UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
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PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

O SISTEMA FLUVIAL DISTRIBUTIVO DA FORMAÇÃO GUARÁ, JURÁSSICO SUPERIOR, GONDWANA OCIDENTAL

ADRIANO DOMINGOS DOS REIS

ORIENTADOR – Prof. Dr. Claiton Marlon dos Santos Scherer

Porto Alegre, 2020

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RESUMO

Os sistemas fluviais distributivos têm sido um dos temas mais discutidos em sedimentologia nos últimos anos. Foi proposto que estes sistemas constituam a maior parte do registro estratigráfico de sistemas fluviais em bacias continentais, contudo o seu reconhecimento exige estudo na escala de bacia que considerem a distribuição espacial das características sedimentológicas. Esta tese investiga a hipótese de que a Formação Guará constitua um sistema fluvial distributivo de grande porte, depositado entre o Sul do Brasil e o Uruguai, por meio do reconhecimento da extensão total da unidade e da construção de um modelo deposicional quantificado em escala de bacia. Foram levantados 1.071,2 m de perfis colunares em 64 localidades (62 afloramentos e 2 poços) entre os estados do Paraná e Rio Grande do Sul, no Brasil, e no nordeste do Uruguai. A análise de fácies permitiu a expansão da área de ocorrência da Formação Guará, antes restrita ao Rio Grande do Sul e Uruguai, até o estado do Paraná, distinguindo esta unidade das Formações Pirambóia e Botucatu. Por meio da quantificação de parâmetros sedimentológicos, foram reconhecidas variações espaciais no sistema ao longo de uma transecta NNE-SSW, paralela as paleocorrentes fluviais. Parâmetros como tamanho de grão, espessura dos corpos arenosos de canais fluviais, número de *storeys* por corpo arenoso e tamanho das barras indicam uma redução na profundidade dos canais, competência do fluxo e canalização para jusante, reflexo do aumento da bifurcação dos canais, infiltração e evapotranspiração. Baseado na distribuição espacial de quatro associações de fácies (canais fluviais perenes, canais fluviais efêmeros, depósitos de planície de inundação e depósitos eólicos) foi construído um modelo deposicional dividido em 4 zonas: zona 1, onde dominam os canais fluviais perenes; zona 2, onde canais perenes e efêmeros se intercalam no registro; zona 3, onde a proporção de depósitos intercanais aumenta, representados principalmente por depósitos eólicos; e zona 4, onde os depósitos intercanais são dominados por planícies de inundação. A complexidade estratigráfica da Formação Guará, que não permite o reconhecimento de padrões de empilhamento regionalmente correlacionáveis, é atribuída a flutuações de descarga controladas por variações climáticas de alta frequência. O modelo deposicional demonstra que a Formação Guará registra a deposição de um megaleque fluvial terminal com interação eólica na sua porção distal, um dos maiores sistemas fluviais distributivos já estudados no registro geológico antigo e recente, com pelo menos 1050 km de extensão. A deposição desta unidade constitui o registro da inversão tectônica e reciclagem da Bacia do Paraná durante o Kimmeridgiano-Tithoniano. A criação de espaço de acomodação para a deposição da Formação Guará, bem como sua posterior deformação e erosão são atribuídas à influência tectônica da pluma Paraná-Etendeka no Gondwana ocidental entre o Jurássico Superior e o Cretáceo Inferior.

PALAVRAS-CHAVE: Sistema fluvial distributivo, quantificação, Bacia do Paraná, Formação Guará, Jurássico Superior, Gondwana Ocidental

ABSTRACT

Distributive fluvial systems have been one of the most discussed topics in sedimentology in recent years. It has been proposed that these systems constitute the major part of the stratigraphic record of fluvial systems in continental basins, however, their recognition requires basin-scale studies that consider the spatial distribution of sedimentological characteristics. This thesis investigates the hypothesis that the Guará Formation constitutes a large distributive fluvial system, deposited between Southern Brazil and Uruguay, through the recognition of the total extension of the unit and the construction of a basin-scale quantified depositional model. A total of 1,071.2 m columnar sections were logged in 64 locations (62 outcrops and 2 wells) between the states of Paraná and Rio Grande do Sul, in Brazil, and in the northeast of Uruguay. The facies analysis allowed the expansion of the occurrence area of the Guará Formation, previously restricted to Rio Grande do Sul and Uruguay, to the state of Paraná, distinguishing this unit from the Pirambóia and Botucatu Formations. Through the quantification of sedimentological parameters, spatial trends were recognized along an NNE-SSW transect, parallel to the fluvial paleocurrents. Parameters such as grain size, thickness of the channel bodies, number of storeys per channel body and bar thickness indicate a reduction in the depth of the channels, competence of the flow and channelling downstream, reflecting an increase in bifurcation, infiltration and evapotranspiration. Based on the spatial distribution of four facies associations (perennial fluvial channels, ephemeral fluvial channels, floodplain deposits and aeolian deposits), a depositional model divided into four zones was constructed: zone 1, where the perennial fluvial channels dominate; zone 2, where perennial and ephemeral channels alternation is recorded; zone 3, where the proportion of inter-channel deposits increases, mainly represented by aeolian deposits; and zone 4, where inter-channel deposits are dominated by floodplain deposits. The stratigraphic complexity of the Guará Formation, which does not allow the recognition of regionally correlated stacking patterns, is attributed to discharge fluctuations controlled by high-frequency climatic variations. The depositional model demonstrates that the Guará Formation records the deposition of a terminal fluvial megafan with aeolian interaction in the distal portion, one of the largest distributive fluvial systems ever studied in the ancient and modern geological record, with at least 1050 km extent. The deposition of this unit constitutes the record of the tectonic inversion and recycling of the Paraná Basin during the Kimmeridgian-Tithonian. The accommodation space creation for the Guará Formation deposition, as well this subsequent deformation and erosion are attributed to the tectonic influence of the Paraná-Etendeka plume in Western Gondwana between the Upper Jurassic and the Lower Cretaceous.

KEYWORDS: Distributive fluvial system, quantification, Paraná Basin, Guará Formation, Upper Jurassic, Western Gondwana

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ESTRUTURA DA TESE

O corpo principal desta tese está estruturado em dois artigos científicos, precedidos por um texto integrador. O artigo 1, intitulado "*Sedimentology of the proximal portion of a large-scale, Upper Jurassic fluvial-aeolian system in Paraná Basin, southwestern Gondwana*", foi publicado no periódico *Journal of South American Earth Sciences* (classificação Qualis Capes A3). O artigo 2, intitulado "*A quantified depositional model of a large distributive fluvial system with terminal aeolian interaction: The Upper Jurassic of Southwestern Gondwana"* foi submetido à revista Sedimentology (classificação Qualis Capes A1). O texto integrador é constituído pelos capítulos: 1) introdução; 2) estado da arte; 3) contexto geológico; 4) dados e métodos; 5) síntese dos resultados e discussões; 6) conclusões; e 7) referências bibliográficas.

1 INTRODUÇÃO

A importância dos sistemas fluviais distributivos no registro de bacias sedimentares continentais tem sido um dos temas mais discutidos em sedimentologia nos últimos anos. Embora reconhecidos desde a década de 80, os sistemas fluviais distributivos ganharam maior notoriedade desde que Weissmann *et al.* (2010) e Hartley *et al.* (2010), a partir de estudos de bacias sedimentares continentais do recente, propuseram que os sistemas fluviais distributivos devem constituir a maior parte do registro estratigráfico fluvial nas sucessões sedimentares continentais do passado. Os mesmos trabalhos destacam que identificação deste tipo de sistema exige estudos na escala de bacia, levando em conta a distribuição espacial de fácies, associações de fácies, tamanho de grão e paleocorrentes ao longo da bacia.

Owen *et al.* (2015, 2019) conduziram estudos quantitativos em escala de bacia que caracterizaram sistemas fluviais distributivos com variadas complexidades que corroboram a relevância dos sistemas fluviais distributivos no registro continental. A Formação Guará – chamada no Uruguai de Membro Batoví da Formação Tacuarembó – consiste no registro de sedimentação fluvial e eólica no Jurássico Superior entre o sul do Brasil e Uruguai. Esta tese investiga a hipótese de que esta unidade tenha sido depositada por um sistema fluvial distributivo de grande porte, se estendendo entre o estado do Paraná e o Uruguai.

