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ARQUITETURA DEPOSICIONAL DA FORMAÇÃO SERRARIA, BACIA DE SERGIPE-ALAGOAS

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Orientador: Prof. Dr. Felipe Torres Figueiredo

DISSERTAÇÃO DE MESTRADO

Programa de Pós-Graduação em Geociências e Análise de Bacias

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Hugo Raphael Santos de Castro

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ARQUITETURA E QUANTIFICAÇÃO DE FÁCIES DOS DEPÓSITOS FLUVIAIS DA FORMAÇÃO SERRARIA, BACIA SERGIPE-ALAGOAS, NORDESTE DO BRASIL

por:

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DISSERTAÇÃO DE MESTRADO

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RESUMO

A criação da acomodação em bacias rifte é controlada principalmente pela tectônica. Entretanto, durante estágios iniciais de riftes, a atividade de falhas normais é dispersa e incipiente, o que torna difícil definir o *rift onset*. O padrão de empilhamento sedimentar dos ambientes deposicionais relacionados ao rift pode ser decisivo quanto a essa questão. Esse trabalho objetiva avaliar o registro sedimentar da Formação Serraria (Tithoniano ou Berriasiano da Bacia de Sergipe-Alagoas), que foi depositada na Depressão Afro-Brasileira durante a distensão inicial do rifteamento sul-atlantino. 14 litofácies foram descritas, interpretadas e agrupadas em sete associações de fácies de origem fluvial, eólica ou flúvio-deltaica. Essas unidades genéticas foram quantificadas a fim de fornecer interpretações mais precisas sobre o ambiente deposicional. Na base da formação ocorre deposição de barras e lençóis de areia dentro de pequenos canais sobre os pelitos lacustres da Formação Bananeiras. Existe uma mudança da arquitetura estratigráfica na seção intermediária, onde os canais fluviais tornam-se mais caudalosos, promovendo maior empilhamento de barras arenosas e cascalhosas. Eventuais depósitos de crevasse splay e campos de dunas restritos poderiam ocorrem adjacentemente aos canais fluviais. Em direção ao topo, a Formação Serraria passa a ser dominada por depósitos de frentes e planícies deltaicas. As associações de fácies de origem fluviais e eólica representam uma diminuição progressiva da acomodação, enquanto que o intervalo fluvio-deltaico superior representa um aumento da acomodação, marcando o clímax do estágio inicial de rifte. Os arenitos fluviais denominados “Caioba”, que ocorrem sobre a Formação Serraria, indicam reestabelecimento das drenagens, dado o tectonismo decrescente. Dessa forma, o padrão de empilhamento sedimentar da Formação Serraria representa ciclos de maior frequência dentro de um trato de sistemas tectônico de início de rifte.

Palavras-chave: Formação Serraria, Bacia de Sergipe-Alagoas, arquitetura deposicional fluvial; estratigrafia de estágio inicial de rifte.

ABSTRACT

Accommodation rates in rift basins are mainly controlled by tectonics. However, during early rift stages, normal faults activity is dispersed and incipient, which makes the definition of the rift onset a difficult task. The sedimentary stacking pattern of rift-related depositional environments can be decisive to solve this question. This paper aimed to evaluate the stratigraphic record of the Tithonian-Berriasian (?) Serraria Formation (Sergipe-Alagoas Basin, Brazil), which was deposited in the Afro-Brazilian Depression, as a result of the early extension of the South Atlantic rifting. 14 lithofacies were described, interpreted and grouped into 7 facies associations of fluvial, aeolian and fluvio-deltaic origin. These genetic units were quantified in order to provide a more accurate depositional system interpretation. At the base of the formation occur bars and sand sheets within small channels, which are on top of lacustrine mudstones of the Bananeiras Formation. There is a change in stratigraphic architecture by the intermediate section, where fluvial channels become deeper due to increasing discharge, promoting greater rates of sand and gravel bar stacking. Crevasse channels and restricted aeolian dune fields could occur adjacent to fluvial channel belts. Upwards, the Serraria Formation becomes dominated by delta front and delta plain deposits. Fluvial and aeolian facies associations represent a progressive decrease in accommodation, while the upper fluvio-deltaic interval means an increase in accommodation, pointing to the early rift stage climax. The fluvial “Caioba” sandstone on top of the Serraria Formation indicate reestablishment of fluvial drainage due to the decreasing tectonism. Thus, the sedimentary stacking pattern of Serraria Formation represents higher frequency cycles within an early rift tectonic system tract.

Keywords: Serraria Formation, Sergipe-Alagoas Basin, fluvial depositional architecture; early rift stage stratigraphy.

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Apresentação:

O preenchimento de bacias sedimentares pode ser avaliado com base na relação dos principais controladores alogênicos: eustasia, tectônica e aporte sedimentar (Posamentier & Vail, 1988; Prosser, 1993; Catuneanu, 2006). Entretanto, em bacias rifte, os efeitos eustáticos são subordinados em relação ao papel da tectônica (subsidência devido a falhas) e do aporte sedimentar (Prosser, 1993; Gawthorpe & Leeder, 2000). Os processos, transporte e padrões de sedimentação, em especial para fases iniciais de bacias rifte (*e.g*. Prosser, 1993; Kuchle & Scherer, 2010), podem ser muito variáveis e de difícil identificação. Durante esse estágio, a atividade de falhas normais ainda é incipiente e os depocentros são pouco delineados. Desse modo, a sedimentação ainda sofre forte influência das condições da fase pré-rifte, tornando uma tarefa complexa separar essas duas fases. A dispersão e transporte sedimentar de sistemas fluviais podem ser decisivos para resolver essa questão, uma vez que as drenagens de fontes distantes (pré-rifte) tendem a se adequar progressivamente às novas configurações estruturais (Prosser, 1993; Gawthorpe & Leeder, 2000). Além disso, as relações estratigráficas com outros sistemas deposicionais geneticamente associados (*e.g*. deltas, lagos) podem fornecer informações importantes sobre a relação aporte sedimentar/acomodação, e consequentemente sobre a evolução deposicional nesse tipo de bacia.

A Formação Serraria da Bacia de Sergipe-Alagoas é um bom exemplo para se avaliar a deposição inicial em bacias do tipo rifte. Essa unidade litoestratigráfica teria sido depositada na Depressão Afro-Brasileira (Estrella, 1972), uma suposta depressão ampla e rasa no interior do *Gondwana*, a qual englobaria parte das bacias do nordeste brasileiro e oeste africano durante o Tithoniano ou Berriasiano (Andares locais Dom João ou base do Rio da Serra) (Schaller, 1969; Kuchle *et al*., 2011). É consenso que o significado tectono-estratigráfico da Depressão Afro-Brasileira seja o reflexo dos estiramentos crustais iniciais, onde viriam a se instalar os riftes cretáceos e consequente abertura do Oceano Atlântico Sul (Magnavita, 1992; Bueno, 2004; Ponte & Asmus, 2004). Entretanto, o termo “pré-rfite” ganhou popularidade entre os geólogos brasileiros ao fazer alusão ao estágio de distensão inicial do rifteamento sul-atlantino (Estrella, 1972; Bueno, 2004). Por outro lado, diversos modelos propõem que a fase pré-rifte esteja completamente dissociada do evento rifte, separada por discordância da ordem de dezenas a centenas de milhões de anos (Prosser, 1993; Boscense, 1998). Dessa forma, a falta de consenso sobre o limite entre as fases pré-rifte e rifte, seja pela ambiguidade da nomenclatura ou pela diversidade de critérios para o posicionamento do *rift onset* (Souza-Lima & Borba, 2007; Borba, 2009;), somada à dificuldade de se identificar em campo superfícies confiáveis para correlação, tem fomentado discussões sobre a origem e o posicionamento estratigráfico da Formação Serraria.

Como forma de contribuir com essas discussões, o presente trabalho traz novos dados e interpretações que vêm a somar à compreensão da historia tectono-deposicional da Formação Serraria. Isso pode ser visto como um exemplo de estudo de padrões deposicionais de estágio de inicio de rifte, aplicado à Bacia de Sergipe-Alagoas. As discussões aqui apresentadas foram baseadas em interpretações paleoambientais para as rochas da Formação Serraria, observando a organização interna, relações espaciais e distribuição de unidades genéticas (*e.g*. fácies, associações de fácies, elementos arquitetônicos).

Esses dados e interpretações foram organizados e discutidos na forma de um artigo científico, intitulado de “DEPOSITIONAL *ARCHITECTURE AND FACIES QUANTIFICATION OF THE SERRARIA FORMATION, SERGIPE-ALAGOAS BASIN, NORTHEASTERN, BRAZIL*”, que encontra-se no Capítulo II desse volume, já submetido à revista *Sedimentary Geology*. As normas de submissão da revista encontra-se no Anexo I.

Objetivos:

O objetivo principal desse trabalho consiste em caracterizar detalhadamente o registro sedimentar da Formação Serraria em escala de afloramento. Dessa forma, espera-se contribuir com as interpretações dos possíveis ambientes deposicionais, dos padrões de transporte, dos principais controles da deposição e acumulação sedimentar, além de fomentar discussões a cerca do contexto tectono-deposicional dessa unidade litoestratigráfica. Como objetivos específicos lista-se:

- Descrever e interpretar as fácies, associações de fácies, suas paleocorrentes e geometrias em afloramentos da Formação Serraria;
- Avaliar as variações laterais e verticais dos ambientes deposicionais da Formação Serraria e seus padrões de transporte sedimentar, e discutir os controles deposicionais que as expliquem;
- Avaliar o contexto tectono-sedimentar da Formação Serraria.
- Quantificar as interpretações de fácies e suas associações através de dados uni e bidimensionais.

Localização da área

A Bacia de Sergipe-Alagoas consiste em uma estreita faixa orientada segundo NE-SW, ao longo do litoral dos Estados homônimos. Na sua porção emersa, a seção aflorante da sequência pré-rifte *sensu* Campos Neto *et al*. (2007) localiza-se próxima ao limite estadual (Rio São Francisco), em geral orientada ao longo da falha de borda da bacia, condicionada por estruturas soerguidas do embasamento, como os altos de Japoatã, Penedo e Palmeira Alta (Figura 1).

A área de estudo desse trabalho compreende grande parte das melhores exposições da Formação Serraria. Na Sub-bacia de Sergipe, os afloramentos são de fácil acesso, localizados em cortes da BR-101 a sudeste da cidade de Muribeca, e no entorno das cidades de Malhada dos Bois, São Francisco e do Povoado Bananeiras. Já na Sub-bacia de Alagoas, as principais áreas aflorantes estão nos flancos da feição geológicageomorfológica conhecida como Domo de Igreja Nova, no Alto de Palmeira Alta, caracterizada como uma estrutura ovalada centralizada nas proximidades da cidade que lhe confere o nome (Figura 1). As coordenadas dos afloramentos estudados nesse trabalho encontram-se no Anexo IV.

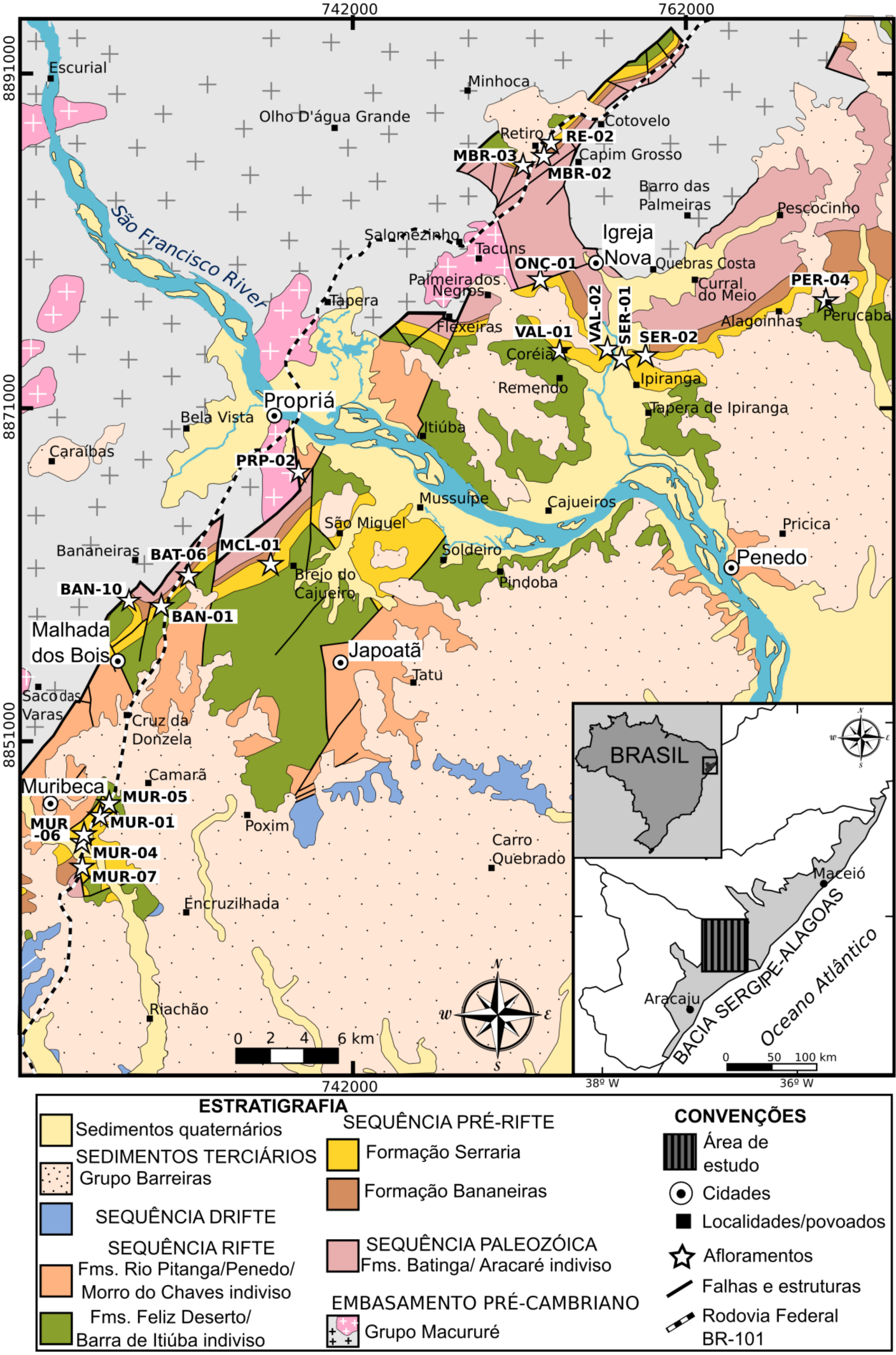

Figura 1: Mapa geológico da área de estudo e localização dos afloramentos estudados. Modificado do banco de dados da CPRM (serviço geológico brasileiro) e de Jardim de Sá (2008).

Métodos de trabalho

Análise de fácies, superfícies limitantes e arquitetura deposicional

O princípio da análise de fácies consiste em diferenciar o conteúdo sedimentar baseado na litologia (composição), textura (granulometria, selecionamento, arredondamento e esfericidade dos grãos), estruturas sedimentares e paleocorrentes. Estruturas biogênicas, conteúdo fossilífero e cor podem auxiliar na definição e distinção de litofácies (Miall, 1996; Tucker, 2014). O conjunto das características que constituem uma fácies permite a interpretações dos processos e condições deposicionais (Ashley, 1990; Nichols, 2009). Diferentes fácies podem ser agrupadas em associações de fácies, implicando em sucessivos processos deposicionais geneticamente relacionados a um mesmo contexto sedimentar (Collinson, 1996). Esse procedimento permite a interpretação e reconstrução do paleoambiente deposicional, que pode ser comparado com modelos de referência da literatura (*e.g*. Walker & James, 1992; Reading, 1996; Posamentier & Walker, 2006). Associações de fácies caracterizadas por geometria específica, relacionada à geomorfologia do ambiente deposicional original, usualmente definida por superfícies limitantes, podem ser chamadas de “elementos arquitetônicos” (Reading, 1996; Dalrymple & James, 2010). Esses, por sua vez, representam segmentos distinguíveis dentro de um sistema deposicional (*e.g*. canais fluviais, barras intracanal, barra em pontal, planícies de inundação).

A classificação hierárquica de superfícies limitantes é uma abordagem utilizada há muito tempo no estudo de sucessões sedimentares de diversos ambientes deposicionais (Brookfield, 1977, 1992; Allen, 1983; Miall, 1985; Bridge, 1993). Apesar de interpretativos, os critérios utilizados para a hierarquização das superfícies limitantes (consequentemente das unidades genéticas) são baseados na relação da superfície e camadas sobre e sotopostas, morfologia (irregular, côncava, convexa), extensão lateral e natureza das fácies associadas (Miall, 1996). Entretanto, a aplicabilidade dessa metodologia a sistemas onde haja interação entre ambientes deposicionais ainda se mostra muito incipiente (Clemmensen & Trisgaard, 1990). Dada essa dificuldade, nesse trabalho, a classificação das superfícies limitantes seguiu principalmente a classificação de Miall (1996), e se utilizou de adaptações a partir de Figueiredo (2013), uma vez que a Formação Serraria é dominantemente fluvial. Nos intervalos com interações entre sistemas deposicionais, foram feitas adaptações das obras de Fryberg *et al.* (1990), Kocurek (1988) e Clemmensen & Trisgaard (1990), apesar da ressalva da dificuldade de hierarquização dessas superfícies.

Nesse trabalho, a metodologia de análise de fácies, suas associações e superfícies limitantes seguiu os preceitos de Miall (1996; 2000); Walker & James (1992) e Tucker (2014), e consistiu basicamente em: 1) Registro fotográfico dos afloramentos e composição de fotomosaicos, com escala e orientação geográfica devidamente anotados; 2) Demarcação das principais superfícies limitantes; 3) Identificação e descrição das fácies presentes no afloramento; 4) Levantamento de perfis colunares em posições estratégicas do afloramento, sempre os localizando no fotomosaico; 5) Medição da direção de mergulho (paleocorrentes) das estratificações e limites de séries, ou outras superfícies quando possível e/ou necessário; 6) Interpretação dos dados.

