction and the fact that mudstones of unit III are superimposed on fluvial channel sandstones of unit II are consistent with the fragmentation of the wide basin in several smaller and deeper basin: the half-grabens (Prosser 1993, Bosence 1998, Gawthorpe & Leeder 2000). According to Prosser (1993) the sedimentary influx of half-graben occurs from different regions, resulting in a high dispersion of the paleocurrent. Therefore, unit III can be considered as deposited during the Half Graben Development Tectonic System Tract (Kuchle & Scherer 2010).

The prodelta mudstone superposed abruptly over anastomosed fluvial channel sandstone bodies characterizes a flooding surface between units II and III. In this way, the succession studied evidence that the passage between rift initiation and half-graben development is extremely rapid and marked by a radical change both in depositional systems and geometric characteristics of the basin.

The abrupt nature of this contact can be consistently demonstrated with subsurface data. The unit I is identified in gamma ray logs by a thick interval of low and uniform values indicating sandstone bodies. The unit II is marked by the first high value of gamma ray after unit I and it is characterized by an intercalation of high values, indicating floodplain deposits, and a small interval of regular and low values, which suggests Caioba anastomosed fluvial sandstones. The Half Graben Development Surface (Kuchle & Scherer 2010) was observed in each subsurface log and is marked by a sharp increase in gamma ray values subsequent to unit II, suggesting a fast flooding of the lacustrine deltaic depositional system. Above this surface there are several cycles of progressive reducing of gamma values, suggesting sandstone bodies on top of mudstone deposits and characterizing progradations stacking pattern typical of Feliz Deserto Formation.

As suggested by Kuchle and Scherer (2010), the rift basin's analysis should be done individually for each half-graben as these may be in different evolutionary stages due to the extensional behavior that varies in time and along the basin. So, considering that the Half-Graben Development Tectonic System Tract is not a synchronic event along the basin, the correlation made in Fig. 8 does not relate events that occurred at the same time, but simply use the Half-Graben Development Surface to differentiate the stages.

CONCLUSIONS

It was possible to individualize three depositional units in the Neo-Jurrasic and Neocomian succession of Sergipe-Alagoas Basin: unit I, which corresponds to the base of Serraria Formation, is characterized by multi-storey and multi-lateral, amalgamated sandstone bodies of braided fluvial channel system; unit II, equivalent to the base of Feliz Deserto Formation, is composed of anastomosed fluvial channel sandstones interlayered with floodplain mudstone deposits; Unit III, that corresponds to the major part of Feliz Deserto Formation and is composed of prodelta and delta front deposits.

The sedimentary succession was deposited during different rift stages. Units I and II were deposited in a wide shallow basin formed during the first stage of rifting associated with low tectonic activity. Unit III was deposited in well-defined half-graben systems allowing the establishment of delta depositional systems bordering the lacustrine bodies. While the paleocurrent direction of unit I is unimodal, toward SE, where was located the depocenter, the paleocurrent direction of unit III has a high dispersion and suggests that an important restructuration and fragmentation of the basin in several half-grabens occurred, each one with its own depocenter and sedimentary influx from different regions.

Based on the results of this work, it is possible to understand the stratigraphic evolution of the initial stages of rifting. Corroborating the proposals of Morley (2002) and Kuchle and Scherer (2010), we conclude that the first stage of rifting (units I and II) is characterized by a wide basin, unlike the models of Prosser (1993), Bosence (1998) and Gawthorpe and Leeder (2000), who suggest the presence of restricted or isolated basins already in the first instants of the rift. This wide basin has a low A/S ratio. The establishment of half-graben occurs at the second stage (unit III), due to increase of tectonic activity and increase of A/S ratio.

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