Os objetivos desta tese são reconhecer a total extensão do registro estratigráfico da Formação Guará na Bacia do Paraná e estabelecer um modelo deposicional quantificado na escala da bacia, para determinar se a unidade foi ou não depositada por um sistema fluvial distributivo.

2 ESTADO DA ARTE

2.1 Sistemas fluviais em forma de leque

2.1.1 Conceitos básicos de sistemas fluviais em forma de leque

Uma grande variedade de termos e conceitos tem sido usada pra definir "sistemas fluviais com dispersão radial que constroem formas em leque quando vistos em planta". Com base nesse conceito geral foram propostos vários modelos que, apesar de inúmeras diferenças, têm em comum a concepção de um fluxo partindo de um ápice e se dispersando para dentro da bacia. A seguir serão descritas as características básicas definidoras de cada modelo, estabelecendo-se uma análise comparativa entre eles.

Os conceitos fundamentais destes sistemas deposicionais vêm sendo construídos desde a década de 1970. Friend (1978) apontou – descrevendo o Sistema Luna, Bacia Ebro, Espanha – características que o distinguiam de qualquer outro sistema fluvial: (1) diminuição na profundidade dos canais para jusante, (2) ausência de incisão fluvial e (3) topografia lobada convexa para o sistema fluvial. Tais características indicariam a deposição em um sistema distributivo que formaria um "leque terminal" (terminal fan), no qual haveria intensa bifurcação de canais, gerando redução da descarga gradativamente para jusante. Referindo-se a este modelo, o autor evoca como exemplo de leque terminal recente o Markanda River descrito por Mukerji (1976). Trabalhos subsequentes detalharam a sedimentologia das mesmas áreas de estudo de Friend (1978), destacando-se os trabalhos de Hirst & Nichols (1986), Nichols (1987) e Friend (1989).

Baseados no clima semiárido do contexto do Markanda River e do suposto clima semiárido a árido dos exemplos da Bacia Ebro, se presumiu que os leques terminais deveriam ser característicos de regiões de clima seco. Parkash *et al.* (1983) realizou uma descrição detalhada das fácies do Markanda River, que posteriormente foi comparada com os depósitos devonianos do sudoeste da Grã Bretanha (Tunbridge, 1984), endossando e fortalecendo o modelo de leques terminais de Friend (1978).

O conceito de leque terminal foi expandido por Kelly & Olsen (1993) usando exemplos devonianos da Groênlandia e da Irlanda, nos quais estabeleceram um zoneamento da arquitetura estratigráfica dos leques terminais, com o entendimento de que todos os canais distributários do sistema fluíam ao mesmo tempo. Os autores propuseram uma divisão do sistema em três zonas, dispostas radialmente a partir do ápice, denominadas de alimentadora, distributária e bacinal. A zona de alimentação se caracteriza por grandes corpos arenosos-cascalhosos de canais associados com depósitos finos entre os canais. Na transição para a zona distributária a frequência dos corpos de canais aumenta, reflexo da intensa bifurcação dos canais. Dentro da zona distributária os depósitos de canal diminuem em escala e frequência, sendo substituídos por depósitos de inundações em lençol, produtos da redução da capacidade da corrente e da profundidade da água para jusante. A principal evidência do caráter terminal do sistema aparece a partir na transição entre as zonas distributária e bacinal, onde ocorrem depósitos de planície de inundação lamosa, playa lakes ou eólicos. A zona bacinal recebe sedimentos finos somente em grandes enchentes, sendo cortada pos canais distributários somente nos eventos extremos (Figura 1). Kelly & Olsen (1993) concluem que as diminuições da capacidade e do tamanho dos canais e o aumento da bifurcação para jusante se dava devido à perda por evaporação e infiltração, sendo, portanto, característicos de regiões semiáridas a áridas.

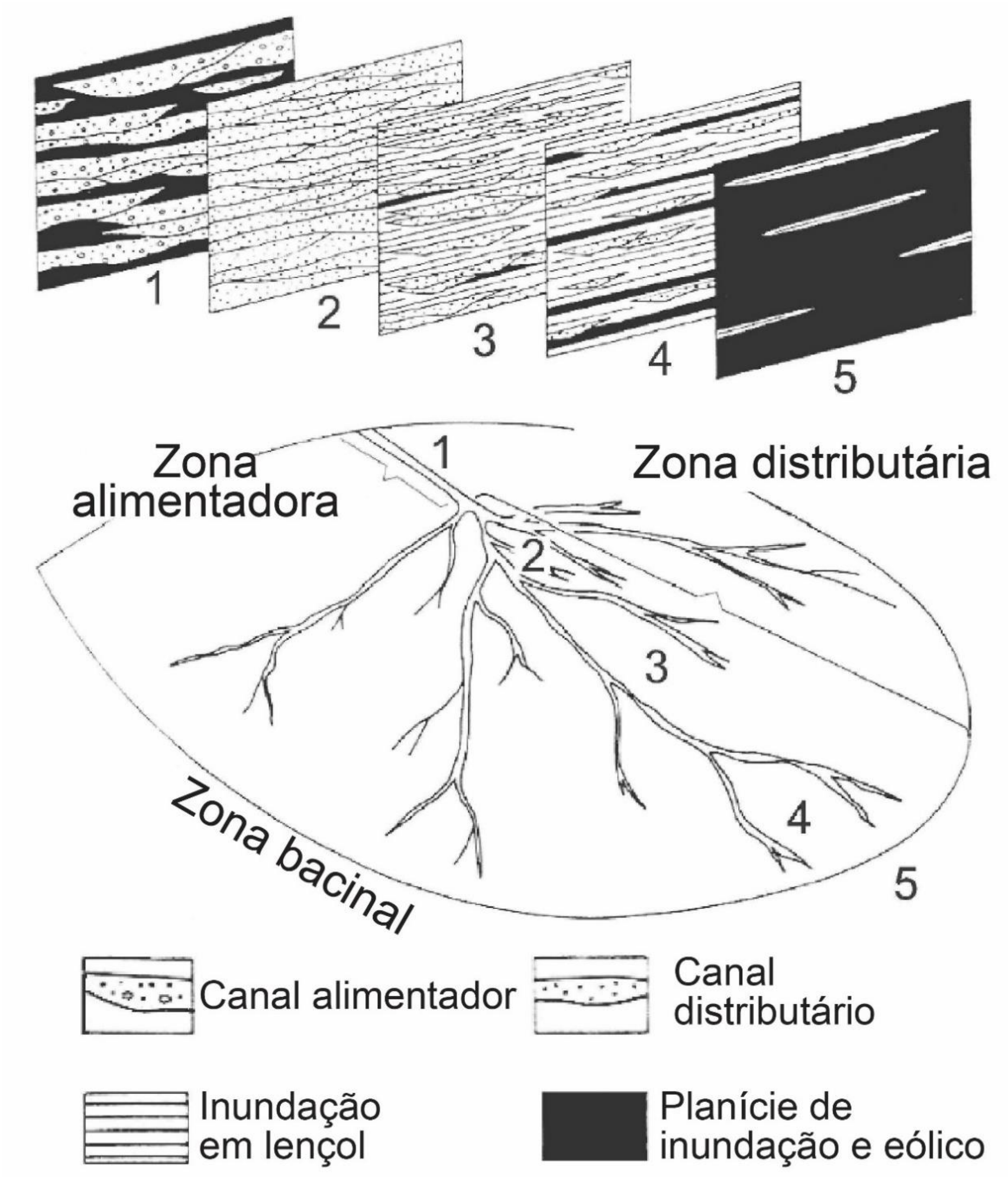

Figura 1. Modelo de fácies do sistema de Leques Terminais com zoneamento em três partes. Modificado de Kelly & Olsen (1993). (1 = zona alimentadora; 2 a 4 = zona distributária; 5 = zona bacinal)

Collinson (1996) usa o termo leque fluvial (*fluvial fan*) para leques caracterizados pela migração de canais permanentes ou intermitentes. Ressalta que sistemas deste tipo são muito extensos e com gradiente fluvial baixo, e cita como exemplos os leques Kosi (160 x 120 km), Gandak e Son, nos Vales do Ganges. Uma mudança arquitetural e de diminuição no tamanho de grão é esperada para jusante, característica que compartilham com os leques terminais. Fica claro que pelo entendimento de Collinson (1996), a construção do leque fluvial se dá principalmente pela migração sistematicamente constante do canal principal ao longo da planície aluvial, dirigida por processos avulsivos.