Além disso, uma das propostas desse trabalho foi quantificar a contribuição de cada unidade genética (associações de fácies e elementos arquitetônicos), como proposto por Colombera *et al*. (2013). Quando possível, quantificou-se a área vertical exposta nos afloramentos (dados 2D) de cada associação de fácies. Isso foi feito através dos fotomosaicos dos afloramentos com o auxílio *software* ImageJ, que permite o cálculo de áreas em fotografias após a definição de uma escala para a foto. Em afloramentos onde não foi possível construir um fotomosaico, utilizou-se a espessura das associações de fácies medidas nas seções colunares (dados 1D). Também foram realizadas análises da probabilidade de transições verticais de fácies, através da computação das interações verticais entre fácies observadas nos levantamentos das seções colunares (total de 790 mudanças verticais de fácies). Além da transição vertical entre fácies distintas, foram também contabilizadas as transições verticais entre mesmas fácies. Devido a essa abordagem, a matriz para a análise da transição vertical de fácies se mostrou mais realista, evitando os zeros diagonais comuns de trabalhos que não consideram auto-transições entre as superfícies limitantes (Carr *et al.,* 1966; Selley, 1970; Colombera *et al*., 2013).

Análise de paleocorrentes

A análise de paleocorrentes é uma ferramenta fundamental para a compreensão da dinâmica deposicional. Diversas estruturas sedimentares (*e.*g. estratificações cruzadas, seixos imbricados, turboglifos) são capazes de registrar a direção, e muitas vezes o sentido, do fluxo responsável pela deposição (Miall, 1996; 2000; Tucker, 2014). No caso de depósitos fluviais, as estratificações cruzadas são as estruturas mais utilizadas para o estudo de paleocorrentes. Considera-se que a direção da paleocorrente era paralela ao rumo do mergulho (*dip direction*) do plano inclinado de estratificações cruzadas tabulares e tangenciais (Potter & Pettijohn, 1977). Já para as estratificações cruzadas acanaladas, assume-se o sentido de mergulho do eixo do festão como sentido da paleocorrente (Potter & Pettijohn, 1977). A aquisição sistemática de dados de paleocorrentes pode auxiliar na construção de modelos de dispersão e transporte sedimentar, úteis em reconstruções paleogeográficas e na inferência da proveniência de sedimentos (Potter & Pettijohn, 1977).

Nesse trabalho, foram tomadas medidas de paleocorrentes em diferentes tipos de estratificações cruzadas. Quando possível, foram medidos também o rumo dos limites basais de séries, entendidos como superfícies de acresção para migração de novas formas de leito.

No total, foram tomadas 605 medidas de paleocorrentes e 198 limites de série. Quando observado basculamento nos afloramentos, as paleocorrentes foram corrigidas em relação ao leito deposicional conforme a proposta de Tucker (1996), através do *software Stereo Net* 8., onde as rosetas das paleocorrentes também foram criadas.

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CAPÍTULO II – ARTIGO SUBMETIDO À REVISTA SEDIMENTARY GEOLOGY:

DEPOSITIONAL ARCHITECTURE AND FACIES QUANTIFICATION OF THE SERRARIA FORMATION, SERGIPE-ALAGOAS BASIN, NORTHEASTERN, BRAZIL

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ABSTRACT

Accommodation rates in rift basins are mainly controlled by tectonics. However, during early rift stages, normal faults activity is dispersed and incipient, which difficult the recognition of early crustal extension imprints. The sedimentary stacking pattern of rift-related depositional environments can be decisive to solve this question. This paper aimed to evaluate the stratigraphic record of the Tithonian-Berriasian (?) Serraria Formation (Sergipe-Alagoas Basin, Brazil), which was deposited in the Afro-Brazilian Depression, as a result of the early extension of the South Atlantic rifting. 14 lithofacies were described, interpreted and grouped into seven facies associations of fluvial, aeolian and fluvio-deltaic origin. These genetic units were quantified in order to provide a more accurate depositional system interpretation. At the base of the formation occur bars and sand sheets within small channels, which are on top of lacustrine mudstones of the Bananeiras Formation. There is a change in stratigraphic architecture by the intermediate section, where fluvial channels become deeper due to increasing discharge, promoting greater rates of sand and gravel bar stacking. Crevasse channels and restricted aeolian dune fields could occur adjacent to fluvial channel belts. Upwards, the Serraria Formation becomes dominated by delta front and delta plain deposits. Fluvial and aeolian facies associations represent a progressive decrease in accommodation, while the upper fluvio-deltaic interval means an increase in accommodation, pointing to the early rift stage climax. The fluvial “Caioba” sandstone on top of the Serraria Formation indicates reestablishment of fluvial drainage due to the decreasing tectonism. Thus, the sedimentary stacking pattern of Serraria Formation represents higher frequency cycles within an early rift tectonic system tract.

Keywords: Serraria Formation, Sergipe-Alagoas Basin, fluvial depositional architecture; early rift stage stratigraphy.

INTRODUCTION

Sedimentary basin fills can be assessed on the basis of allogenic controls, such as eustasy, tectonics and sediment supply (Posamentier and Vail, 1988; Prosser, 1993; Catuneanu, 2006). However, in rift basins, eustatic effects are subordinate when compared to the role of tectonics and sedimentary supply (Prosser, 1993; Gawthorpe and Leeder, 2000). In early rift stages, when accommodation space is low, processes responsible for both transport and deposition of particles, and the modes of architectural preservation, are difficult to predict or even identify (e.g., Prosser, 1993; Kuchle and Scherer, 2010), especially because during this stage, activity of normal faults is incipient, and depocenters and graben shoulders are poorly developed. In that sense, one can assume that sedimentation would begin within catchment areas still strongly influenced by inherited pre-rift basement structures, which makes it difficult to distinguish sedimentation of pre-rift from early rift stages. In order to tackle this problem, the analysis of sediment dispersal from fluvial depositional systems can be decisive, since drainage from distal sources (pre-rift river systems) tends to adapt progressively to the new basin structural framework, and may also vary in fluvial style (Prosser, 1993; Gawthorpe and Leeder, 2000). Furthermore, stratigraphic relations with other genetically-linked depositional systems (e.g., deltas and lakes) can provide relevant information on the sediment supply/accommodation ratio, and consequently on depositional evolution at rift basins.

The Serraria Formation of the Sergipe-Alagoas Basin, Northeastern Brazil, is a good example to contribute to evaluation of initial deposition in rift systems. This Tithonian to Berriasian unit (Schaller, 1969; Kuchle et al., 2011) was deposited in the Afro-Brazilian Depression (Estrella, 1972), a shallow and broad depression inside West Gondwana, that encompassed most of the Brazilian northeast basins. Although some researchers name Afro-Brazilian Depression as “pre-rift” (e.g., Magnavita, 1992; Bueno, 2004), it is widely recognized that it represents the initial crustal stretching phase whereas the Cretaceous rifts settled later, resulting in the rupture of West Gondwana and consequent opening of the South Atlantic Ocean (Chang et al., 1992; Matos, 1999). Previous works presented the distribution of paleoenvironments based on vertical stratigraphic sections and paleocurrent analysis in a widespread area of the basin (e.g. Garcia and Wilbert, 1995; Garcia et al., 2005). Nevertheless, only few works present detailed outcrop interpretations that explain possible variations in depositional architecture and their distribution through time (e.g., Garcia, 1991; Souza-Lima, 2007; Kifumbi et al., 2017). Furthermore, those works are mostly based on qualitative approach of traditional facies associations, which triggers a lack of quantitative data regarding outcrop information of the Serraria Formation.

Colombera et al. (2013) have already pointed out problems related to the ambiguity of qualitative approaches of traditional facies models (e.g. Miall, 1985; Walker & James, 1992). Thereby, a quantitative approach is important to understand and interpret spatial relations between genetic units, in addition to evaluate uncertainties and the predictive capacity of facies models (Bridge et al., 2000; Colombera, 2013; Lunt et al., 2013). The application of architectural quantitative data can also contribute to the building of upscaled models, of great importance to predict the distribution of sand-bodies between seismic and drill cores scales, applied in the petroleum industry (e.g., Gonzalo and Martinius, 1993; Bridge et al., 2000; Martinius and Naess, 2005; Viste, 2008).

This paper aims to describe and interpret facies associations and depositional architecture at the outcrop scale, in order to build a more reliable model that represents paleoenvironmental changes in Serraria Formation. Our work contributes to discussion of sediment transport patterns and the main forcing factors on sedimentary fills and accumulation related to early extension of South Atlantic rifting in the Sergipe-Alagoas Basin. These new data and interpretations contribute to reconstruction of the tectono-depositional history of the Afro-Brazilian Depression during the rift onset in the Sergipe-Alagoas Basin, and can be seen as a practical example of depositional style during early rift stages.

GEOLOGICAL SETTING

The Sergipe-Alagoas Basin (Fig. 1) is genetically related to lithospheric stretching in West Gondwana, which resulted in the development of the present eastern continental margin Brazilian basins (Chang et al., 1992; Szatimari and Milani, 2016). The southern and southeastern portion of the extensional zone was subjected to crustal doming due to Paraná-Etendeka Igneous Province basaltic magmatism (Bueno, 2004). In marginal areas of this uplift, peripheral depressions developed, whose depositional climax occurred during the Tithonian or Berriasian (Estrella, 1972; Matos, 1999). The Afro-Brazilian Depression stands out in this scenario, corresponding to a north-south elongated broad and shallow depression (Cesero and Ponte, 1997).

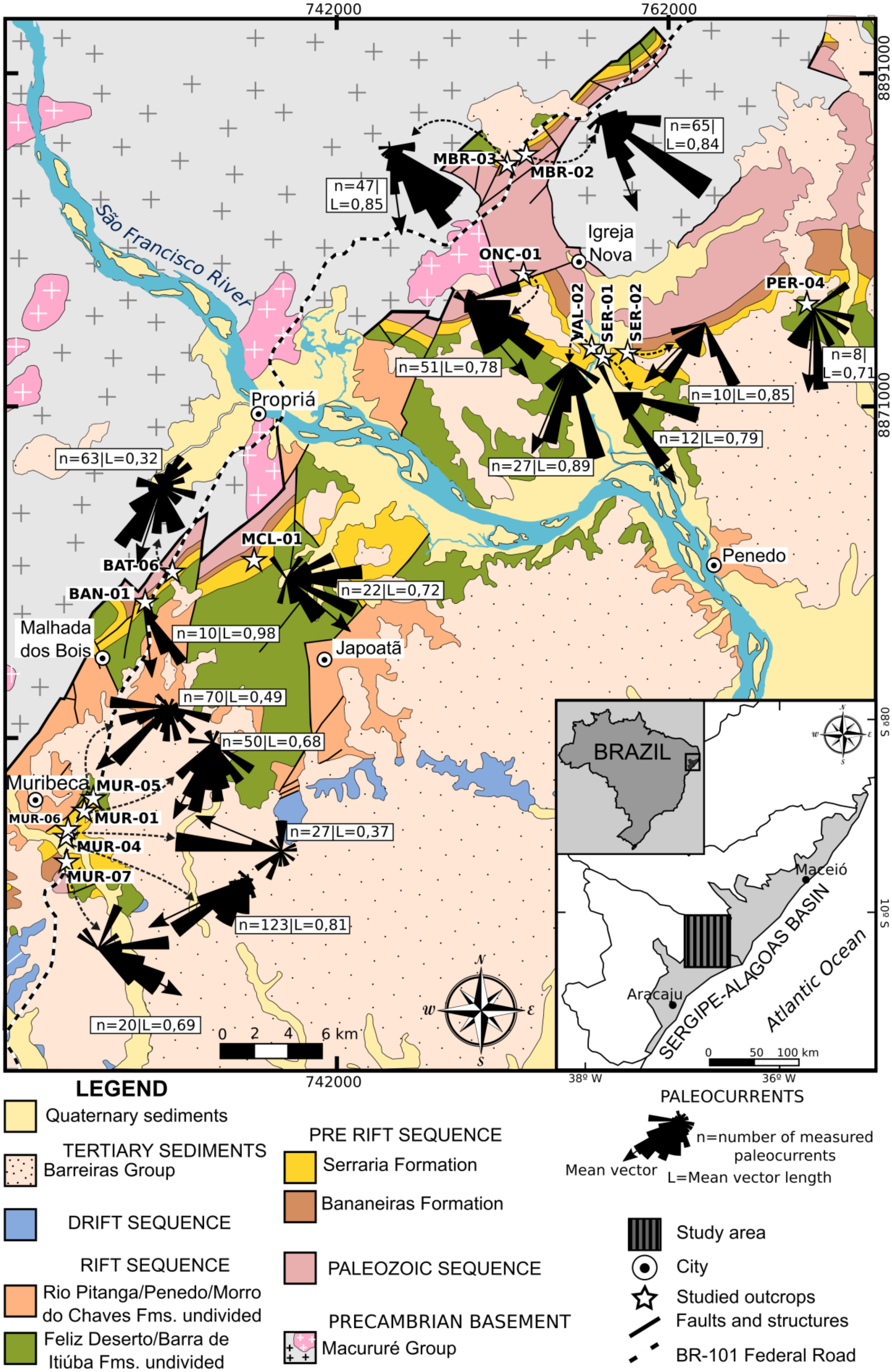


Figure 1: Geological map with the location of the Serraria Formation in the study area. Paleocurrents measured in outcrops are localized. Modified from the CPRM (Brazilian Geological Survey) database and Jardim de Sá (2008).

The development of the Afro-Brazilian Depression would have been conditioned by this extensional event during the formation of rift basins, aulacogens and passive margin basins in the present region of Northeast Brazil and West Africa (Fig. 2). This includes several basins such as Almada, Camamu, Recôncavo, Tucano, Jatobá, Araripe, Sergipe-Alagoas, Congo-Cambinada, Gabon, as well as small sedimentary basins in northeastern Brazil’s interior (Garcia and Wilbert, 1995; Cesero and Ponte, 1997; Kuchle et al., 2011). Afro-Brazilian Depression sedimentation has been preserved beneath each of these basins and is still a subject of discussion. Many authors name it as a pre-rift sedimentary fill (e.g., Schaller 1969, Viana et al., 1971; Garcia 1991; Campos Neto et al., 2007), although their descriptions coincide with early rift models *sensu* Lambiase and Morley (1999) Gawthorpe and Leeder (2000) Morley (2002). Recent works has evaluated Afro-Brazilian Depression sedimentation as the product of an early rift tectonic system tract (e.g., Scherer et al., 2007, 2014; Kuchle et al., 2011; Fambrini et al., 2011,2017).

The fluvial deposition is a remarkable characteristic of the final phase of Afro-Brazilian Depression filling. Fluvial deposits extend beyond the current limits of the Sergipe Alagoas Basin, as shown by the correlative sedimentation in other neighboring basins (Fig. 2). Garcia and Wilbert (1995) and Garcia et al. (1998) suggest that by this time, the climate was more humid but hot in northern portion of the Afro-Brazilian Depression while the southern segment would be under hot and dry climatic conditions (Fig. 2).

From a stratigraphic view, the Serraria Formation lies on top of lacustrine pelitic rocks of the Bananeiras Formation. The upper contact is transitional with greenish shales deposited in deep lakes of the Feliz Deserto Formation, interpreted as rift phase sediments (Campos Neto et al.,2007). In the contact between the Serraria and Feliz Deserto formations there is a sandstone layer about 10 m thick, referred as the “Caioba Sandstone” (Garcia, 1991; Souza-Lima, 2007; Jardim de Sá, 2008). This layer can be correlated to the Água Grande Formation fluvial sandstones (Borba, 2009), designated as pre-rift phases in the Recôncavo Basin (Silva et al.,2007).

Despite the rare occurrence of non-marine ostracods in the Serraria Formation (Souza-Lima, 2007), they do not present diagnostic age. In this way, stratigraphic relations with upper and lower units set the Serraria Formation within Dom João or Rio da Serra local Stages, corresponding to the Tithonian-Berriasian interval (Arai et al., 1989; Arai, 2006; Kuchle et al., 2011).

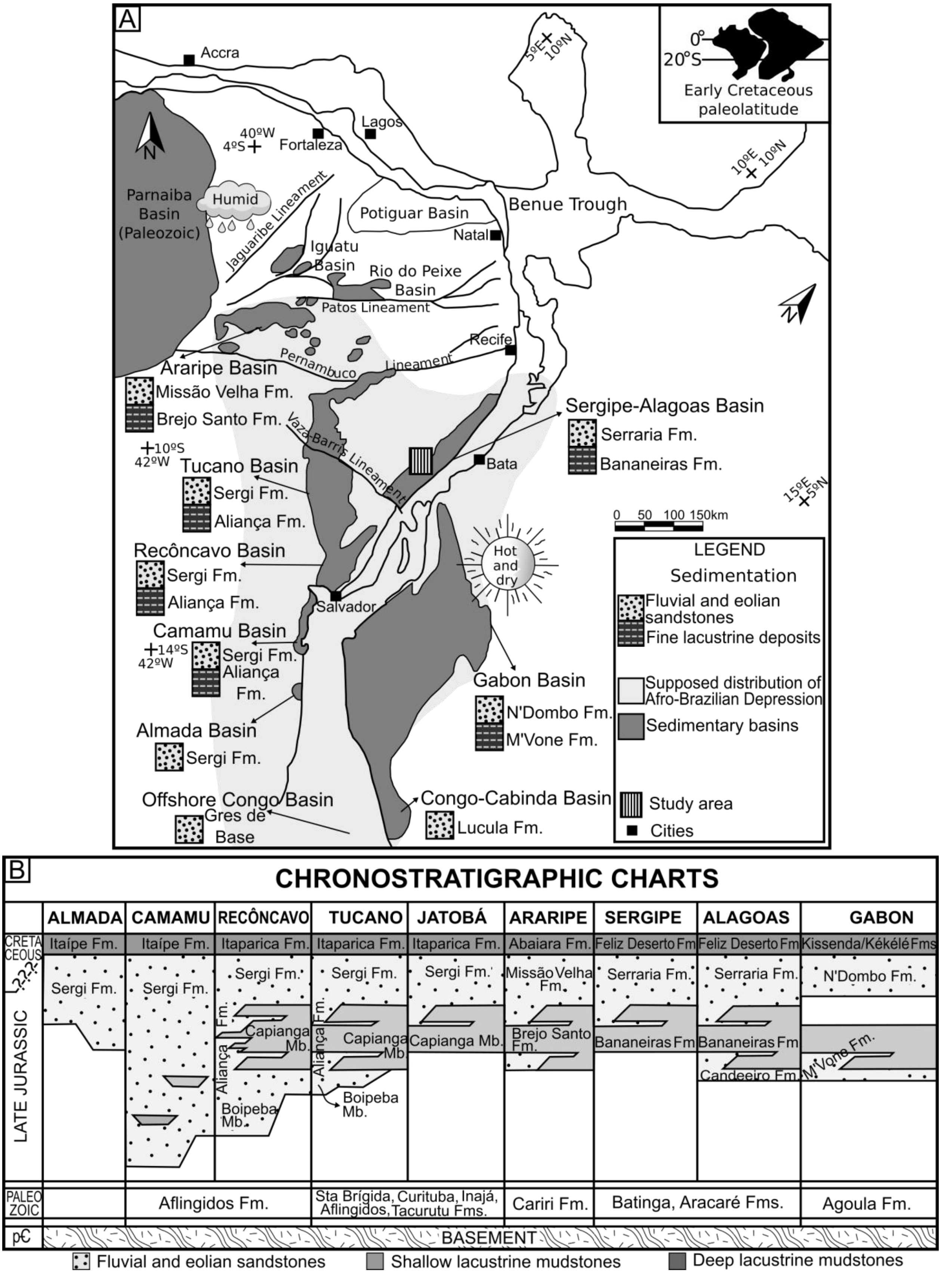


Figure 2: Sedimentary record of the Afro-Brazilian Depression. A) Sketch of the paleogeographic reconstruction of the Afro-Brazilian Depression. Modified from Garcia & Wilbert (1995); Garcia et al. (2005), Oliveira (2005). B) Chronostratigraphic charts of the main basins inserted in the context of the Afro-Brazilian Depression. Adapted from Kuchle et al. (2011).