Um megaleque fluvial (*fluvial megafan*) consiste em um leque fluvial de grandes dimensões (103-105 km2) que emana da boca de um vale vindo de uma cadeia de montanhas (Gohain & Parkash, 1990; DeCelles & Cavazza, 1999). Não possui caráter terminal, e nem implica que todos os canais que o formam fluam simultaneamente, em padrão distributário. O modelo de megaleque foi construído sobre leque Kosi, mas como conceito foi usado para descrever diversos sistemas atuais (Wells & Dorr, 1987; Gohain & Parkash, 1990; DeCelles & Cavazza, 1999; Shukla *et al.*, 2001; Assine, 2005; Leier *et al.*, 2005; Gibling, 2006).

Stanistreet & McCarthy (1993), por sua vez, usaram o leque Kosi como modelo principal de um leque fluvial entrelaçado (*braided fluvial fan*), ao mesmo tempo que propuseram uma nova classificação geral para o que chamaram de leques subaéreos (*subaerial fans*). Para os leques subaéreos os autores propuseram a divisão em leque de fluxo de detritos (*debris flow fan*), leque fluvial entrelaçado (*braided fluvial fan*) e *losimean fan*. Os leques de fluxos de detritos são dominados, como o nome está dizendo, por depósitos de fluxos de detritos, intercalados com depósitos aluviais de fluxos entrelaçados rasos e fluxos em lençol, que retrabalham os fluxos de detritos, mas mantém a granulometria grossa dos sedimentos. Este mesmo conceito foi posteriormnente usado pera definir “leque aluvial” (*alluvial fan*) por Blair & McPherson (1994) e separá-los dos depósitos formados por processos fluviais. Os leques fluviais entrelaçados são dominados, pelo menos nas porções proximal e intermediária, por canais preenchidos por barras transversais e longitudinais, em padrão claramente entrelaçado, e com pouca ou nenhuma influência de vegetação. Por sua vez, a designação de *losimean fan* foi cunhada pelos autores, como resultado da fusão das palavras *low*, de *low sinuosity*, com *meandering*, consistindo em leques de baixíssimo gradiente, dominado por canais meandrantes, de baixa sinuosidade, altamente vegetados.

O termo Sistema Fluvial Distributário (*Fluvial Distributary System*) foi introduzido muito cedo, logo após as proposições dos modelos de leques terminais (Nichols, 1987; Nichols & Hirst, 1998), mas o modelo deposicional foi estritamente definido no trabalho de Nichols & Fisher (2007). Os autores definem *fluvial distributary system* como um sistema com o formato de um “leque fluvial”, com uma diminuição de descarga para jusante, o qual possui uma porção distal de "espraiamentos terminais" (*terminal splays*) quando não existe lago, ou pode formar um delta de lago com planícies de inundação em tempos de nível de lago alto.

Cabe um destaque especial para os modelos de sistemas fluviais distributários e sua distinção do antecessor leque terminal (*terminal fan*). Nichols & Fisher (2007), no trabalho que sintetiza e caracteriza os sistemas fluviais distributários, se debruçam sobre as suas diferenças para o modelo dos leques terminais. Destacam que muitos sistemas fluviais distributários podem de fato ser leques terminais, mas alguns deles podem sofrer influência do nível de base de um lago que possa existir na porção central da bacia. Neste caso, o sistema só seria terminal, ou seja, com espraiamentos terminais de planície em sua porção distal, em momentos de nível de lago baixo. Quando o nível do lago estivesse alto a porção distal se tornaria um delta de lago (*lake delta*) adentrando o corpo d`água, embora as porções intermediária e proximal do sistema possam manter as mesmas características de sistema fluvial distributário. Cain & Mountney (2009) apresentaram um diagrama com o resumo do modelo de leques terminais e de sistemas fluviais distributários à época (Figura 2).

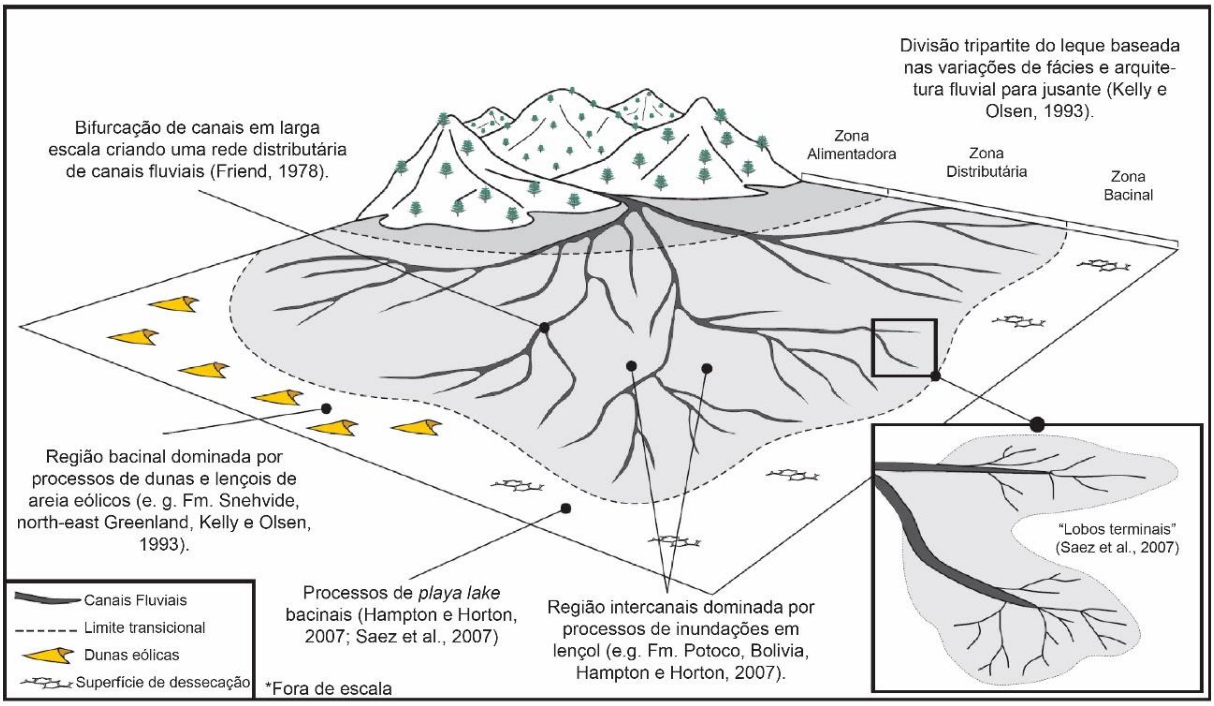

Figura 2. Modelo de fácies compilando as percepções sobre os modelos de "leques terminais" e "sistemas fluviais distributários". Modificado de Cain & Mountney (2009), construído com base em Friend (1978), Kelly & Olsen (1993), Hampton & Horton (2007) e Sáez *et al.* (2007).

Uma crítica importante e bastante contundente aos modelos de leques terminais e fluviais distributários foi realizada por North & Warwick (2007), sugerindo que os modelos propostos para as formações Luna e Huesca foram baseadas em exemplos atuais cuja interpretação foi errônea. Primeiramente invalidam os modelos baseados no Markanda River, exemplo utilizado no pioneiro trabalho sobre leques terminais de Friend (1978), primeiramente descrito por Mukerji (1976), complementado por Parkash *et al.* (1983) e incluído na síntese de Kelly & Olsen (1993). Os autores sugerem que o "*terminal fan*" do Markanda é herança de um clima mais úmido, monsonal, e que as pesadas interferências antrópicas sobre esse sistema influenciam sobremaneira o caráter terminal. Sobre um segundo análogo do modelo original, o Gash River, no Sudão, descrito por Abdullatif (1989), sobressaem dúvidas acima de seu caráter realmente terminal ou sazonal, e se sua geometria configura realmente um leque distributário. Recai sobre este exemplo a centenária "domesticação" deste rio pelos povos africanos, o que teria contribuído muito para a construção do padrão distributário que hoje se encontra. North & Warwick (2007) invocam a definição de distributário consagrada na Geomorfologia: braços de um canal principal que distribuem a água e a carga sedimentar em muitos pequenos canais que não reencontram o canal principal. Desta forma, o termo deveria ser preservado apenas para aqueles sistemas em que os diversos canais distributários fluem ao mesmo tempo. Segundo as observações dos autores, esta não é a regra para os sistemas fluviais em forma de leque. Eles concluem, suportados por observações de experimentos em tanques conduzidas por outros pesquisadores, que leques fluviais evoluem como resultados de múltiplas avulsões nodais e não por bifurcação de canais (Figura 3). Talvez venha daí a principal contribuição do trabalho de North e Warwick: o caráter verdadeiramente distributário, com diversos rios se bifurcando e fluindo contemporaneamente, parece ser uma exceção, e não uma regra nos ambientes de leques fluviais recentes, além de ser de difícil reconhecimento no registro sedimentar do passado. A partir daí se reforça a conclusão de ser a avulsão nodal o principal processo gerador das formas em leque dos sistemas distributivos.

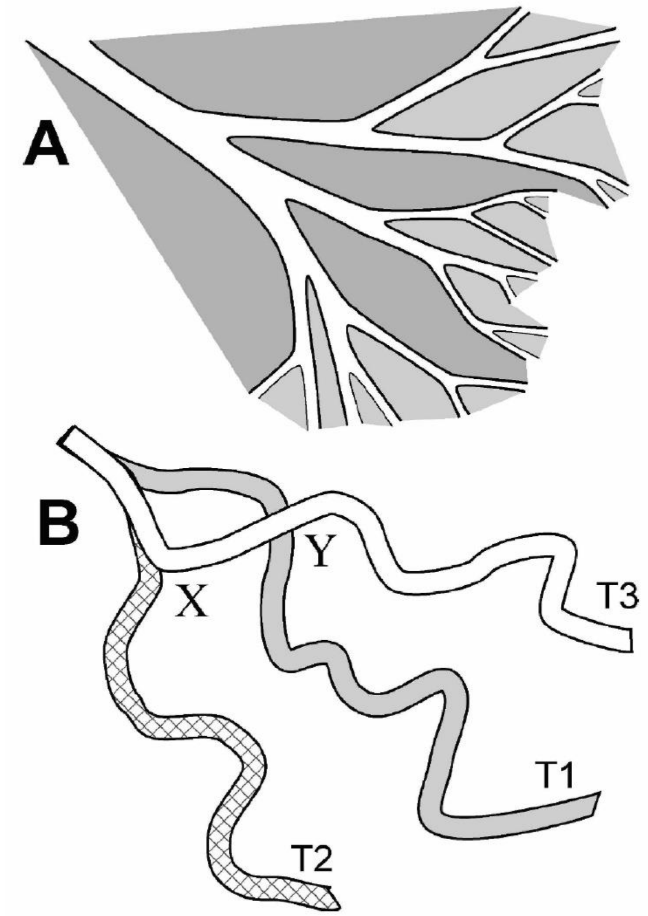

Figura 3. A) A definição geomorfológica de canais distributários, que são ativos simultaneamente. B) padrão radial de canais produzido por sucessivas avulsões nodais, onde em geral apenas um dos canais está ativo por vez (T1, seguido por T2, seguido por T3). Uma redução sistemática na profundidade e largura dos canais é produzida em (A), porque a descarga é dividida entre os canais em cada bifurcação. Em (B) esta variação sistemática não é esperada. Nos pontos de avulsão nodal X e Y pode ser produzida uma bifurcação aparente, causada pela superposição de canais. Modificado de North & Warwick (2007).

Como sumário das conclusões do trabalho de North & Warwick (2007) pode-se ressaltar:

- Os modelos deposicionais de "*terminal fan*" (Friend, 1978; Kelly & Olsen, 1993) e "*fluvial distributary system*" (Nichols & Fisher, 2007) devem ser abandonados, por estarem construídos sobre exemplos mal fundamentados e por considerarem de maneira inadequada o significado geomorfológico da palavra "*distributary*";
- Os modelos preveem diminuição de largura e profundidade dos canais para jusante. Isso é falso, os canais podem mesmo aumentar no sentido do fluxo;
- A geometria em leque e o padrão distributivo podem ser herdados de sistemas e padrões climáticos anteriores;

- Não existe um padrão climático específico, visto que sistemas fluviais em forma de leque podem ocorrer em qualquer contexto climático;
- Não existe padrão exclusivo de litofácies. A diminuição do tamanho de grão para jusante não é exclusiva dos sistemas distributivos, sendo comum em qualquer sistema fluvial;
- Análises de formas de leque atuais devem ser feitas utilizando fortemente análise temporal por imagens orbitais;
- O principal mecanismo de construção das formas fluviais em leque é a avulsão nodal, com canais fluindo diacronamente ao longo da superfície de deposição. O padrão distributário "verdadeiro" é raro e excepcional.

Hartley *et al.* (2010) e Weissmann *et al.* (2010) propuseram, a partir de uma pesquisa com mais de 700 exemplos recentes, um novo modelo intitulado Sistemas Fluviais Distributivos (*Distributive Fluvial Systems, DFS*). Os sistemas fluviais distributivos são definidos como depósitos de um sistema fluvial que mostra em planta um padrão de canais distributivo radial, a partir de um ápice localizado onde o rio adentra a bacia sedimentar. Este conceito, bastante dilatado, engloba os megaleques em megaescala, os leques fluviais em mesoescala e os leques aluviais em escala local, segundo os autores. Embora tenham este entendimento sobre os leques aluviais, alguns tipos de leques aluviais são dominados por processos gravitacionais, onde processos fluviais não são tão importantes (Blair & McPherson, 1994), não devendo ser classificados como sistemas fluviais distributivos. Com o termo "*distributive*" os autores fogem do equívoco do uso de "*distributary*" apontado por North & Warwick (2007), introduzindo um novo conceito que engloba tanto os processos genuinamente distributários quanto a construção diácrona de formas em leque por avulsão nodal, confirmando ser esse o principal processo de distribuição radial dos canais ao longo do tempo.

Com este trabalho abrangente, fica claro que os sistemas fluviais distributivos são o estilo deposicional dominante nos contextos agradacionais continentais, preferencialmente em áreas com subsidência ativa, mas também em contextos com pouco espaço de acomodação (Hartley *et al.*, 2010; Weissmann *et al.*, 2010). Sistemas deste tipo foram identificados em diversos contextos tectônicos, seja em bacias endorreicas ou exorreicas. Os sistemas mais extensos lateralmente tendem a se formar em bacias cratônicas e de *foreland* periférico onde o gradiente suave e a alto espaço de acomodação lateral permitem um espraiamento maior dos depósitos. Bacias extensionais, *strike slip* e *piggy back* tendem a formar sistemas mais curtos. Os *DFS* também foram encontrados em nos mais diversos contextos climáticos, desde subglacial até árido, passando pelos tropicais úmidos. Apesar disso, sistemas terminais são realmente mais comuns em contextos secos onde a descarga é menor. Talvez a mais importante conclusão que vem de Hartley *et al.* (2010) e de Weissmann *et al.* (2010) seja que devida as suas características especiais de acumulação e preservação, os *DFS* devem constituir a maioria do registro sedimentar fluvial, portanto têm sido subreconhecidos em trabalhos com rochas sedimentares antigas, especialmente porque o seu reconhecimento exige uma abordagem em escala de bacia. Daí advém um questionamento importante sobre os modelos de fácies fluviais construídos até hoje, historicamente baseados em rios degradacionais encaixados em vales, contextos com pouco potencial de preservação, e não em contextos agradacionais distributivos.