METHODS AND DATABASE

Collected data was based on the study of 15 outcrops of the Serraria Formation located in the Sergipe-Alagoas Basin (Fig. 1). Facies and facies associations werer observed on each outcrop and latter compared to a known reference depositional model for continental and transitional environments, as proposed by Walker and James (1992), Miall (1996) and Reading (1996). Detailed columnar sections were constructed in order to assess vertical facies changes and followed the proposals of Miall (1977). Photomosaics of outcrops were constructed in order to assess the lateral variation, geometry and contact interactions between facies and facies associations. Paleocurrent measurements in several cross strata types were taken and positioned in each section as proposed by Miall (1996). Whenever possible, the attitude of accretion surfaces was also measured in order to interpret the bedform migration pattern through the difference between dip direction of paleocurrents and their respective accretion surfaces (Miall, 1996). In total, 605 paleoflow data and 198 cross dip direction of accretion surfaces were taken. When tilting was observed in outcrops, paleocurrents were corrected to the depositional bedding as proposed by Tucker (1996) through Stereo Net 8 software. Paleocurrent rose diagrams were constructed with the same software.

The bounding surface hierarchical classification is a long used approach in studies of sedimentary successions, and applied to several depositional environments (Brookfield, 1977, 1992; Allen, 1983; Bridge, 1993; Miall, 1985). However, the applicability of this method to systems where there is interaction between depositional environments is still poorly constrained (Clemmensen and Trisgaard, 1990). Given this difficulty, in this work, the bounding surface classification followed mainly the classification of Miall (1996), with some adaptations from Figueiredo (2013). In intervals with interactions between fluvial and eolian depositional systems, adaptations of Kocurek (1988), Fryberg et al. (1990) and Clemmensen and Trisgaard (1990) were used.

Photomosaics in 10 outcrops were used in order to assess the lateral variation, geometry and contact interactions between facies associations.. The exposed of facies associations(2D data) was quantifiedthrough the outcrops photomosaics supported by ImageJ software, which allows areas and lengths to be calculated, after defining a scale for the photo. In outcrops where it was not possible to construct a photomosaic, the thickness of the facies associations measured in columnar sections (1D data) was utilized.

In addition, vertical facies transition probability analyses were performed. This analysis is a useful tool for predictive model construction, very common in subsurface data (Colombera et al., 2013), through which it is possible to assess the probability of one single facies or several facies to reappear in a given vertical section from a specific area of the basin.. In this paper, this method is applied as a way to measure and evaluate the interplay of individual facies as a result of their depositional context. All vertical interactions between facies seen in columnar sections measurements were computed, totalizing 790 vertical changes of facies. Besides the vertical transition between distinct facies, the vertical transitions between the same facies (usually through basal cross bed set boundary) were also accounted for, thanks to the bounding surfaces hierarchization. Due to this approach, the matrix for vertical facies transitions analysis was more realistic, avoiding the diagonal zeros, commonly seen in works that do not consider self-transitions between bounding surfaces (Carr et al., 1966; Selley, 1970; Colombera et al., 2013).

FACIES, FACIES ASSOCIATIONS AND BOUNDING SURFACES

Facies analysis was carried out on 15 outcrops and allowed interpretation of 14 facies (Table 1, Figs. 3 and 4) grouped in 7 facies associations: FA1- Lacustrine facies association, FA2 – Small channel downstream accretion bar facies association, FA3 – Braided channel and bar facies association, FA4 – Crevasse splay facies association, FA5 – Gravel bar facies associations, FA6 – Delta front/ delta plain facies association, and FA7 – Aeolian dune facies association, summarized in Fig. 5.

Table 1: Summary of description and interpretation of identified lithofacies.

Code	Facies	Description	Interpretation

F	Massive and laminated mudstones	Massive or horizontal laminated, reddish, greenish or dark purple, sometimes mottled or bioturbated mudstones. Beds can be up to 4.5 m thick, usually between 10 and 70 cm. Usually the contacts are irregular/erosive with facies Sm, St, Sh, Gm, Gcs or SFh, but when transitional, it is marked by a gradual increase in sand content.	Deposition due suspension in fluvial plains or lakes. When mottled, suggests subaerial exposure. The dark mudstones, usually associated to SFh, represent prodelta deposition
St	Sandstone with trough cross bedding	Very fine to conglomeratic sandstones, with trough/ asymptotical cross bedding. This facies is well sorted when in fine sands, and moderately to poorly sorted in coarser grains. The cross bedding sets range between 0.1 and 2.7 m. Contacts are usually made by same facies festoons truncation. Normal grading internally to foresets laminae are common, as well as sparse or imbricated granules, pebbles or muddy intraclasts.	Product of 3D subaqueous dunes migration under lower flow regime. The presence of muddy intraclasts points to reworking of mud plains adjacent to fluvial channels during high stage flows.
Sp	Sandstone with planar cross bedding	Sandstone with planar cross bedding and texture similar to facies St. The cross sets thickness range between 0.1 and 2.5 m, usually truncated by cross bed set bounding surfaces (S1). In thick sets, commonly in coarse sand, slumps can occur in steep foresets (>25º).	Product of 2D subaqueous dunes migration (lower flow regime). Foreset convolutions represent loose sediments slumps due to flow shear stress or small seismic activities.
Sl	Sandstone with low angle cross bedding	Sandstone with texture and sedimentary structures similar to facies St and Sp. However, foresets dip angle are less than 10º. Laterally it can become sigmoidal. Cross bed sets are usually 10 to 60 cm thick.	Small linguoid or straight crests subaqueous dunes migration, or attenuation of 2D or 3D dunes in lower/upper flow regime transition.
Sc	Sandstone with compound cross bedding	Sandstone with texture similar to facies St and Sp, but with compound cross bedding (internal truncation of planar and trough cross laminae). Sets are 10 to 70 cm thick. Cossets can reach up to 3 m thick.	Agradation of diferente hierarchy bedforms over compound macroforms and/or dunes.
Sm	Massive sandstone	Massive sandstone with texture similar to facies St and Sp. It can be conglomeratic (either intraformational or not). Bed sets are 10 to 70 cm thick, and can be normal or inverse graded.	Product of rapid deposition through suspension during high stage events due to deceleration of hyperpycnal flows.
Sr	Sandstone with ripple cross lamination	Very fine to medium sandstones, well rounded, well sorted, with climbing ripple cross lamination, usually subcritic. Ripples are less than 5 cm in amplitude and 10 cm in wave length. Cosets of this facies are up to 1.5 m thick, truncated by facies Sm, Sp, St or Sl.	Product of subaqueous ripple migration under lower flow conditions, thin water column and high sedimentation rates.
Sh	Sandstone with horizontal lamination	Very fine to medium, well sorted sandstones with horizontal lamination. Beds are 10 to 65 cm thick, usually bounded by Sp facies cross bed set bounding surfaces (S1) or coset bounding surfaces (S2).	Deposition in upper plane bed conditions due ephemeral poorly channeled flows, or due acceleration of shallow currents over bar tops.

Sd	Sandstone with convoluted bedding (deformed)	Very fine to coarse sandstones, sometimes silty, deformed by convolution structures. It includes flame structures, convolute folds, fluid scape and fluidization structures. Bed sets are 10 cm to 70 cm. It occurs locally, usually associated to facies St, Sp or Sot. In some cases, soft sediment deformations can be related to deformation bands.	Fluidization of water saturated sediments under high sedimentation rates, due sedimentary loading and fluids scape. Sin-depositional small seismic activity (in association with deformation bands).
Sot	Sandstone with overturned cross bedding	Very fine to medium sandstones with overturned cross bedding. Bed sets are 10 to 50 cm thick. This facies occurs locally, usually grading laterally to facies Sp or St.	Cross bedding deformation due subaqueous current shear stress over loose water saturated sediments.
SFh	Sandstones/ mudstones with heterolithic bedding	Intercalation of mudstones and sandstones laminae, forming packages up to 1.5 m thick. Very fine to coarse sandstones laminae are centimetric, while mudstones laminae are sub-centimetric. Climbing ripples up to 5 cm in amplitude, load structures, and decimetric cross bedding with mud laminae on foresets can occur. This facies is usually associated with facies F, Sp or St in erosive/ irregular or transitional boundaries.	Product of alternating traction and decantation depositional processes under high sedimentation rates, typical of delta fronts. Rheological differences between sand and mud generate load structures
S(ae)	Sandstones with aeolian bedding	Very fine to medium, well rounded, very well sorted sandstones with trough cross bedding and pin and stripe structure. Cross bed sets are 0.2 to 2 m thick, with foresets dipping up to 30º. Internally, 2 to 5 cm thick asymptotical laminae can thin towards bottom set, where they alternate with fine to very fine sand climbing ripples.	Product of aeolian dune migration. Laminae that thin downward are interpreted as grain flow deposits that alternate with translatent ripples at the base
Gm	Massive conglomerate	Para and ortho massive conglomerates (rarely with incipient horizontal lamination). They tend to be oligomictic, dominated by rounded quartz pebbles (up to 6 cm). Mud intraclasts (up to 40 cm) are common, and can form intraformational conglomerates. This facies often occurs as lags, but can be up to 1m thick. Matrix is usually coarse sand rich. Decimetric fragments of silicified trunks are common, but some can reach up to 4.5 m long.	Deposition due abrupt deceleration of high internal cohesion subaqueous currents, associated to the base of channels or base of bars and longitudinal dunes. Intraclasts suggest erosion of mud plains adjacent to fluvial channels.
Gcs	Conglomerate and conglomeratic sandstones with cross bedding	Para and ortho oligomictic conglomerates and conglomeratic sandstones with planar or trough cross bedding. Texture is similar to facies Gm. This facies is restricted, generally in contact with facies Gm, Sp and/or St. Cross bedding sets are up to 65 cm.	Product of gravel macroforms migration; deposition on channels bottom; or chutes fill.

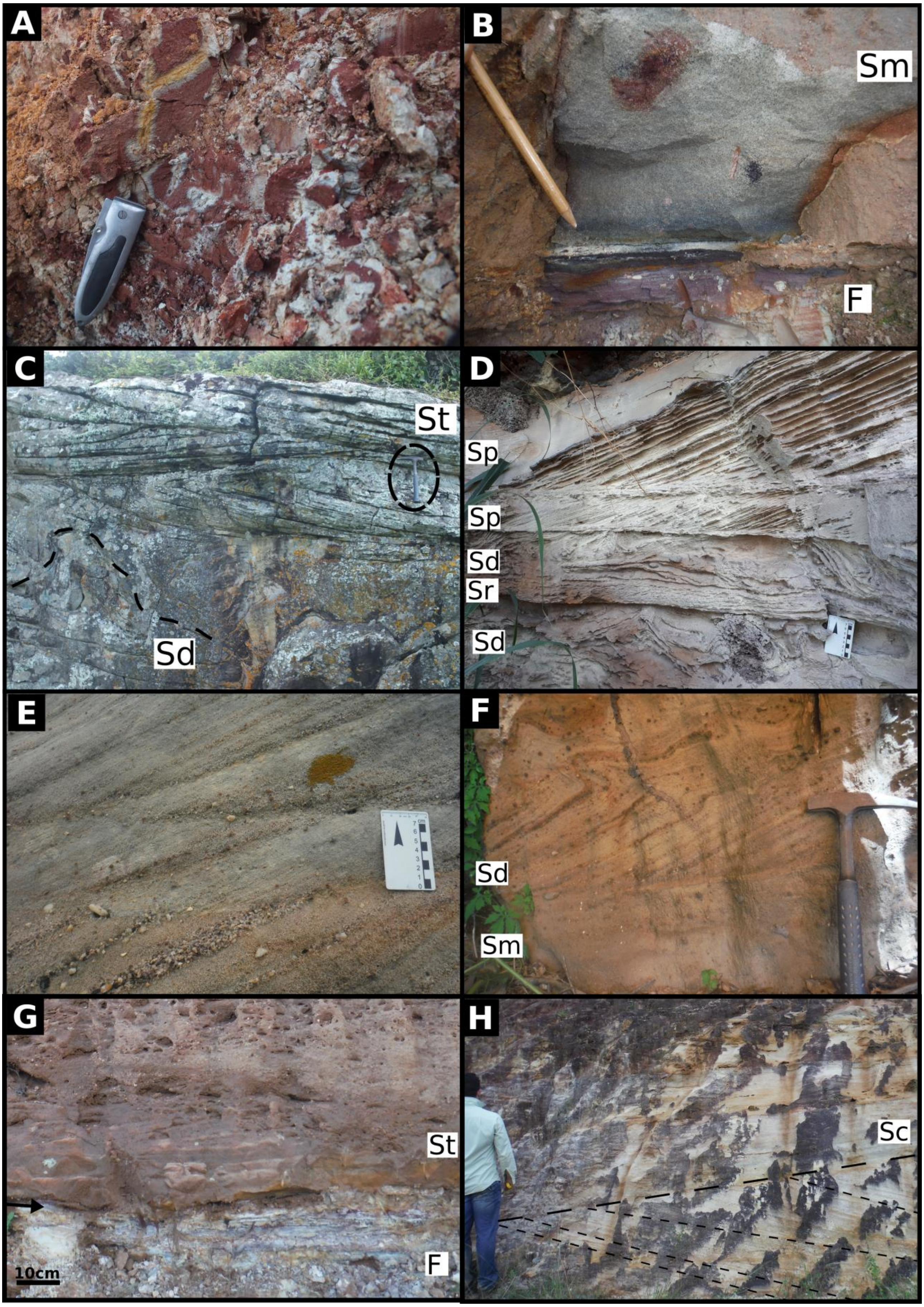


Figure 3: Examples of facies from the Serraria Formation at study area: A) Mottled massive mudstones (facies F). Switch blade is 10 cm. B) Laminated mudstone (F) overlain by fine, massive sandstone (Sm). C) Sandstone

convoluted beds (Sd) overlain by trough cross stratification (St). Hammer is 33 cm. D) Convoluted sandstone bed sets (Sd) alternated with climbing ripple beds (Sr), overlain by sandstones with planar cross bedding (Sp). Scale are in centimeters. E) Coset of sandstones with trough (St) and planar (Sp) cross bedding with open-framework gravel. F) Set of sandstones with planar cross bedding (Sp), which laterally evolve into convoluted sandstones within the same set. G) Erosive based pebbly sandstone rich in intraclasts with trough cross-bedding (St) over mudstones (F). Position of picture referenced in Fig. 10. H) Highlighted is a large cross-bed set that thickens downstream and pinch out upstream. Over this, there are smaller sets of compound cross bedding. Geologist is 1.75 m high.

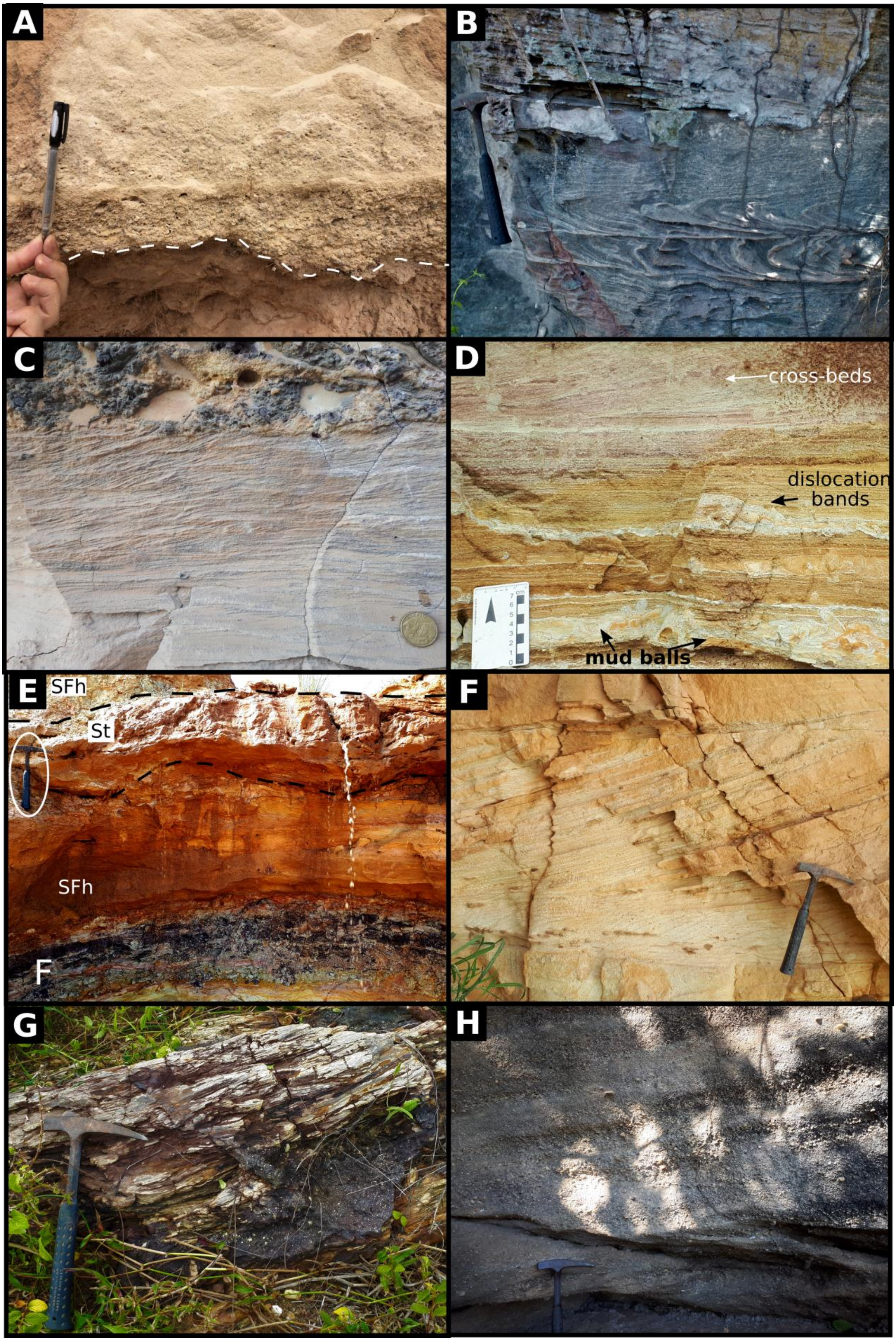

A
B
C
D
cross-beds
dislocation bands
mud balls
E
SFh
St
SFh
F
F
G
H

Figure 4: Examples of facies from the Serraria Formation at the study area (continuation): A) Massive sandstone with erosive base and normal grading (Sm). Pen is 16 cm high. B) Coset of sandstones with overturned cross beds. Hammer hanging on the contact with Sandstones with low angle cross bedding (Sl) is 33 cm. C) Coset of sandstones with subcritic climbing ripples (facies Sr). Coin diameter is 1.5 cm. D) Heterolith sandstones (facies SFh) with mud-balls ate the base, dislocations bands, and on the top of picture there is a cross bed. Scale is in centimeters. E) Succession of dark, massive mudstones (F) overlain by heterolithic sandstones (SFh), interbedded with cross-bedded, coarse sandstone (St) with erosive base. Hammer highlighted at left is 33 cm high. F) Sandstones with aeolian bedding (S(ae)) composed of translatent ripples at the bottom of grain flow strata. G) Fragment of silicified fossil trunk (*Agathoxylon*?) in massive conglomerate (facies Gm). H) Conglomerate with trough cross bedding (facies Gcs).

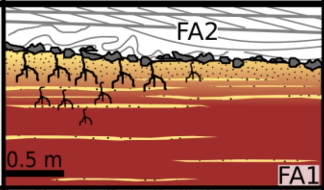
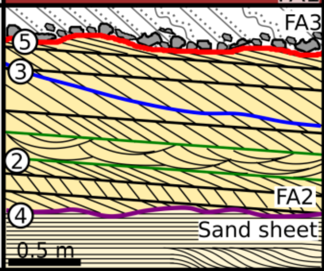
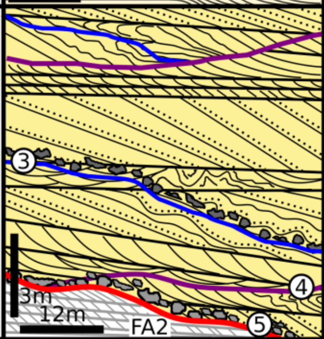
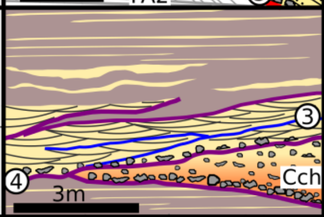
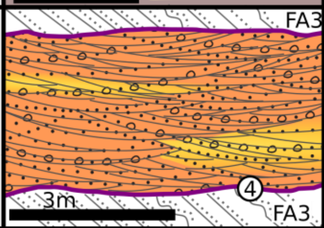
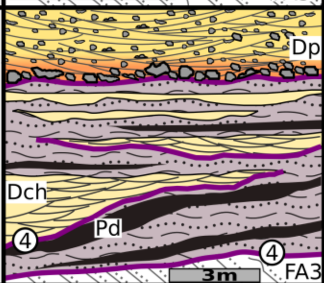
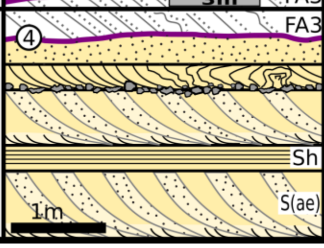
FACIES ASSOC.	GEOMETRY	DESCRIPTION	INTERPRETATION
Lacustrine (FA1)		Dominated by reddish, sometimes mottled, massive or laminated mudstones, organized in tabular strata up to 4.5 m thick and few hundreds of meters of lateral continuity. cm scale sandstone laminae occur. Upper part is sandier.	Product of mud settling in still shallow water bodies. The mottled texture is related to subaerial exposure and paleosol formation. Sandstone laminae and the coarsening upward is interpreted as increasing influx of sand by small fluvial channels.
Small channel downstream accretion bar (FA2)		Mostly composed by sets of massive and planar, eventualy trough, cross bedded fine grained sandstones. Sets range from 10 to 40cm, with accretion surfaces dipping downstream, organized in geometries of single or multstorey fill. Reactivation surfaces have minor occurence, less than 15m long, diping downstream. Laminated sand sheets occur internally.	Migration of linguoid dunes or vertical stacking of small bars under lower flow regimes (SB or DA element; Miall, 1996). Laminated sand sheets suggest deposition in upper flow-regime during flash floods due to variations of flow depth on top of bars, or by poorly confined ephemeral channels. The main explanation is deposition by small braided channels associated with high stage events.
Braided channel and bar (FA3)		Dominated by medium to very coarse/conglomeratic sandstones with trough and planar cross bedding, with sets up to 2.65 m thick, organized in arranged in multistorey sheets. Cross bed sets migrate downstream and tend to be thicker than FA2, and may show compound cross bedding. Deformed foresets are frequent. Bedform reactivation surfaces are more frequent and erosive than in FA2, with deeper scours dipping downstream.	The increase in grain size and crossbed thickness, and deeper reactivation surfaces, suggest deeper fluvial channels, capable of erode and transport coarser sediments. This change is marked by an erosive surface, interpreted as channel base, associated with an abrupt increase in fluvial discharge. The downstream dip of reactivation and accretion surfaces, the low dispersal in paleocurrent direction, the absence of mud layers, and the multistorey geometry suggest deposition from medium to big braided rivers
Crevasse splay (FA4)		This FA is interfingered with FA3. It is composed of fine to coarse, massive or cross bedded sandstones with ribbon geometry (0.3 to 2 m thick) and erosive bases, that may show fining upward. Ribbons can be stacked bounded by erosive surfaces, or be isolated amid mudstones, which can have sandstones laminae.	Interfingering with FA3 suggests deposition in the overbank area adjacent to channel belt. The erosive-based sandstones are interpreted as a product of bedload transport inside crevasse channels eroding distal floodplain deposits represented by mudstones.
Gravel bar (FA5)		Dominated by massive and cross bedded conglomerates ranging from 0.5 to 4 m thick, which may contain silicified conifers trunks up to 4.5 m long. Trough and planar cross bedded sandstones are also found. This FA is interbedded with FA3 through erosive surfaces, marked by abrupt grain coarsening.	The cross bedded conglomerates and sandstones indicate a channeled unidirectional flow capable of transport coarse grains, promoting bedform migration under lower flow condition. Association with FA3 suggests restricted deposition inside fluvial channels controlled by autogenic factors.
Delta front/ delta plain (FA6)		At the base FA6 is composed of heterolithic sandstones , interbedded with dark mudstones up to 70cm thick, and medium to coarse grained sandstone ribbons up to 3m thick, bounded by pebble lags. The upper portion of FA6 overlies an erosive surface containing intraclasts of heterolithic composition. Upwards, occur beds of coarse to very coarse cross bedded sandstones.	Mud couplets indicate traction and still water deposition in a subaqueous non-channeled environment, such as distal delta front or proximal delta plain. Sandstone ribbons represent distributary channels or mouth bars, suggesting river dominated deltas. Dark mudstones represent prodelta drownings. The amalgamated sandstone bodies at the upper interval represent delta plain progradation, and delta front reworking.
Aeolian dune (FA7)		Tabular beds composed of fine to medium sandstones with pin stripe lamination, trough cross bedding sets with steep foresets with translatent ripples at the base. Beds of sandstones with horizontal, overturned, massive or convoluted structures also occur and may be bounded by erosive surfaces with intraclasts. FA7 is interbedded with FA3.	Steep foresets, and grain flow deposits alternated with translatent ripples suggest migration of aeolian dunes. Horizontal and overturned bedding sets, bounded by erosive surfaces indicate local reworking by poorly confined streams. Massive and convoluted sandstones points to water table rises. Interfingering with FA3 points to restricted dune fields, adjacent to fluvial channels.

Figure 5: Summary of facies associations of the Serraria Formation. Codes: Cch (crevasse channel); Dp (Delta plain); Dch (Distributary channel); S(ae) (Aeolian cross stratification).

In addition, five orders of bounding surfaces were hierarchized: Cross-bed set bounding surface, Coset bounding surface, Bedform reactivation surface, Facies association/ architectural element surface; Major channel/ channel complex surface (Fig. 6).

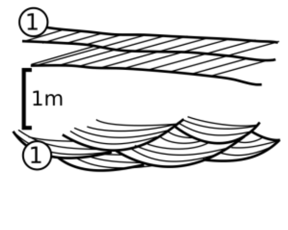
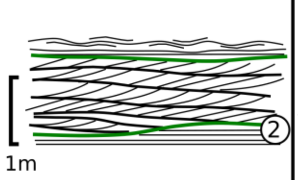
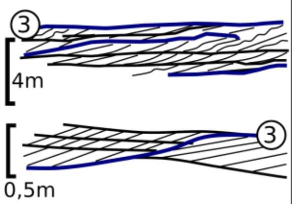
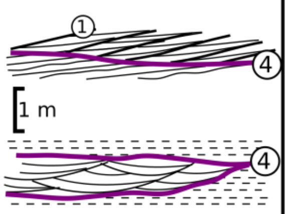
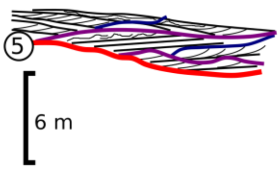
SURFACE	GEOMETRY	DESCRIPTION	INTERPRETATION
Cross-bed set bounding surface (accretion surface)		Surfaces that limit sets of planar and trough cross bedding. When bounding planar cross bedding, this surface horizontal to sub horizontal, relatively flat and with great lateral continuity (up to tens of meters). In trough cross bedding, this surface is curvilinear, laterally bounded by surfaces of the same hierarchy.	It represents the erosion of the back and top of previous dune, forming a new depositional bed for continuous sedimentation of trains of bedforms of similar type. Equivalent to the first order surface of Miall (1996).
Coset bounding surface		Sub-horizontal, gently concave up surfaces. They are generally concordant with accretion surfaces, although locally may truncate lower hierarchy surfaces at low angles. They bound cosets of different bedding sets.	Theses surfaces result from changes in bedforms types or migration direction . This implies in hydrodynamic condition changes without a big depositional hiatus. Equivalent to 2nd order from Miall (1996).
Bedform reactivation surface		Irregular surfaces of lateral continuity ranging from sub-metric to tens of meters. They can be truncated by the same or higher hierarchy surfaces. Usually they crosscut and are overlain by bed sets of a same facies, or can crosscut several facies indistinctly, commonly associated with pebbly and intraclasts lags.	Product of the reworking of dunes or bars, interpreted as erosion followed by new depositional events. This implies in changes in water column depth and new phases of sedimentation increment. Equivalent to the 3rd order surface of Miall (1996), and surfaces 2 and 4 of Figueiredo (2013).
Facies association/ architectural element surface		Irregular, concave up gently dipping surfaces. They occur as pebbly lags, sometimes with intraclasts. Their lateral extension vary from meters to hundreds of meters, and usually points out abrupt facies changes.	These surfaces bound different facies associations or architectural elements, in the same or distinct depositional environments. They generally represent bars stacking inside fluvial channels, channels abandonments, and incision of chute channels inside or outside channel belts, or even in deltaic context. They still can represent changes in sedimentation environment (e.g. superposition of delta fronts over fluvial bars). They are comparable to Miall's (1996) 4th order, surfaces 5, 7 and 8 of Figueiredo (2013), supersurfaces of Fryberg et al. (1990) and Kokurek (1988), or even sand drift suface of Clemmense & Trisgaard (1990).
Major channel/ channel complex surface		Surface only observed in two outcrops, even though it is very expressive and laterally continuous up to hundreds of meters. It shows an irregular concave up geometry, clearly dipping to north. It crosscuts indistinctly several types of facies and lower hierarchy surfaces, and usually is overlain by intraformacional conglomerates, with decimetric intraclasts.	This surface represents major channel or channel belts incisions. Internal lower order channels and downstream accretion bars would be bounded by facies association/ architectural element surfaces, as proposed by Miall (1996). This surface is equivalent do 5th order surface of Miall (1996).

Figure 6: Bounding surfaces. Adapted from Miall (1996) and Figueiredo (2013).

FA1 – Lacustrine facies association

This facies association is dominated by reddish, massive or laminated mudstones (Fig. 3A), organized in tabular strata sets ranging from 1.4 to 4.5 m thick and few hundreds of meters of lateral continuity. The lower boundary was not observed, once this facies association always appeared at the base of outcrops. Schaller (1969) and Souza Lima (2007) reported the presence of ostracods in this stratigraphic interval. Sub cm-scale sandstones laminae are eventually found, and become more frequent upward. The upper section of FA1 becomes sandier (coarsening upward) and may progressively present elongated gray to yellow-brownish mottles at some localities.

Interpretation

This facies association was interpreted as the product of mud settling in still shallow water bodies. Ostracods described by Shaller (1969) suggests to a lacustrine environment for this stratigraphic interval. Sandstones laminae suggest high frequency climate cycles, when small drainages were able to deliver sand into the lake during wetter periods (Renaut and Gierlowski-Kordesch, 2011). However, the reddish color and mottled texture, interpreted as root marks (Kraus and Hasiotis, 2006), are related to subaerial exposure and soil development. The coarsening upward is interpreted as increasing influx of sand by small fluvial channels.

FA2 – Small channel downstream accretion bar facies association

This facies association is arranged mostly as sheet and tabular geometries of multistorey fill (Friend et al*.,* 1979), composed of sets of massive and planar or trough cross bedded sandstones. The cross bedding sets are relatively thin, ranging from 10 cm to 60 cm thick, and accretion surfaces usually dip downstream. Locally, overturned cross bedding (Sot) and fluid escape deformation (Sd) can be observed (Fig. 3D). Bedform reactivation surfaces are less common, but can crosscut sand bodies, usually dipping downstream at low angles, and are less than 15 m long (Figs 7-9). Within this facies association, laminated sand sheets limited by coset bounding surfaces or bedform reactivation surfaces can be distinguished (Fig. 7-9). These sand sheets are dominated by sandstones with horizontal lamination and low angle cross bedding, that can become laterally sigmoidal. The basal contact of this facies association is with underlying lacustrine mudstones (facies association FA1), usually through pebbly lags, mostly composed of vein quartz lithoclasts and mud intraclasts, that pass upward to inverse graded muddy fine-grained sandstones.

Interpretation

The geometry and thickness of cross bedding sets accreting over downstream dipping bounding surfaces favors the interpretation of migration of linguoid subaqueous dunes (SB element; Miall, 1996) or vertical stacking of small bars under lower flow regimes (DA element; Miall, 1996). Laminated sand sheets (LS element; Miall, 1996) suggest deposition in upper flow-regime bed condition during flash floods (Ashley, 1990; Fielding, 2006), or shear stress increase due to flow acceleration on bar tops (Bristow, 1993). Convoluted and overturned bedding are, respectively, interpreted as product of water escape and current shear under high stage flow (Mills, 1983; Owen et al., 2011). The main explanation for this facies association is deposition by small braided river channels associated with high stage events likewise the Platte River (Miall, 1977).

FA3 – Braided channel and bar facies association

This facies association has the broadest occurrence over the basin, and is evidenced in most of the studied outcrops. It is dominated either by medium to very coarse or conglomeratic sandstones with trough and planar cross bedding organized in tabular sets up to 2.65 m thick, and can reach lateral continuity of tens of meters. The cross bedded strata may present alternating gravel and coarse to medium sandstones on foresets, where mud intraclasts and pebbles may be imbricated (Fig. 3E). Cross bed sets migrate downstream and tend to be thicker compared to FA2 (Table 2). Sometimes single cross-bed set becomes gradually thicker downstream, ranging from a pinch out geometry to a 2.65 m bed set (Fig. 3H). Overturned and convoluted foresets are frequent, and occur more often as internal deformation within the bed set, although it can rarely disrupt coset bounding surfaces (Fig. 3C and 3F) or be related to deformation (disaggregation) bands (Fossen, 2010). This facies association is arranged in multistorey sheets a few hundreds of meters wide (Figs. 7-9). Bedform reactivation surfaces are more expressive than in FA2, showing deeper scours with lateral extensions of tens of meters. The lower boundary of this facies association with FA2 is an erosive surface overlain by intraformational conglomerates up to 40 cm thick, containing angular intraclasts up to 30 cm diameter (Fig. 8). This surface may be tracked continuously along one kilometer in close spaced outcrops, and may be seen in outcrops 40 km away. The upper part of FA3 records intercalations with gravel bar facies association (FA5) through erosive contacts (Fig. 7), and silicified conifer trunks (Fig. 4G) are more common in this upper portion. The upper boundary of FA3 is transitional with delta front/delta plain facies association (FA6), marked by a progressive increase of heterolithic sandstones/mudstones (facies SFh).