Além disso, o modelo de *DFS* presume a presença de rios axiais ou confinados associados aos sistemas distributivos, o que amplia ainda mais a abrangência do modelo, permitindo sua atualização na compreensão total da distribuição da fácies ao longo da bacia (Figura 4). Rio confinados podem ocorrer: (1) como rios axiais localizados entre *DFS* opostos, ou entre um *DFS* e a borda da bacia; (2) entre áreas de *DFS*, onde o rio flui entre *DFS* adjacentes, e (3) rios que estão incisos em seus *DFS* (Figura 4).

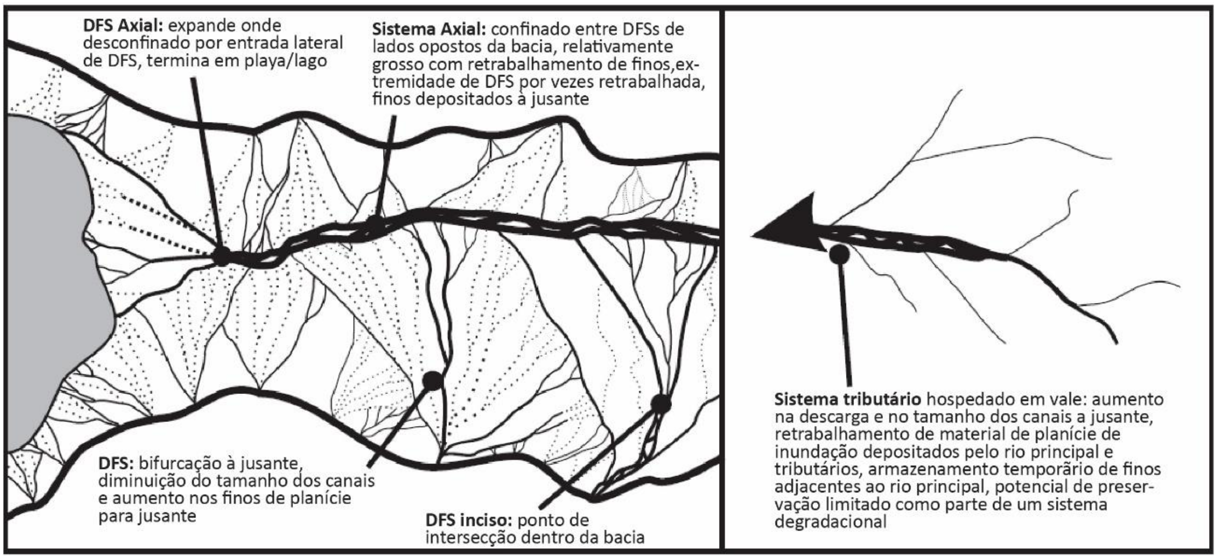

Figura 4. Características dos sistemas fluviais distributivos típicos de contextos agradacionais em comparação com os sistemas tributários de contextos degradacionais. Modificado de Weissmann *et al.* (2010).

A comparação entre a variedade de termos e modelos deposicionais distributivos pode ser complicada. A Figura 5 resume a relação entre os conceitos dos vários modelos de sistemas fluvial em forma de leque, mostrando sua abrangência e quanto eles podem se sobrepor. Destaca-se especialmente o modelo sistema fluvial distributivo, que, devido a sua grande abrangência, parece ter tido sucesso em resumir todas as variantes em um único modelo.

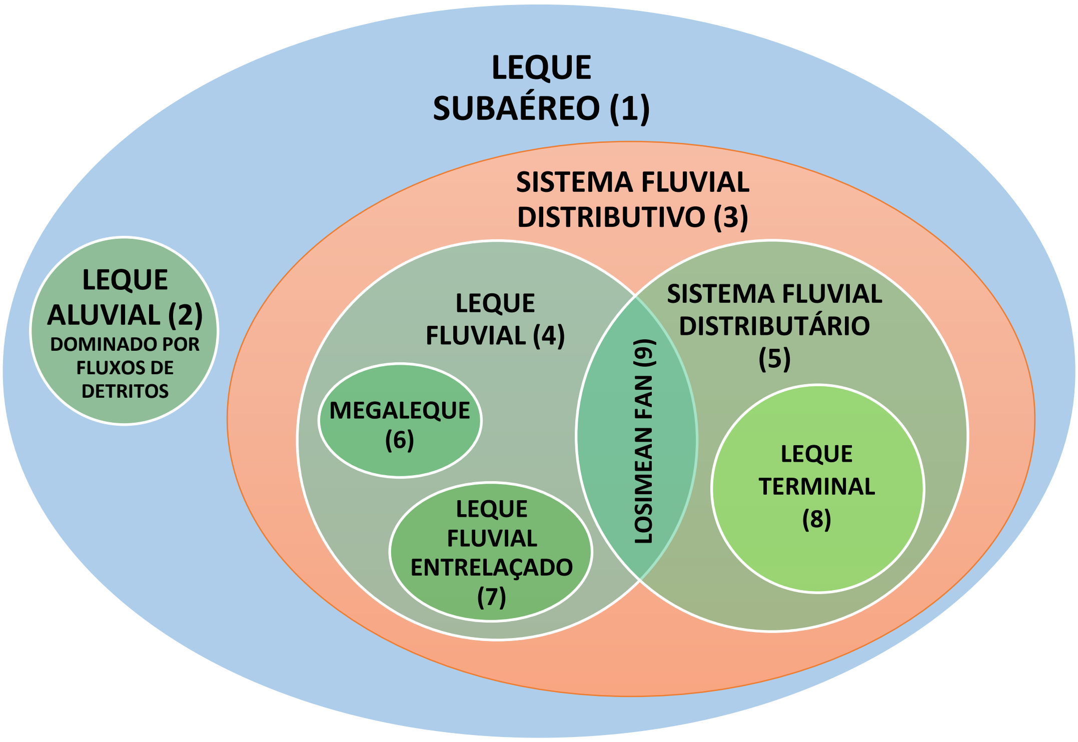

Figura 5. Relações entre os conceitos dos diversos modelos de sistemas em forma de leque. Os números indicam as principais referências para cada modelo: (1) Stanistreet & McCarthy, 1993; (2) Stanistreet & McCarthy, 1993; Blair & McPherson, 1994; (3) Hartley et al., 2010; Weissmann et al., 2010; (4) Collinson, 1996; (5) Nichols, 1987; Nichols & Hirst, 1998; Nichols & Fisher, 2007; (6) Gohain & Parkash, 1990; DeCelles & Cavazza, 1999; Leier et al., 2005; (7) Stanistreet & McCarthy, 1993; Krapf et al., 2005; (8) Friend, 1978; Tunbridge, 1984; Hirst & Nichols, 1986; Kelly & Olsen, 1993; (9) Stanistreet & McCarthy, 1993.

2.1.2 Arquitetura deposicional dos sistemas fluviais distributivos

Baseados em modelos atuais e antigos de sistemas fluviais distributivos é possível identificar um zoneamento arquitetural de montante para jusante. Esse zoneamento parte do pressuposto que ocorrem mudanças de fácies e arquiteturais ao longo do sistema, resultado da variação na descarga aquosa e/ou da variação da geometria dos canais. Os sistemas fluviais distributivos podem ser subdivididos em três zonas (Figuras 1, 6 e 7; Kelly & Olsen, 1993; Nichols & Fisher, 2007): (1) zona alimentadora ou proximal; (2) zona distributária ou intermediária e (3) zona bacinal ou distal. Weissmann *et al.* (2013) produziram um modelo de arquitetura estratigráfica para sistemas fluviais distributivos progradacionais, que considera a variação da razão acomodação/suprimento (A/S) entre as zonas dos sistemas (Figura 8).