Interpretation

The increase in grain size and cross bed thickness, and deeper and more erosive bedform reactivation surfaces, suggests a deeper fluvial channel, more capable of erode and transport coarse sediments (Bridge, 1993; Leclair and Bridge, 2001). This change is marked by an expressive and erosive surface, here interpreted as 5th order surface *sensu* Miall (1996), and is more likely associated with an abrupt increase in fluvial system discharge. The record of intraclast boulders could indicate abandonment of the main channel and the lateral shift of subqueous dunes capable to rip-up mud from the former channel position (Slingerland and Smith 2004). Alternating gravel and sand on large foresets are interpreted as open-framework gravel, as a result of superimposition of smaller bedform on stoss side of larger bedforms (Lunt et al., 2004). The gradual downstream thickening of cross bedding sets suggests growth of bedforms in pools in front of downstream accretion bedforms, as suggested by Chakraborty (1999). The downstream dip of bedform reactivation surfaces and subsequent downstream accretions, the low dispersal in paleocurrent direction and accretion surfaces, the absence of muddy layers, and the multistorey sheet geometry of the sand bodies suggest deposition from perennial medium to large braided rivers (Miall, 1996; Best et al., 2003; Bridge, 2006). Gravel bar migration could also occur, which is suggested by intercalations with facies association FA5 (Smith et al., 2006; Reesink et al., 2015).

Table 2: Bedform and bankfull channel depths estimations based on Leclair and Bridge (2001). 146 and 328 cross sets were measured for FA2 and FA3, respectively. Bankfull depth is calculated from mean bedform high estimation, assuming that bankfull depth to bedform high ratio is between 6 and 10.

Facies Association	Cross set mean thickness (m)	Bedform height (m)			Bankfull Channel depth (for mean bedform height) (m)		
		Min	Mean	Max	Min	Mean	Max
FA2	0.18	0.39	0.522	0.64	3.13	4.17	5.22
FA3	0.34	0.73	0.9715	1.2	5.82	7.77	9.71

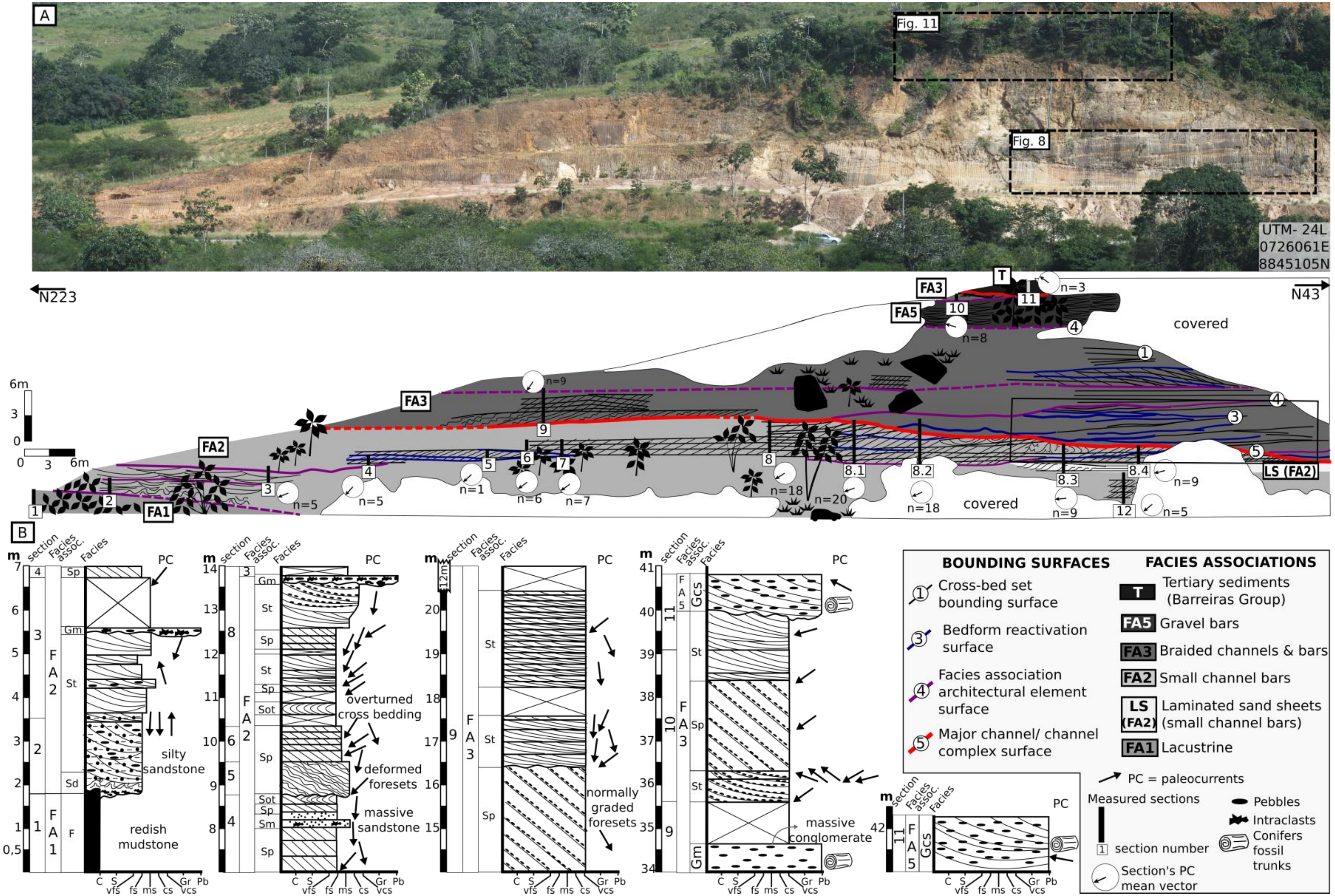


Figure 7: Interpretation of the depositional architecture of Serraria Formation (outcrop MUR-04, see Fig. 1). A) Outcrop overview. Note the car at the lower part as a scale. B) Composite section representative of the outcrop (sections indicated in photomosaic).

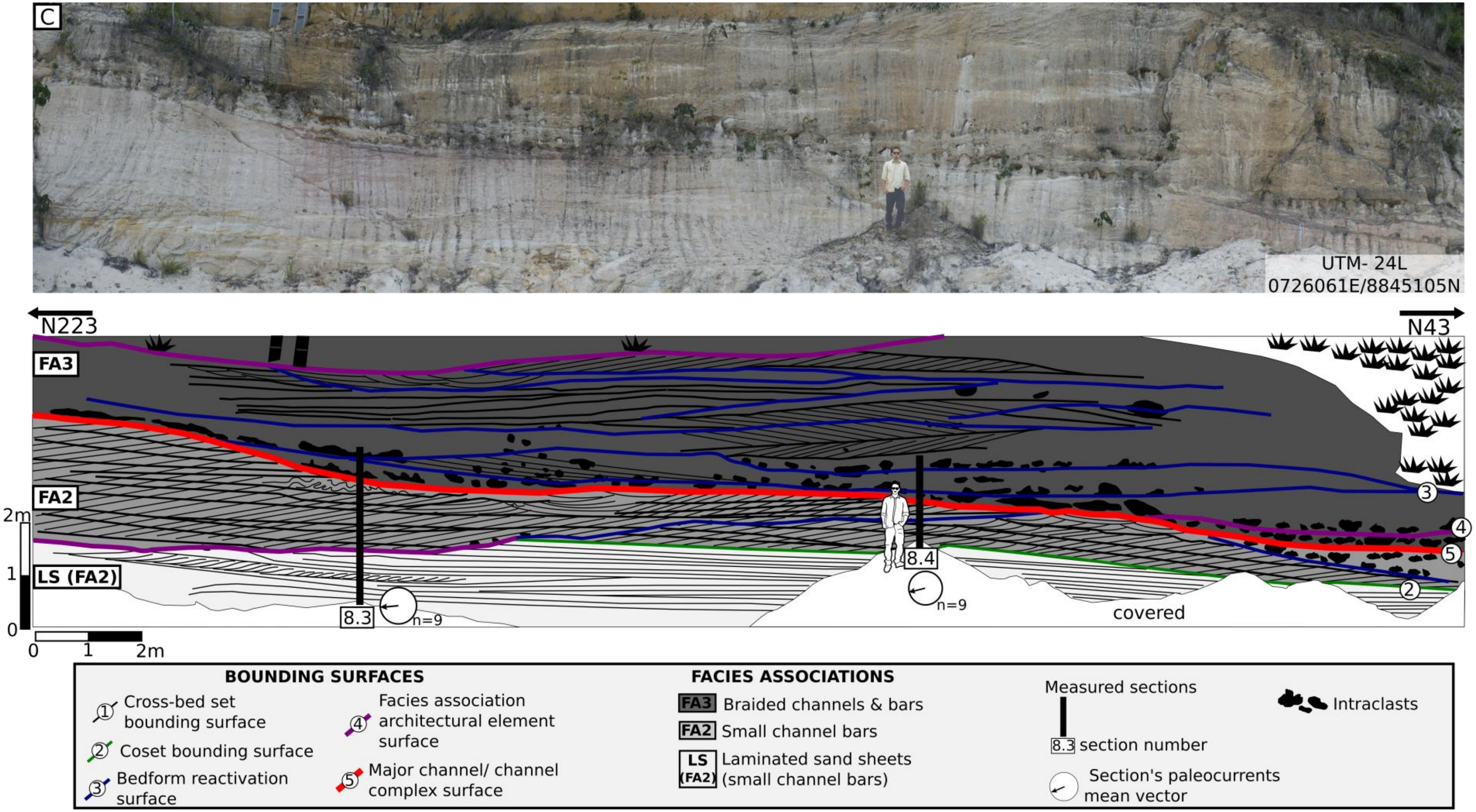


Figure 8: Interpretation of the depositional architecture of the Serraria Formation: detail of intermediate portion of outcrop MUR-04 (indicated in Figure 1). Note the major channel surface (5) that marks the contact between FA2 and FA3 facies associations.

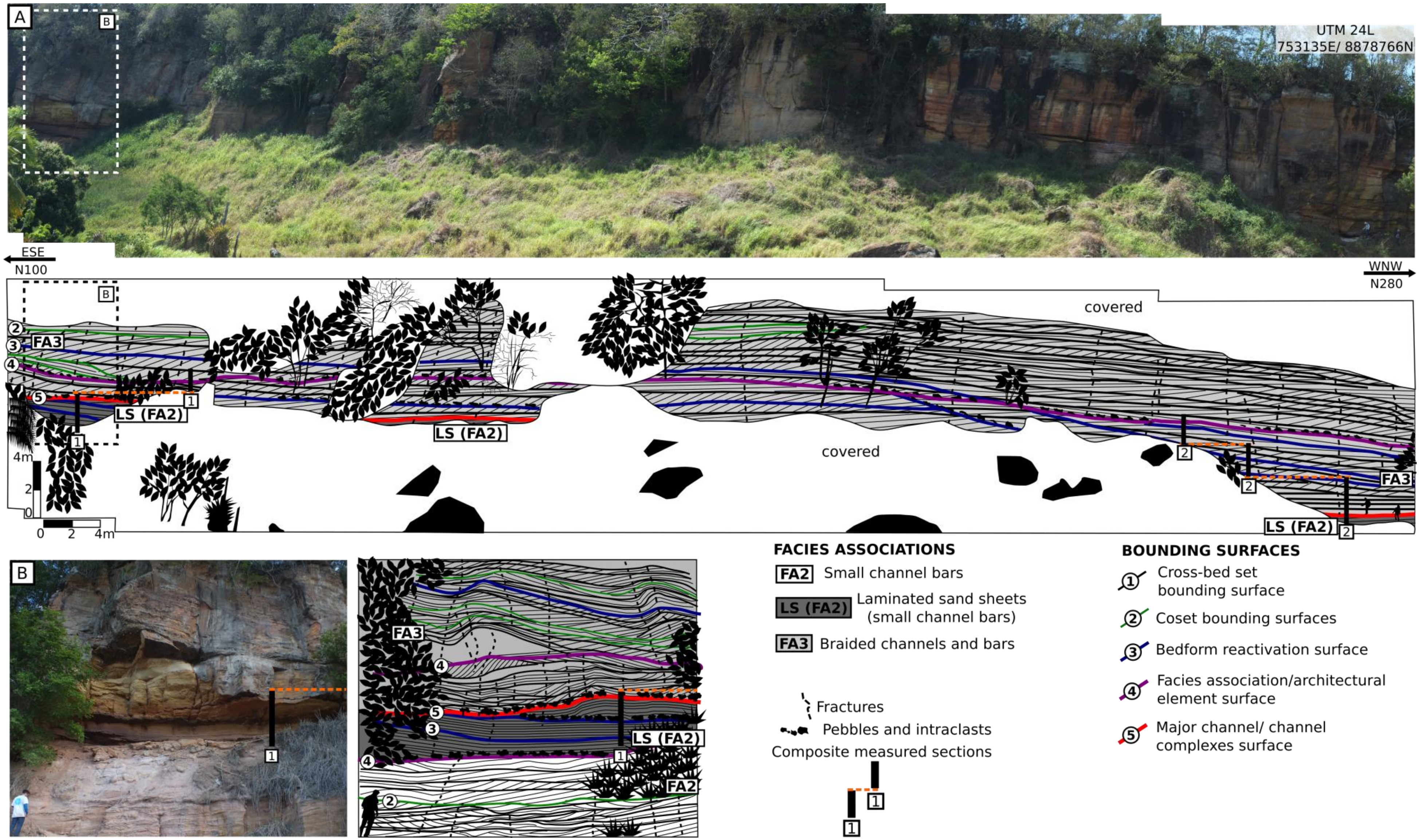


Figure 9:Braided bars of the intermediate interval of the Serraria Formation. A) Outcrop overview at locality ONÇ-01 (see Fig. 1). The geologists for scale at the lower right corner. B) Detail of the transition between facies associations FA2 and FA3 (indicated in A).

FA4 – Crevasse splay facies association

This facies association is laterally and vertically interfingered with braided channel and bar facies association (FA3) in outcrop MUR-06, which is around 50 m wide and 4.5 m high (Fig. 10). At the base, the association is composed of massive or cross-bedded conglomeratic sandstones with intraclasts, organized in a wedge shaped bed with erosive base over mudstones (Fig. 3G). FA4 is dominated by sandstone bodies with ribbon geometry, ranging from 0.3 to 2 m thick, composed of fine to medium massive or cross bedded sandstones (Fig. 10). Sandstone ribbons are isolated amid massive or horizontally laminated mudstones with cm-scale sandstones laminae (Fig. 3B). However, eventually, sandstones ribbons can be stacked, bounded by erosive architectural element surfaces (4) (Fig. 10).

Interpretation

Sandstone ribbons interbedded with mudstones and the nature of lateral and upper boundaries with facies association FA3 suggest that deposition took place in the overbank area adjacent to channel belt (Miall, 1996; Gulliford et al., 2017). The erosive-based coarse sandstones with intraclasts are interpreted as a product of bedload transport inside crevasse channels, that reworked adjacent floodplain deposits during levee breaching episodes (e.g., Miall 1996; Reading 1996,; Bristow et al., 1999). The mudstones are interpreted as decantation of fine grained sediments of distal crevasse splay to floodplain deposits (Gulliford et al., 2017).

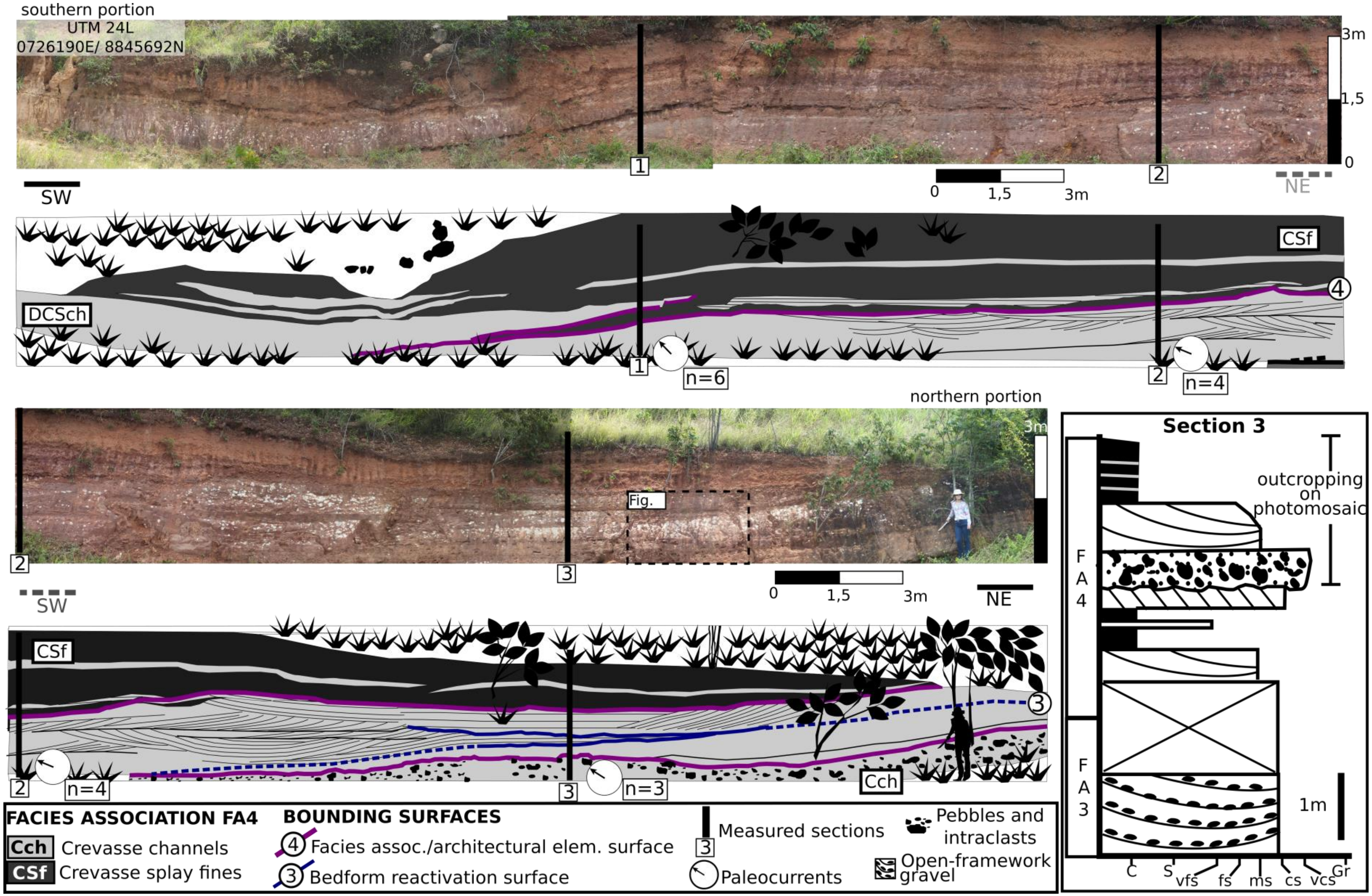


Figure 10: Crevasse splay facies association (FA4) at outcrop MUR-06 (see fig. 1 for location). Geologist is 1.60 m high.