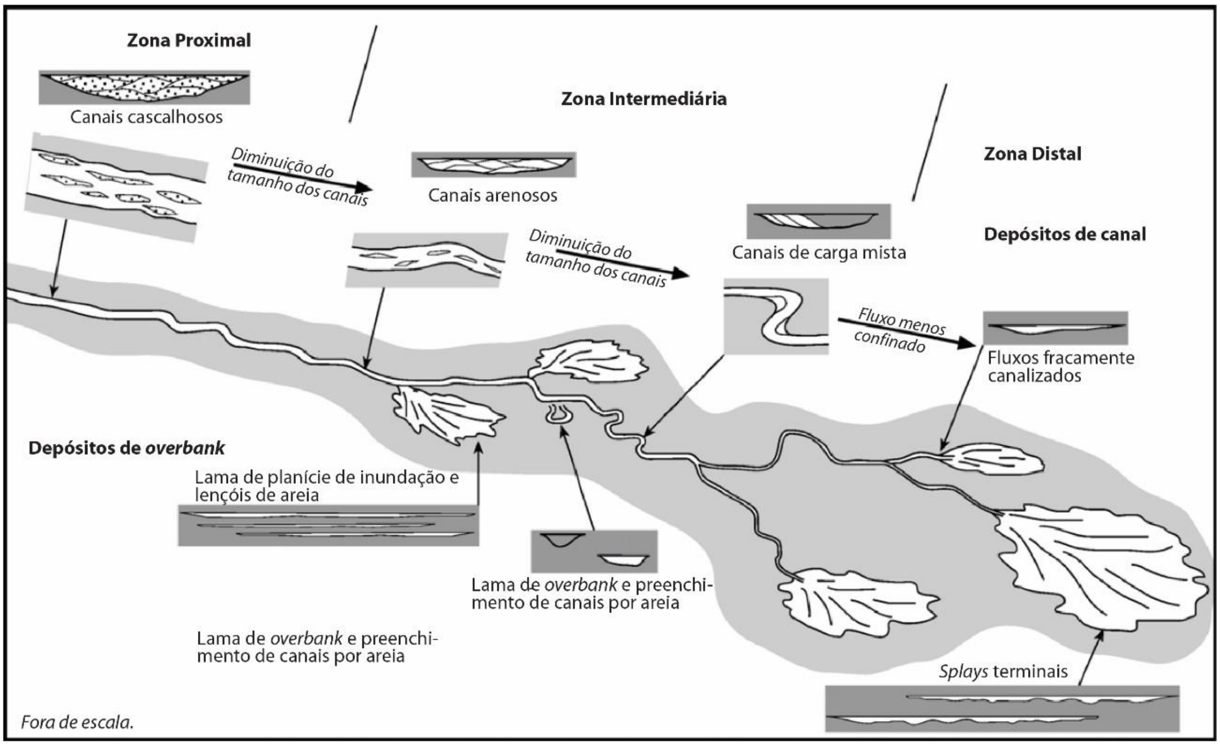

Figura 6. Mudanças arquiteturais de montante para jusante de um sistema fluvial distributivo. Modificado de Nichols & Fisher (2007).

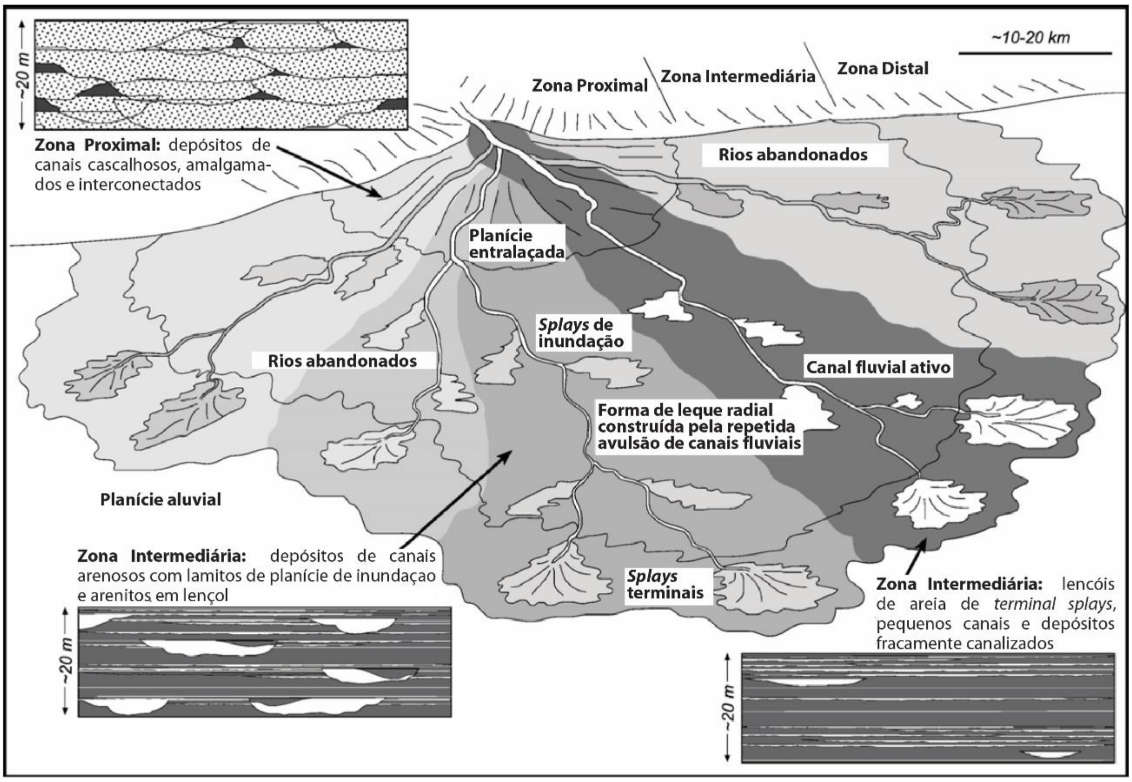

Figura 7. Características arquiteturais das zonas proximal, intermediária e distal. Modificado de Nichols & Fisher (2007).

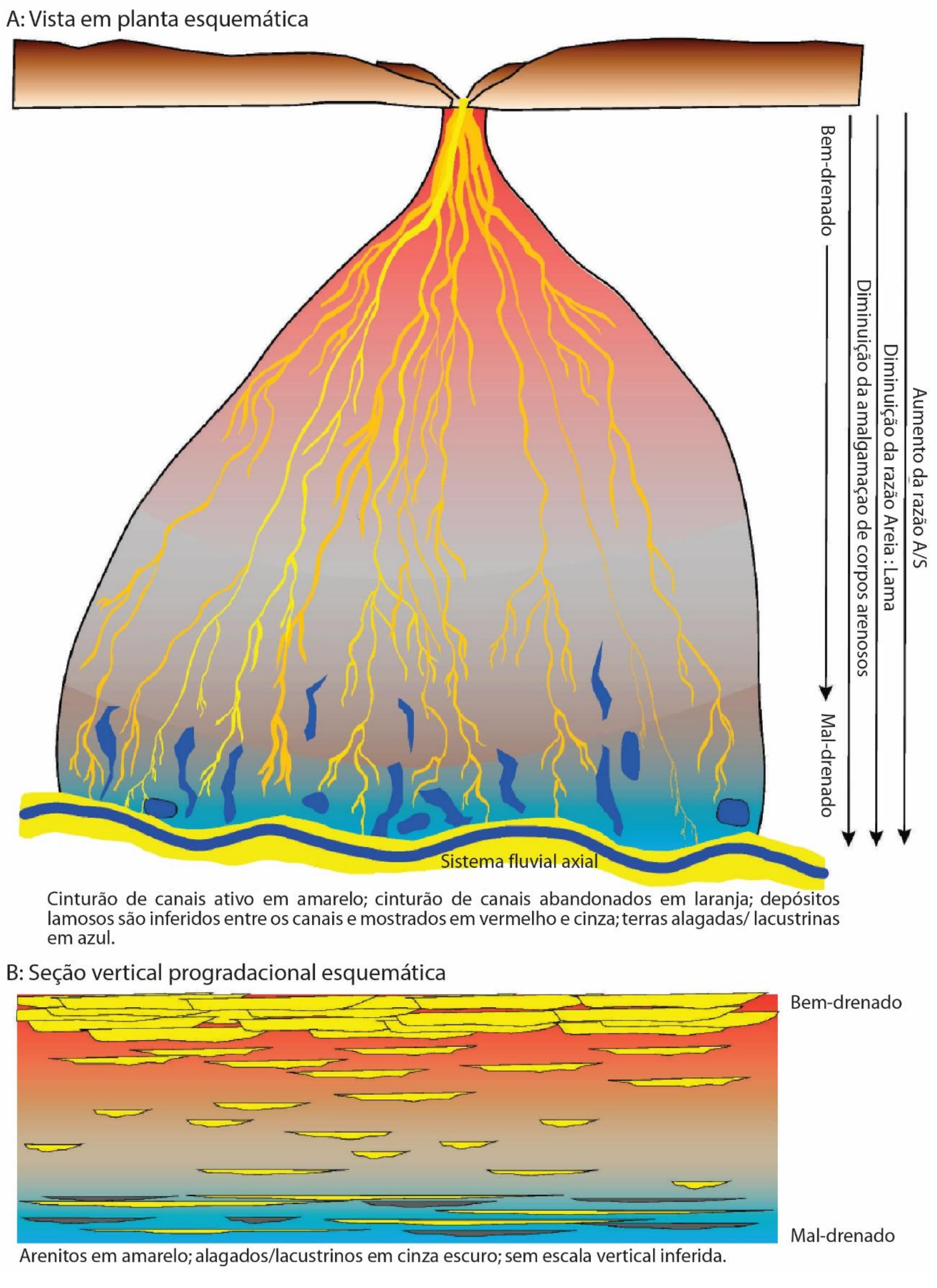

Figura 8. A) Diagrama esquemático da zonação de um sistema fluvial distributivo; B) Seção transversal hipotética de uma sucessão progradacional de um DFS. Modificado de Weissmann *et al.* (2013).

O zoneamento é baseado nas mudanças arquiteturais que ocorrem nos sistemas fluviais distributivos de montante para jusante. As mudanças ocorrem devido a diversos fatores interdependentes:

- Variação no gradiente fluvial ao longo do sistema;
- Diminuição na descarga ao longo do sistema, resultado de perdas por evapotranspiração, infiltração e pela divisão do fluxo;
- Diferentes razões A/S ao longo do sistema.

Hartley *et al.* (2013) também considera para divisão das zonas o tipo de solos, reflexo do substrato sedimentar e das variações de umidade ao longo do sistema (Figura 9).

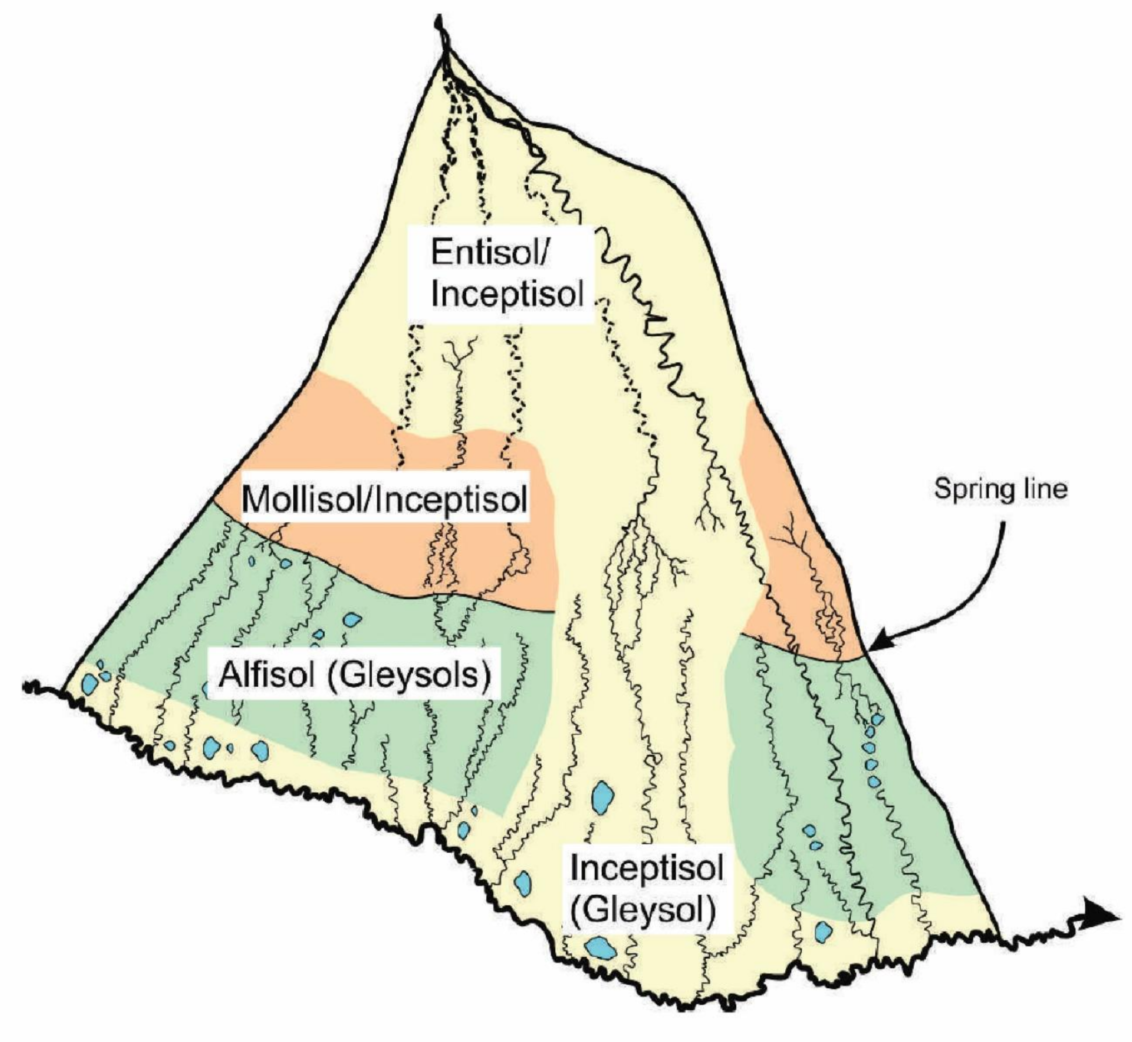

Figura 9. Representação esquemática de um DFS mostrando mudança na distribuição dos solos e aumento da umidade do solo para jusante.

A seguir serão abordadas as principais características arquiteturais das diferentes zonas de sistemas fluviais distributivos, segundo diversos autores.

2.1.2.1 Zona Proximal

A zona proximal é a região do sistema distributivo imediatamente anexa ao ápice, a jusante, onde o sistema fluvial adentra a região agradacional da bacia. É caracterizada pela rápida expansão e desaceleração do fluxo, sendo a menor e mais ativa região de um sistema fluvial distributivo. Também é a porção do leque com as características arquiteturais e faciológicas mais homogêneas entre todos os modelos de fácies.

É nesta zona que se concentram os sedimentos mais grossos do sistema, sendo comuns arenitos grossos a muito grossos e conglomerados, maciços ou estratificados (Friend, 1989; Alonzo Zarza *et al.*, 1993; Kelly & Olsen, 1993; Nichols & Fisher, 2007; Owen *et al.*, 2017). Estas fácies preenchem canais rasos ou profundos, dominantemente perenes (Hampton & Horton, 2007; Nichols & Fisher, 2007; Ielpi & Ghinassi, 2016) e de baixa sinuosidade (Tunbridge, 1984; Sadler & Kelly, 1993) evidenciada pela presença de barras cascalhosas longitudinais e barras arenosas (Stanistreet & McCarthy, 1993; Shukla *et al.*, 2001). Em contextos onde o suprimento sedimentar tem menor calibre podem ocorrer arenitos médios a grossos com estratificações cruzadas e plano-paralelas preenchendo os canais (Tunbridge, 1984). Mais raramente, em contexto de gradiente extremamente baixo, esta zona pode ser dominada por cinturões de canais meandrantes profundos limitados por *levees* vegetados (Stanistreet & McCarthy, 1993).