FA5 – Gravel bar facies association

This facies association is dominated by massive conglomerates (Gm) and cross bedded conglomerates (Gcs) (Fig. 4H) ranging from 0.5 to 4 m thick (Fig. 11), which sometimes contains silicified conifers trunks up to 4.5 m long. Trough and planar cross bedded sandstones are also found subordinately. This facies association is restricted, usually interbedded with braided channel and bar facies (FA3) through erosive surfaces, marked by abrupt grain coarsening (Fig. 7).

Interpretation

The coarse-grained sandstones with cross bedding and conglomerates indicate a channeled unidirectional flow capable of transport coarse grains, promoting bedform migration under lower flow condition (Ashley, 1990). The limited occurrence of this facies association, usually associated with FA3, suggests restricted deposition inside fluvial channels. Deposition at gravel bar deposits is controlled by autogenic factors (Miall, 1996; Ramos and Sopeña, 2009; Joeckel et al., 2015), or by scour and fill of small channels (Miall, 1996; Bridge, 2006). The association of conglomerates to fossil tree trunks could be due to shallowing of the river, that in turn would create local barriers to water flow and consequent deposition with further abandonment of the main river course (Mazzorana et al., 2011).

Figure 11: Geometry of gravel bar facies association (FA5) bounded by erosive surfaces with braided channel and bar facies association (FA3) at outcrop MUR-04 (see Figs. 1 and 7 for location). Sets of cross bedded conglomerates dip downstream.

FA6 – Delta plain/delta front facies association

The lower contact is gradational to medium and coarse sandstones of facies association FA3 (Fig. 12). At the base, delta plain/delta front facies association (FA6) is composed of sandstones with heterolithic lamination (SFh), where climbing ripples, load structures (pillars, dishes and mudballs) are abundant (Fig. 4D) and are interbedded with up to 70 cm thick of massive, dark mudstones (facies F in Fig. 4E). Medium to coarse grained cross-bedded sandstone ribbons up to 3 m thick, bounded by erosive surfaces associated to pebble lags, are present amid heterolithic sandstones (facies St in Fig. 4E). This facies association presents a coarsening-upward, once at the top of FA6 tabular beds of coarse to very coarse sandstone with cross bedding overlies erosive surfaces containing intraclasts of heterolithic composition up to 25 cm in diameter (Fig. 12).

Interpretation

The predominance of mud couplets (SFh facies) in basal portions of this facies association indicates alternation between traction and stillwater depositional processes, which suggests deposition under a subaqueous non-channeled environment. Climbing ripples, load and fluid escape structures point to high sedimentation rates. These features are compatible with a distributary depositional context, such as distal delta front to proximal delta plain (Olariu et al., 2010). In this context, sandstone ribbons could also be interpreted as the product of small distributary channels or mouth bars, suggesting the existence of river dominated deltas (Bhattacharya, 1991). Decimetric dark shales represent drowning events with eventual preservation of prodelta deposition (Bowman, 2016). The amalgamated sandstone bodies in the upper interval can be interpreted as delta plain progradation, which reworked and incorporated delta front fragments (Boyd et al., 2006; Bhattacharya, 2011). The more dispersed paleocurrent pattern (compared to fluvial FA2 and FA3, Fig. 13) measured in sandstone bodies are compatible with overall range of distributary channels presented by Olariu and Bhattacharya (2006) in modern deltas and supports this interpretation.

FA7 – Aeolian dune facies association

The aeolian dune facies association is preserved in small areas of the basin. The beds have tabular geometry composed of fine to medium sandstones with pin-stripe lamination, trough cross bedding sets up to 60 cm thick, with steep foresets, which can alternate with translatent ripples at the base (facies S(ae), Fig. 4F). It is associated with beds up to 50 cm thick of sandstones with horizontal, overturned, massive or convoluted structures. Internal facies boundaries are either given by flat cross bed and cosset bounding surfaces or by irregular surfaces containing rip up mudclasts. Eventually, cm-scale laminae of greenish mudstones may be deposited over cross-bed set surfaces. This facies association occurs interbedded with the braided channel and bar facies association (FA3) through erosive surfaces (Fig. 12).

Interpretation

Medium scale cross bedding sets with steep foresets, and grain flow deposits alternated with translatent ripples at foreset bases (facies S(ae)) suggest sedimentation due to migration of aeolian sand dunes with well-developed slipfaces (Frank and Kokurek, 1996). Horizontal and overturned bedding sets (Sh and Sot) interbedded with facies S(ae), bounded by erosive surfaces with intraclasts, is indicative of local reworking by poorly confined rivers or ephemeral streams (Mountney, 2006). Massive and convoluted sandstones could be deformed by sediment fluidization during water table rise events (Fryberg et al., 1990). Thin laminae composed of mudstones represent the settle of fine sediments in damp interdune sub-environments due to high water table level. The interplay of aeolian dune facies association (FA7) over FA3 fluvial deposits characterizes the “sand drift surfaces” of Clemmensen and Trisgaard (1990), while erosive surfaces with intraclasts indicate abrupt changes in aeolian depositional context (Kokurec, 1988; Fryberg et al., 1990), which could mean development of fluvial systems over aeolian deposition, possibly as coeval depositional environment. However, the less expressive FA7 occurrence points to restricted dune fields, adjacent to the fluvial channels.

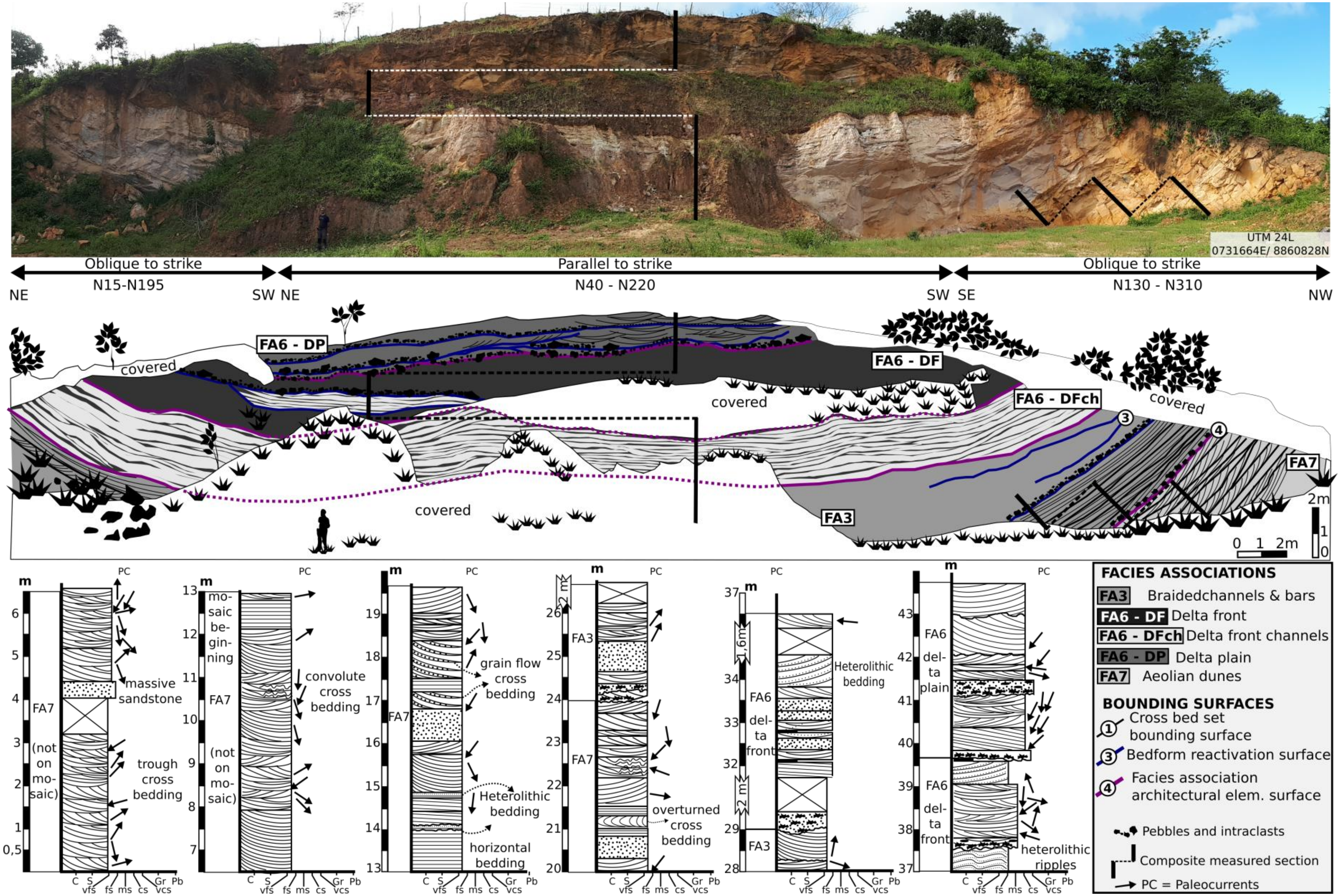


Figure 12: Depositional architecture of upper portion of Serraria Formation and measured section at outcrop BAT-06. See location in Fig. 1. The geologist is 1.75 m high.

PALEOFLOW DATA

Mesoforms arranged in small channel accretion bars (FA2) show unimodal rose diagrams for both paleocrurrent and accretion surfaces, with minor angular difference between their mean vectors corroborating with mid-channel bar interpretations (Miall, 1996). Paleocurrent mean vector shows a southwestward paleoflow for small channel downstream accretion bar facies association (FA2) (Fig. 13).

Bigger dunes preserved on braided channel and bar facies association (FA3) also present paleocurrent and accretion surfaces features compatible with mid-channel bars. However, FA3 paleocurrent mean vector points to southeast, recording a change in fluvial paleoflow (Fig. 13).

Crevasse splay facies association (FA4) show a dispersive pattern of migrating mesoforms, with a mean vector to the west (Fig. 13), which corroborates with the transport of crevasse splay deposits oblique to the FA3 main fluvial flow (Gulliford et al., 2017).

Delta front/delta plain facies association (FA6) also shows a distributary flow pattern, with mean vector to WSW, which is in accordance with deltaic dispersive fans (Olariu and Bhattacharya, 2006).

Paleocurrent rose diagrams of aeolian dunes facies association (FA7) indicate wind-driven bedforms were most frequently migrating to southeast (Fig. 13).

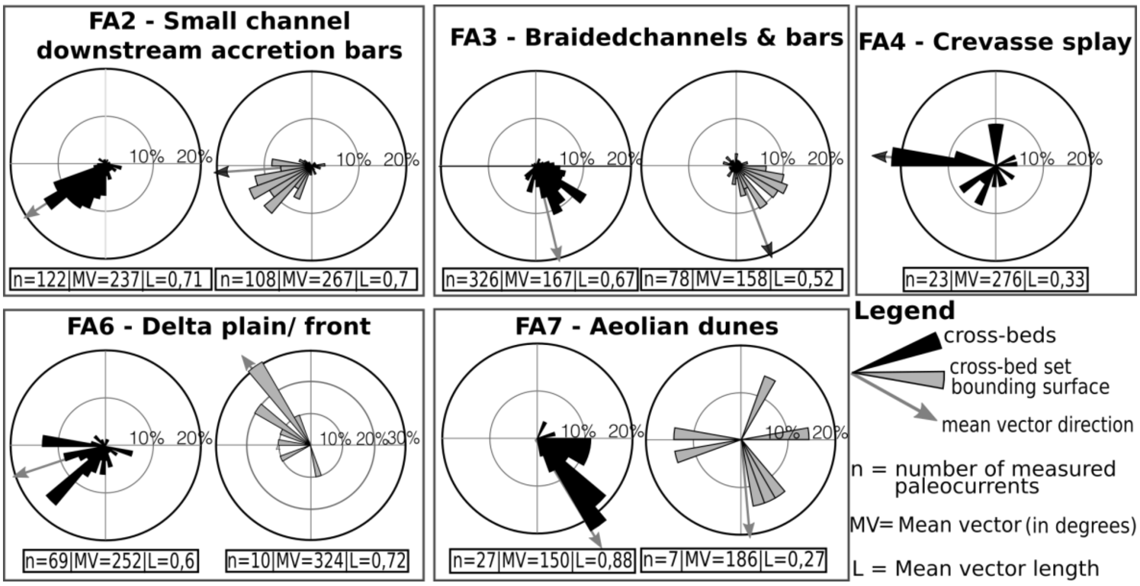


Figure 13: Facies associations paleocurrent and accretion surfaces directions. "n" reffers to the sum of measured planes in all studied outcrops for each facies association.

QUANTITATIVE APPROACH

A quantitative approach of facies association showed that FA2 and FA3 comprehend the most representative record of the Serraria Formation in both 1D and 2D data (Fig. 14). Small channel downstream accretion bars crop out at the base of the unit, representing 26% of the bi-dimensional data (23% undistinguished FA2 and 3% of FA2 laminated sand sheets), and 19% of the one-dimensional data. Braided channel and bar facies association (FA3) majorly occurs on intermediate stratigraphic intervals and comprises 54% of 2D data (49% undistinguished and 5% compound bars), and 77% of 1D data (Fig. 14). These data suggest that fluvial environment was largely dominant in the Serraria Formation, or that basal and intermediate fluvial systems had a greater potential for preservation.

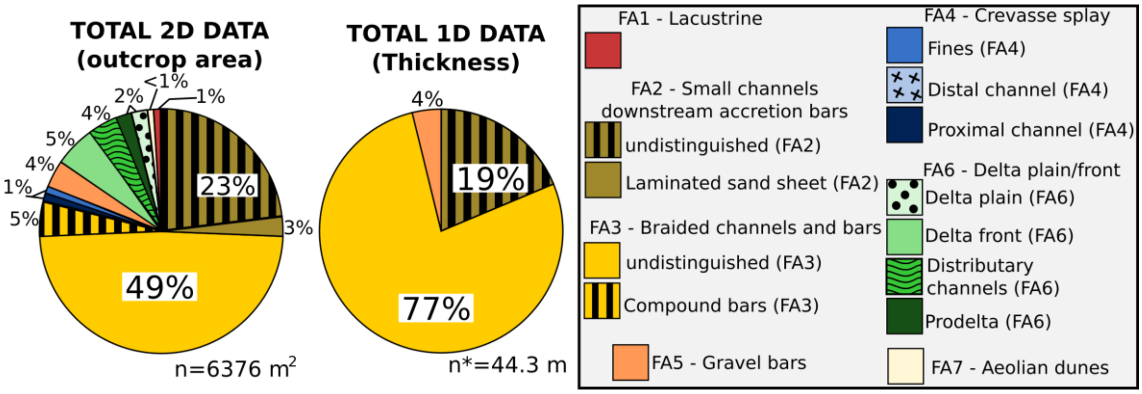


Figure 14: Proportion of genetic units (facies associations and architectural elements). “n” refers to total outcropping area (2D data) in m², and “n*” to total thickness (1D data) in meters.

The proportion of facies associations FA2, FA3 and FA5 in total 2D data (Fig. 15) suggests predominance of sedimentation inside fluvial channels (83%) when compared to other facies associations, interpreted as a product of adjacent depositional environments, beyond the main channel margins: lacustrine (FA1 – 1%), crevasse splay (FA4 – 2%), deltaic (FA6 - 14%) and aeolian (FA7 – less than 1%). Thus, it is possible to infer a depositional system compatible with morphological style of braided rivers, in which channels/flood plains ratio is high (Collinson, 1996; Miall, 1996, Bridge, 2006; Lunt et al., 2013).

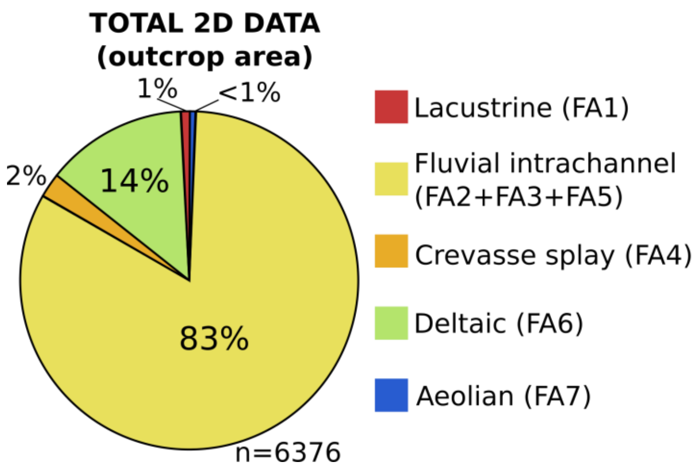


Figure 15: Distinction between intrachannel facies associations and other environments. Total 2D (Fig. 14) data were used. “n” refers to outcropping area in m².

The individual facies quantification from measured sections (1D data) showed that 70% of them are the product of sandy bedforms under low flow regime (St – 47%, Sp – 17%, Sc – 5%, Sl – 5%, Sr – 1%). This is compatible to the migration of bedforms in sand-dominated rivers for the Serraria Formation, as already proposed by other authors (e.g. Garcia, 1991; Garcia and Wilbert, 1995; Souza-Lima, 2007). However, flood events and unconfined flow capable to form upper flow regime facies could be less significant than presented in those previous models, as pointed by the low amount of sandstones with horizontal lamination (Sh - 3%) and of massive sandstones (Sm – 6%) (Fig. 16). This could imply in a small influence of seasonal climatic effects, or at least in a low preservation potential for these effects in the geological record, since the rate of discharge change is an important factor for the development and preservation of sedimentary structures (Fielding et al., 2018).

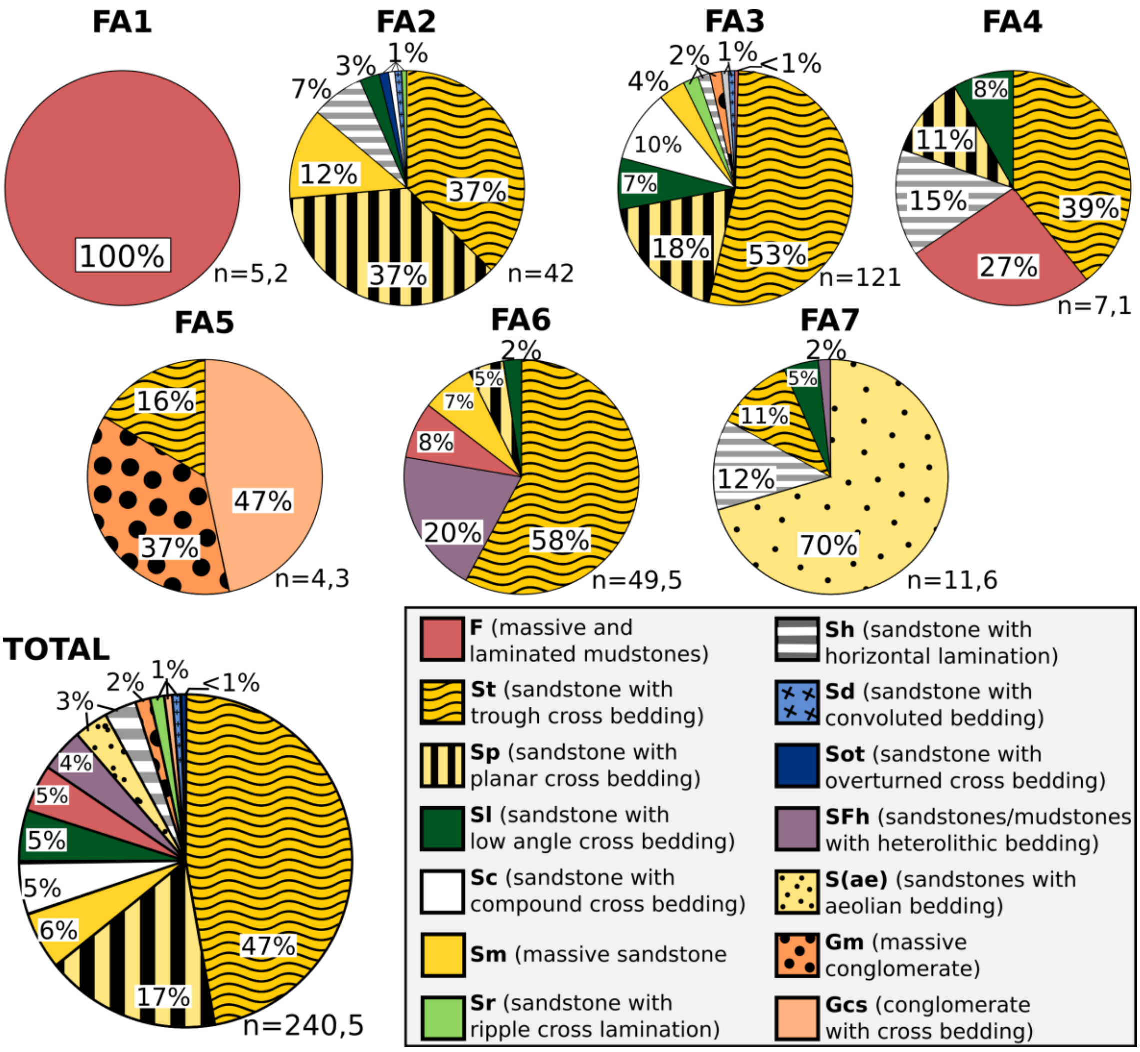


Figure 16: Facies proportions (in each facies association, and for total data). “n” refers to thickness in meters.

Vertical facies transitions analysis

The distribution of facies throughout vertical sections showed that sandstones with trough and planar cross bedding (St and Sp) are the more frequent facies, either overlapping the same facies (self-overlapping) or other facies (Fig. 17). Results from sandstones with trough cross bedding showed that of the 386 times that facies was overlain by some bed, in 80% of the cases (310 overlaps) vertical transition was given by a cross bed set of the same facies St. On the other side, of the 160 times a sandstone with planar cross bedding was recorded, in 74 % of the cases it was self-overlapped. This, together with facies and facies associations quantification (Figs. 14 and 15), highlights the role of fluvial aggradation through sand dunes stacking and bars construction inside fluvial channels of Serraria river system.

In this paper, specific affinities of vertical facies transitions are also observed in contexts influenced by deltas and aeolian dune fields. Heterolithic sandstone facies (SFh) commonly occurs in a delta front environment, being overlain by facies SFh itself 52% of times (Fig. 17). This indicates a tendendy to vertical aggradation in environments where deposition by traction currents and settling processes of particles alternates. Facies Gm and St overlap facies SFh 4% and 20% of times, respectively (Fig. 17), which suggests distributary channels (St) with basal pebbly lags (Gm) in delta fronts. In the same way, sandstones with aeolian cross bedding (S(ae)), genetically associated to dune fields, is overlain by the same facies S(ae) 96% of the times, and only 4% by facies SFh (Fig. 17). This suggests that in the aeolian intervals of Serraria Formation, the stacking of aeolian dunes (S(ae)) predominated, with rare preservation of fine grained sediments in interdune areas (SFh).

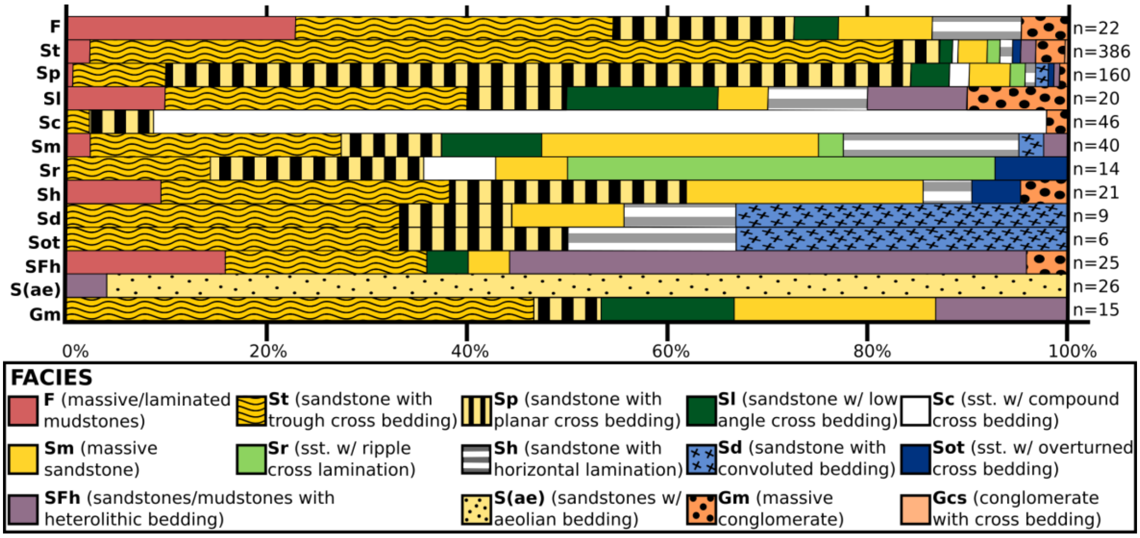


Figure 17: Vertical facies transition statistics quantifying the percentage of types of facies (coded in the colored bars) deposited over a given type of facies (vertical axis). “n” refers to the total number of times reported that a given facies is overlain.

DISCUSSION

Depositional environment evolution

The Serraria Formation revealed facies associations and geometries compatible with braided fluvial systems, although fluvial style changes and interaction with adjacent depositional systems could be observed (Fig. 18). Such changes can be related to variations in the main allogenic (tectonism, climate and source area) and autogenic controls, discussed below.

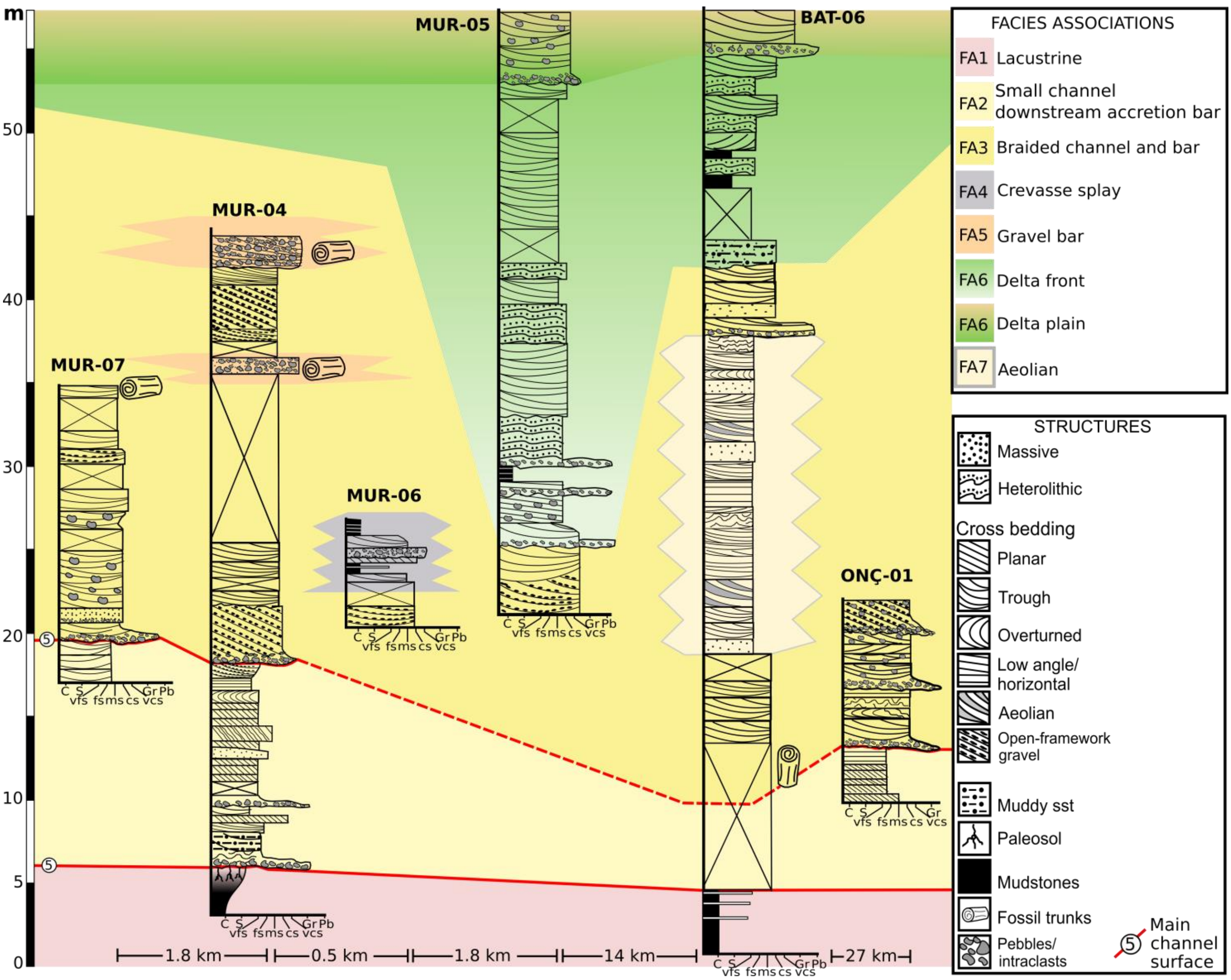


Figure 18: Correlation of stratigraphic sections. See Fig. 1 for location.

The lacustrine facies association (FA1) could be associated with a distal floodplain environment. However, the relatively thick layers, and its stratigraphic position, always overlain by sandstones of the Serraria Formation, suggests that FA1 represents the lacustrine mudstones of Bananeiras Formation, as defined by Schaller (1969) and Campos Neto et al. (2007), which reported lacustrine ostracods in the reddish mudstones beneath Serraria Formation. The oxidized aspect of these fine sediments, with occasional root marks and paleosol in upper sections, suggest the settling of mud in shallow lakes or ponds under high evaporation rates, which could contract in periods of drier climate. Thin sand sheets found interbedded within FA1 may represent fluvial incursions on this shallow lake, which may imply in some wet and dry high climate ciclicity (Renaut and Gierlowski-Kordesch, 2011).

Small channel downstream accretion (FA2) occurs over mudstones of lacustrine facies association (FA1). This marks the progradation of the Serraria fluvial system with relatively small braided channels with paleoflow southwestward over the shallow lakes recorded by the Bananeiras Formation, (Fig. 19). In spite of abundant dunes and macroforms, laminated sand sheets record shallowing or poorly confined flow events. It is possible that the Serraria fluvial system would present a mid-peak discharge variability *sensu* Fielding et al. (2018), similar to the Platte River depositional model (Miall, 1996). The water balance between shallow lakes and small channel rivers possibly would have allowed facies associations FA1 and FA2 to coexist, until autogenic processes of bars and channels migration filled the Bananeiras Formation lake (Fig. 19).

The braided channel and bar facies association (FA3) occurs above this interval through an erosive contact indicative of a new braided channel belt or main channel incision, presenting a greater power of fluvial incision, greater competence and deeper channels (Table 2), where erosion and amalgamation of channels and bars become more frequent, marked be recurrent erosive surfaces of bedform reactivation and architectural element limit. In this scenario, the fluvial discharges of FA3 should be much larger compared to facies association FA2 suggesting that equilibrium of water balance with shallow lakes of Bananeiras Formation (FA1) were no more possible. Furthermore, rose diagrams also point to a river system change with reorganization of paleodrainages that pass to flow south-southeastward in FA3 (Fig. 13). There are also massive and cross bedded conglomerates of gravel bars facies association (FA5) interbedded with FA3, which indicates more erosive currents with higher transport competence, that were able to cause the migration of gravel bars in the same depositional context of FA3. In this interval, fossil trunks of conifers become frequent, especially in facies association FA5.

Fielding et al. (2018) proposed a model in which large woody debris may be related to growth of trees within river channels during periods of subaerial exposure, from high to very high peak discharge variability rivers. However, some evidence shows that braided bars and gravel bars (FA3 and FA5) represent low peak discharge variability rivers, such as the dominance of cross bedding structures organized into macroforms; the absence of pedogenetically modified mudstones, even though muddy intraclasts are common; absence of vegetation-induced sedimentary structures (Rygel et al., 2004); and lack of situ rooted logs. This supports that trunks were only transported by the river system from north and northwest, in accordance to the proposal of Garcia (1991), who suggested the existence of a large conifer forest north of the Afro-Brazilian Depression. Alternative explanations would be either the direct collapse of river bends associated with local delivery, and deposition of wood trees by debris flows processes during a landslide (Mazzorana et al., 2011), or tree fall by windthrow accompanied by deposition of wood from floodplains, later reworked by cutoffs or floodplain avulsion (Gregory et al., 2003).

Both FA2 and FA3 facies associations mainly represent downstream bars migration (Fig. 13). However, besides the clear granulometric difference, the distribution of facies proportions also indicates differences in flow regime (Fig. 16). Comparatively, FA2 shows a higher percentage of facies Sp (deposited due 2D dunes) and Sh (deposited due laminated sand sheets). In facies association FA3, it is observed that facies St (deposited by 3D dunes) is much more abundant, and have a clear increase in percentage of facies Sc (deposited by compound bedforms), and Gm (associated with pebbly lags on erosive surfaces). According to bedform stability diagrams, 2D dunes tend to stabilize at slower flow velocities than 3D dunes, near the field of lower plane bed (Ashley 1990). This suggests that in FA2, river currents should be slower, probably in smaller channels, which eventually accelerated during floods, depositing facies Sh in laminated sand sheets, under upper plane bed conditions. In FA3, the fluvial system should be more powerful, capable of moving coarse grained 3D (St) and compound (Sc) bedforms, and able to erode and deposit pebbles (Gm) more frequently.

Laterally to facies association FA3 channels, crevasse splay events occur as recorded in FA4. The small and limited occurrence of this facies association can mean a low preservation potential for this sub-environment. This could be explained by high migration rates of channel belts and consequent erosion of crevasse splay and flood plain deposits (Fig. 19). However it does not mean low frequency of levees breaching events. Facies proportions distribution in FA4 (Fig. 16) points to a change from facies of channeled lower flow regime (St and Sp) to typically transitional (Sl) and non-channeled upper flow (Sh) regimes, immersed in crevasse splay mudstones (facies F). The elevated sandy to muddy facies ratio compared to other crevasse splay facies models (O'Brien & Wells, 1986; Bristow et al., 1999; Gulliford et al., 2017) suggests occurrence of poorly developed flood plains, where crevasse channels migration was dominant over crevasse splay fines.

The aeolian dunes facies association (FA7) occurs locally, frequently interbedded with FA3, suggesting the existence of dune field plains often reworked by fluvial channels (e.g. Mountney, 2006; Almeida et al., 2009; Bongiolo et al., 2010) (Fig. 19). The model proposed by Garcia (1991) indicates that winds blew from southeast to northwest for the whole Afro-Brazilian Depression. Scherer et al. (2007) and Kuchle et al. (2011) propose winds from N to SW in Recôncavo and Camamu-Almada basins, although their rose diagrams may show some paleocurrent dispersion. However, in this study aeolian paleocurrents mean vector suggest southeastward winds (Fig. 13). This suggests that, contrary on what was proposed by Garcia (1991), the winds could act locally instead of a main wind-flow direction for the entire Afro-Brazilian Depression. Dune fields would be restricted, adjacent and reworked by the fluvial systems inside the Afro-Brazilian Depression (the Sergi and Serraria formations).

The delta plain/delta front facies association (FA6) occurs in the upper portion of the Serraria Formation, marked by a higher content of fine grained sediments, commonly in the form of heterolithic bedding. This is interpreted as channeled fluvial flow evolving into non-channeled distal delta plain to proximal delta fronts (Olariu and Bhattacharya, 2006). The abundance of channeled sandstone bodies of varying thicknesses with trough cross bedding amid heterolithic sediments points to a river dominated deltaic environment. The dispersed paleocurrent pattern confirms the distributive nature of this environment (Fig. 13). Interfingered dark mudstones beds indicate eventual prodelta drowning events. In the uppermost part of FA6, the stacked erosive sandstone bodies, rich in intraclasts of heterolithic composition result from delta plain progradation. The fluvio-deltaic facies association FA6 means a paleoenvironmental evolution from typical fluvial sandstones of the Serraria Formation into the deltaic-lacustrine deposits of the Feliz Deserto Formation, due to an increase in tectonic subsidence rate in the Sergipe-Alagoas Basin (Fig. 19).

Tectonic evolution

The difficulty of distinguishing the effects of allogenic controls and coastline variation on the rivers makes the stratigraphic analysis of fluvial systems a difficult task (Shanley and McCabe, 1994). This complexity becomes even bigger in early rift stages, where depocenters and half grabens are still poorly defined due to the dispersion of mechanical subsidence in the form of several disconnected faults of small displacement over a wide area (Gawthorpe and Leeder, 2000; Morley, 2002). In this way, the drainage and sedimentary fill patterns are still strongly influenced by the tectonic stability phase (pre-rift), and it is difficult to differentiate these two tectonic stages.

However, it is possible to evaluate the stratigraphic record of fluvial systems in intervals of high or low accommodation based on the degree of fluvial channels amalgamation (Halbrook, 2001; Catuneanu, 2006). Facies association FA1 represents a high accommodation interval (possibly with internal higher frequency cycles) marked by lacustrine deposition. The onset of the Serraria fluvial system (FA2) marks the beginning of a low accommodation interval, in which channels become gradually more amalgamated, even presenting interactions with aeolian dunes (facies associations FA3, FA4, FA5, FA7), reflecting a progressive accommodation decrease (Fig. 17). Facies association FA6, of deltaic nature, represents the transition to a stratigraphic interval of high accommodation. The fluvial sandstones named as “Caioba Sandstone” (not studied in this paper) occurs in the very uppermost portion of the Serraria Formation (Garcia, 1991). This relatively thin sandstone (maximum 10 m thick) marks the last low accommodation interval.

This stratigraphic stacking pattern can be considered as a tectonic pulse within an “early rift tectonic system tract” *sensu* Prosser (1993) and Kuchle and Scherer (2010), as mentioned before by Kuchle et al. (2011) and Scherer et al. (2014) in context of Afro-Brazilian Depression. Therefore, the Serraria Formation’s intervals of high and low accommodation may represent higher frequency cycles inside an early rift tectonic system tract.

At the time of deposition, the rifts troughs of the present basins that made up the Afro-Brazilian Depression were not delimited yet, due to minor tectonic activity. The Serraria fluvial system, coming from long distances in the north as an inherited drainage (e.g., Prosser, 1993; Garcia and Wilbert, 1995; Kuchle et al., 2011), would tend to slowly adjust to this structural control. In this sense, paleodrainages would run southwestward, axially to Sergipe-Alagoas proto-rift troughs, as shown by the paleocurrent pattern of facies association FA2. The contact between facies associations FA2 and FA3 possibly corresponds to the boundary between sequences 1 and 2 of Kuchle et al. (2011). These authors identified this unconformity associated with an abrupt grain size increase and paleocurrent direction changes in a broad Afro-Brazilian Depression regional scale correlation, which was also noted in the present work. In FA3, paleocurrents begin to point to drainage flowing south-southeastward. This corroborates with interpretations of structural rearrangements within the Afro-Brazilian Depression, resulting from still very incipient early rift tectonic movements, proposed by Kuchle et al. (2011). Da Rosa and Garcia (2000) reported tectonic activity in the northern portion of the Afro-Brazilian Depression, recorded by a change in the sediment's source-area of the Antenor Navarro Formation (Rio do Peixe Basin). These authors attribute activations of Serraria fluvial system to this tectonic event, in conjunction with wetter climates implementation at the drainage headwaters. In fact, although the transition between facies associations FA2 and FA3 is associated with incipient tectonism in the basin, this change appears to have a significant climatic control, since the more voluminous rivers recorded in FA3 would be the result of a more humid climate with relatively more constant rainfall.

Facies association FA6 represents a high accommodation interval, marked by the development of a river dominated deltas. At this time-interval, the early rift tectonic pulse would be at its climax, making possible the initial development of lakes conditioned to the proto hemi-grabens structures. This fluvio-deltaic context marks the beginning of the Feliz Deserto Formation tectonic lake, as already reported by Garcia (1991). Facies association FA6 possibly corresponds to Unit II of Kifumbi et al. (2017). These authors suggests deposition of anastomosed rivers in a context of increasing mechanical subsidence and accommodation rate, but still in an early rift stage.

The Caioba Sandstone, which lies above Serraria Formation, represents a low accommodation period. This interval can mean a decline in early rift pulse tectonic activity, favoring the reestablishment and expansion of fluvial drainages.

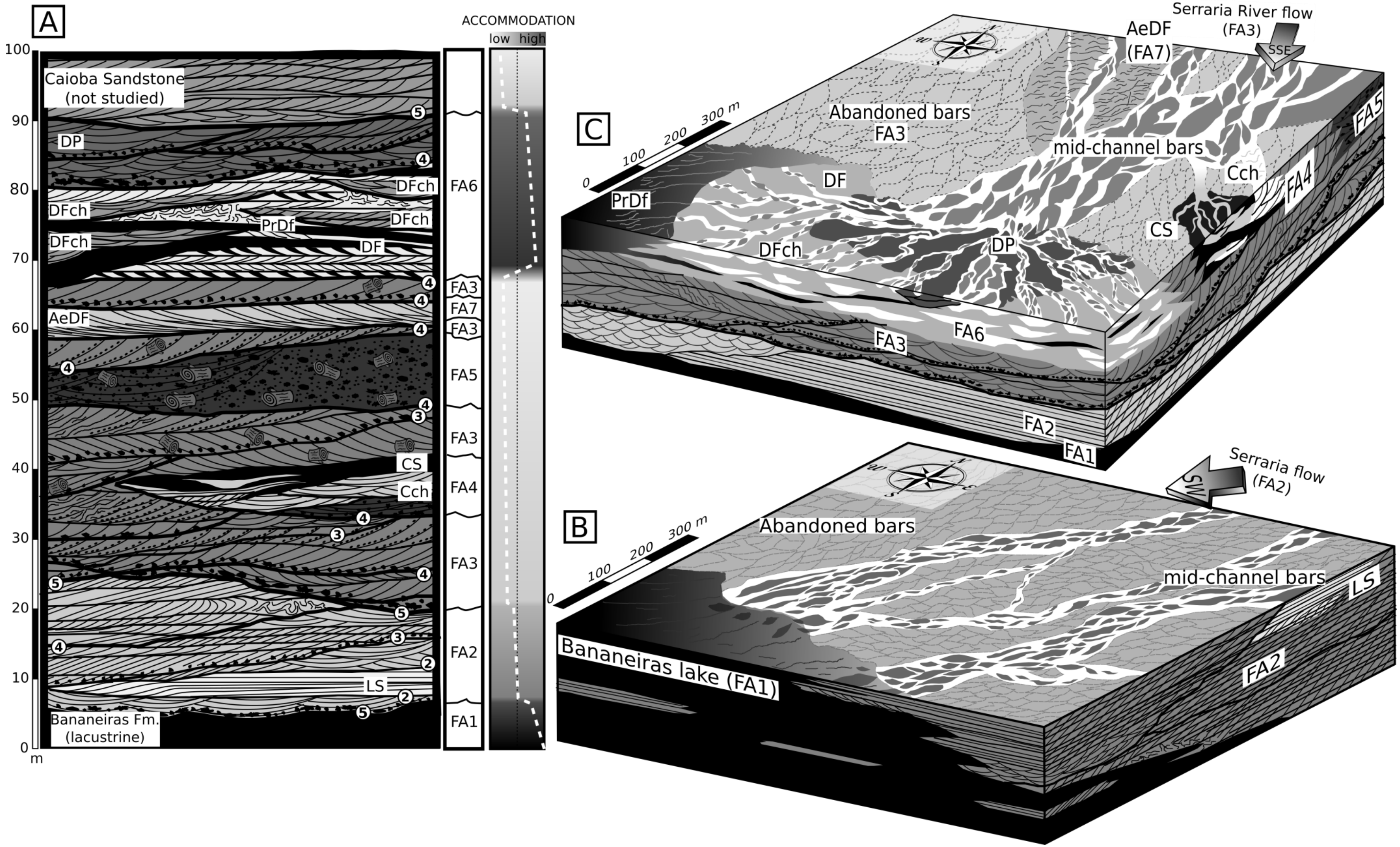

A
ACCOMMODATION
low
high
Caioba Sandstone
(not studied)
DP
DFch
DFch
PrDf
DFch
DFch
DF
AeDF
CS
Cch
LS
Bananeiras Fm.
(lacustrine)
FA6
FA3
FA7
FA3
FA5
FA3
FA4
FA3
FA2
FA1
m
C
0
100
200
300 m
AeDF
(FA7)
Serraria River flow
(FA3)
SSE
Abandoned bars
FA3
mid-channel bars
PrDf
DF
Cch
CS
DFch
DP
FA5
FA4
FA6
FA3
FA2
FA1
B
0
100
200
300 m
Serraria flow
(FA2)
SW
Abandoned bars
mid-channel bars
LS
Bananeiras lake (FA1)
FA2

Figure 19: Architecture and depositional environments interpretation of Serraria Formation. A) 2D idealized model for Serraria Formation depositional architecture. Circulated numbers refers to bounding surfaces orders. B) Depositional model for facies associations FA1 and FA2. C) Depositional model for facies associations FA3 to FA7. Codes: Laminated sand sheets (LS), Aeolian dune fields (AeDF), Crevasse channel (Cch), Crevasse splay fines/distal flood plain (CSf), Delta front (DF), Delta front channel (DFch), Delta plain (DP), Prodelta fines (PrDf).

CONCLUSIONS

The Serraria Formation presents depositional characteristics of sand dominated rivers with deposition of downstream accretion braided bars. However, depositional variations are observed in response to different allogenic controls. In the lower portion, over the Bananeiras Formation lacustrine mudstones (FA1), occurs the deposition of meso and macro bedforms, as well as laminated sand sheets inside fine sand dominated small channels (FA2). In the intermediate section, the fluvial system presents distinct characteristics, marked by facies association FA3. At that time, channels were larger and more powerful, with a greater degree of incision and amalgamation of bars and channels. Preservation of gravel bars and channel bottoms (facies association FA5) would be common by this time. Laterally, crevasse splay events (FA4) could happen, although rarely preserved due to frequent channel avulsions and migrations. Climatic and environmental variations could promote the development of restricted dune fields (FA7) adjacent to fluvial drainages. The top of the Serraria Formation presents a transitional character to deltaic environment. Facies association FA6 is marked by coarsening upward, where distributary channels dominated delta fronts are overlain by delta plain coarse sandstones.

Stratigraphic architecture variations in the Serraria Formation demonstrate how subsidence and climate can control sedimentary fill in an early rift stage. The fluvial and aeolian facies associations (FA2, FA3, FA4, FA5 and FA7) represent a progressive accommodation decrease, controlled mainly by climatic factors, favoring sediment supply. The transition to a fluvio-deltaic context (FA6) marks a subsidence increment, and represents the early rift stage climax. The Caioba Sandstone occurrence above the Serraria Formation is attributed to the end of this tectonic stage and fluvial drainage reestablishment. Only with the implementation of deltaic-lacustrine environment of the Feliz Deserto Formation, the Sergipe-Alagoas Basin begins to delineate its half-grabens.

The quantification of genetic units interpreted from qualitative criteria of traditional facies analysis methodology assisted the interpretation regarding the depositional environments and tectonic context of the Serraria Formation. The results presented here may contribute to development of more quantitative and accurate predictive models that can be applied to the study of reservoir analogues of fluvial deposits.

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CAPÍTULO III – CONCLUSÃO

A utilização do método de análise de fácies associado à quantificação de fácies se mostrou uma ferramenta útil na caracterização e interpretação do registro sedimentar da Formação Serraria em termos de variações de ambientes deposicionais, padrões de transporte e seus principais controles.

Dessa forma conclui-se que na Formação Serraria predomina a deposição de barras de acresção à jusante por rios de carga arenosa. Entretanto, Variações deposicionais são observadas. Na seção basal, acima dos pelitos lacustres da Formação Bananeiras (FA1), ocorre deposição de meso e macroformas, assim como lençóis de areia laminados em pequenos canais (FA2). Na seção intermediária, o sistema fluvial muda suas características, registrado na associação de fácies FA3. Nesse tempo os canais passaram a ser mais volumosos e com maior poder de erosão, causando amalgamação de barras e canais. A preservação de barras cascalhosas (FA5) seria comum nesse contexto. Rompimentos de canal principal (FA4) poderiam ocorrer, porém raramente preservados. Mudanças climáticas e ambientais poderiam desenvolver campos de dunas restritos (FA7), adjacentes às drenagens fluviais (FA3). O topo da Formação Serraria mostra uma transição pra um ambiente flúvio-deltaico, representado pela associação de fácies FA6, caracterizada por um *coarsening-upward*, onde frentes deltaicas distais, dominadas por canais distributários são sobrepostas por arenitos de planície deltaica.

As variações arquiteturais na Formação Serraria demostram como subisidência e clima podem controlar o preenchimento em estágios iniciais de rifte. As associações de fácies fluviais e eólica (FA2, FA3, FA4, FA5, FA7) representam um decréscimo progressivo na acomodação. A transição para um contexto fluvio-deltaico marca um incremento na subsidência, representando o clímax do início de rifte. O Arenito Caioba, acima da Formação Serraria, é atribuído ao fim desse estágio tectônico e reestabelecimento das drenagens fluviais. Apenas durante a deposição deltaica-lacustre da Formação Feliz Deserto que as calhas do rifte começam a ser delineadas na Bacia de Sergipe-Alagoas.

A quantificação de unidades genéticas auxiliou as interpretações dos sistemas deposicionais e contexto tectônico da Formação Serraria. Os resultados aqui apresentados podem contribuir com a construção de modelos preditivos mais acurados, que podem ser aplicados em trabalhos de análogos de reservatórios fluviais.

ANEXO I

Normas de submissão da revista *Sedimentary Geology*

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ANEXO II

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Manuscript Number: SEDGEO6798

Title: ARCHITECTURE AND FACIES QUANTIFICATION ON FLUVIAL DEPOSITS OF THE SERRARIA FORMATION, SERGIPE-ALAGOAS BASIN, NORTHEASTERN BRAZIL

Article Type: Research Paper

Keywords: Serraria Formation; Sergipe-Alagoas Basin; fluvial depositional architecture; facies quantification; early rift stage stratigraphy

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ANEXO III

Justificativas de coautorias

Em acordo à resolução 01/2018 do colegiado do PGAB, segue a justificativa da participação dos coautores nos artigos aqui propostos (outros autores além do aluno do programa e seu orientador):

Luisa Sampaio Franco: a coautora desenvolveu suas atividades de iniciação científica e trabalho de conclusão de graduação em consonância a essa pesquisa de mestrado. A coautora foi fundamental nas campanhas de campo para levantamentos dos dados, posterior tratamento e interpretação dos dados, edição de figuras e discussões aqui apresentadas.

Pedro Victor Oliveira Gomes: o coautor desenvolveu suas atividades de iniciação científica como parte complementar a essa pesquisa de mestrado. O coautor contribuiu com a aquisição de dados de campo, tratamento e interpretação dos dados, edição de figuras e discussões, especialmente dos modelos de contexto tectônico.

Isabela Ramos Soares: contribuiu nas campanhas de campo para levantamentos dos dados, e posterior tratamento dos dados. A coautora foi fundamental nas discussões sobre modelos deposicionais.

Larissa Lins Andrade: a coautora contribuiu na aquisição de dados durante as campanhas de campo, no tratamento e interpretação dos dados, na edição de figuras, e nas discussões do trabalho.

Marcela Aragão de Carvalho Ramos: a coautora realizou suas atividades de conclusão de curso de graduação em geologia em contribuição a esse projeto. Sua atuação foi fundamental para aquisição de dados de campo, tratamento e interpretação dos dados e edição de figuras. Sua contribuição foi fundamental nas discussões sobre modelos deposicionais.

Joice Dias dos Santos Moraes: a coautora realizou seu trabalho de conclusão de curso de graduação em geologia como um segmento desse projeto. Sua contribuição se deu nas campanhas de campo para aquisição de dados, no tratamento e interpretação dos dados, na edição de figuras, e nas discussões aqui apresentadas.

ANEXO IV

Coordenadas dos afloramentos estudados

SUB-BACIA DE ALAGOAS			
Ponto	**Abreviação**	**Latitude**	**Longitude**
Serraria 1	SER-01	757849	8873778
Serraria 2	SER-02	759333	8873940
Maraba 2	MRB-02	753003	8885678
Maraba 3	MRB-03	752303	8885198
Cova da Onça 1	ONÇ-01	752998	8878318
Perucaba 4	PER-04	770217	8876886
Vista Alegre 1	VAL-01	754703	8874387
Vista Alegre 2	VAL-02	757221	8874237
Retiro 2	RE-02	754506	8886900

	SUB-BACIA DE SERGIPE		
Ponto	**Abreviação**	**Latitude**	**Longitude**
Muribeca 4	MUR-04	726061	8845105
Muribeca 5	MUR-05	727044	8847091
Muribeca 6	MUR-06	726190	8845692
Muribeca 7	MUR-07	725451	8843526
Batinga 6	BAT-06	731753	8860793
Montes Claros 1	MCL-01	736938	8861487
Bananeiras 10	BAN-10	728903	8859581
Bananeiras 1	BAN-01	730421	8858935
Propriá 2	PRP-02	738656	8867295
Muribeca 1	MUR-01	726318	8846022

Datum: SIRGAS 2000/ UTM zone 24S.