Os canais costumam ser *multistorey*, altamente amalgamados e interconectados, formando corpos arenosos em lençol (Tunbridge, 1984; Friend, 1989; Alonzo Zarza *et al.*, 1993; Kelly & Olsen, 1993; Cain & Mountney, 2009; Weissmann *et al.*, 2013; Owen *et al.*, 2017). Nestes corpos é comum o canibalismo erosivo dos canais, derivado da alta mobilidade promovida pela constante avulsão (Tunbridge, 1984; Friend, 1989; Alonzo Zarza *et al.*, 1993; Nichols & Fisher, 2007; Cain & Mountney, 2009; Weissmann *et al.*, 2013).

Nesta zona a preservação de depósitos de tamanho de grão fino é baixa, predominando os sedimentos das frações cascalho e areia (Tunbridge, 1984; Cain & Mountney, 2009; Weissmann *et al.*, 2013; Owen *et al.*, 2017). Quando preservados, ocorrem como lamitos vermelhos ou castanhos mosqueados, com concreções carbonáticas, depositados nos interflúvios (Alonzo Zarza *et al.*, 1993; Hampton & Horton, 2007). Ocasionalmente, em contextos fluvio-eólicos, podem ocorrer depósitos eólicos nesta porção do sistema (Kelly & Olsen, 1993).

A zona proximal dos DFS é tipicamente uma região de baixa acomodação, com a razão A/S muito baixa, o que ocasiona um intenso *bypass* de sedimentos (Weissmann *et al.*, 2013, Figura 6). Sua notável escassez de sedimentos finos podem ter várias causas concomitantes: a frequente mudança e migração dos canais, que causa o retrabalhamento dos depósitos de overbank (Nichols & Fisher, 2007); a alta competência do fluxo próximo ao ápice, não permitindo a deposição de finos; e a perda abrupta da energia com o desconfinamento do fluxo, provocando a rápida sedimentação da carga de fundo, que preenche todo o espaço de acomodação disponível (Weissmann *et al.*, 2013; Figura 8).

O substrato arenoso da zona proximal tem alta permeabilidade, gerando desde já uma diminuição do fluxo e no tamanho dos canais (Owen *et al.*, 2017). Nessa região são mais comuns os solos bem drenados e pouco desenvolvidos (entissolos e inceptissolos, raramente aridissolos), visto que ocorre um frequente retrabalhamento pelos canais fluviais (Figura 9; Hartley *et al.*, 2013; Weissmann *et al.*, 2013).

2.1.2.2 Zona Intermediária

A zona intermediária é zona em que a arquitetura muda em função na queda da descarga e da bifurcação do fluxo. Nesta porção aumenta a proporção dos depósitos de *overbank*, com corpos de canais fluviais envelopados por camadas de lamitos e lençóis de areia delgados (Hampton & Horton, 2007; Nichols & Fisher, 2007). O aumento na proporção dos depósitos de *overbank* se deve à diminuição do tamanho dos canais, e consequente aumento da área intercanais, o que permite a deposição e preservação dos depósitos finos (Weissmann *et al.*, 2013). A diminuição no porte dos canais está ligada a bifurcação e divisão do fluxo (Friend, 1989; Shukla *et al.*, 2001; Weissmann *et al.*, 2013). Os corpos possuem razão largura espessura maior do que aqueles presentes na zona proximal, indicando canais relativamente mais rasos na zona intermediária (Nichols & Fisher, 2007). Por outro lado, em alguns casos, a avulsão nesta porção pode ser intensa, e a grande mobilidade dos canais pode impedir uma preservação significativa de depósitos finos (Friend, 1989; Sadler & Kelly, 1993; Shukla *et al.*, 2001; Weissmann *et al.*, 2013).

Os corpos arenosos de canais fluviais podem formar tanto complexos amalgamados (Kelly & Olsen, 1993; Sadler & Kelly, 1993; Shukla *et al.*, 2001; Sáez *et al.*, 2007; Cain & Mountney, 2009), quanto formar corpos isolados com geometria em fita ou em lençol (Kelly & Olsen, 1993) sendo estes últimos mais comuns nas porções mais distais da zona intermediária (Tunbridge, 1984). Os corpos arenosos isolados, com geometria em fita, podem representar rios anastomosados com *levees* vegetados, com pouca mobilidade lateral (Friend, 1989; Sadler & Kelly, 1993;

Stanistreet & McCarthy, 1993; Shukla *et al.*, 2001; Sáez *et al.*, 2007; Cain & Mountney, 2009; Owen *et al.*, 2017). O grau de incisão dos canais fluviais é altamente variado (Nichols & Fisher, 2007).

Outros elementos que se tornam muito comuns na zona intermediária são lençóis de areia delgados, isolados entre lamitos, que podem representar *crevasse splay*, *splays* terminais ou inundações em lençol (Tunbridge, 1984; Friend, 1989; Kelly & Olsen, 1993; Sadler & Kelly, 1993; Hampton & Horton, 2007; Nichols & Fisher, 2007; Sáez *et al.*, 2007; Cain & Mountney, 2009; Owen *et al.*, 2017).

É notável uma diminuição geral do tamanho de grão nas fácies arenosas, em relação à porção proximal (Tunbridge, 1984; Shukla *et al.*, 2001; Nichols & Fisher, 2007; Cain & Mountney, 2009). Os depósitos cascalhosos são raros (Nichols & Fisher, 2007; Cain & Mountney, 2009), restringindo-se na maioria das vezes a *lags* conglomeráticos na base dos canais fluviais e/ou na base de camadas de arenitos com estratificações cruzadas (Alonzo Zarza *et al.*, 1993).

Nesta zona, os depósitos finos de planície de inundação ganham importância. Arenitos muito finos, siltitos e lamitos, com evidências de ressecamento e formação de solos hidromórficos (Alonzo Zarza *et al.*, 1993; Nichols & Fisher, 2007; Sáez *et al.*, 2007; Weissmann *et al.*, 2013). O substrato misto de argila, silte e areia, e a umidade moderada, favorece a formação de molissolos e inceptissolos (Hartley *et al.*, 2013; Figura 9). Também podem ocorrer depósitos eólicos (Kelly & Olsen, 1993; Cain & Mountney, 2009).

A arquitetura deposicional na zona intermediária, com corpos de canais amalgamados isolados entre lamitos e solos moderadamente drenados, demonstra uma razão A/S mais equilibrada, com menor *bypass* de sedimentos em relação à zona proximal (Weissmann *et al.*, 2013; Figura 8).

2.1.2.3 Zona Distal

A zona distal, porção do sistema radialmente mais afastada do ápice, é a região onde dominam os processos desconfinados. Também é a região mais diversa do sistema fluvial distributivo, onde ocorrem processos de inundação, evaporíticos, eólicos e até o encontro com rios axiais e/ou corpos lacustres (Figura 8; Weissmann *et al.*, 2010, 2013; Ielpi & Ghinassi, 2016).

Na porção mais distal do sistema, é alta a proporção de lamitos de planície de inundação (Tunbridge, 1984; Kelly & Olsen, 1993; Sadler & Kelly, 1993; Fisher *et* *al.*, 2007; Hampton & Horton, 2007; Nichols & Fisher, 2007; Sáez *et al.*, 2007; Weissmann *et al.*, 2013; Owen *et al.*, 2017). Os lamitos frequentemente mostram evidências do desenvolvimento de paleossolos (Nichols & Fisher, 2007). Os solos são geralmente mal drenados, permitindo alta preservação de matéria orgânica. Os tipos mais comuns são inceptissolos cinza com mosqueamento castanho, e molissolos (Figura 8 e 9; Hartley *et al.*, 2013; Weissmann *et al.*, 2013).

Os depósitos arenosos predominantes nesta porção são arenitos em lençol delgados, representando depósitos de *crevasse splay*, *splay* terminal e inundações em lençol distais (Tunbridge, 1984; Sadler & Kelly, 1993; Fisher *et al.*, 2007; Hampton & Horton, 2007; Nichols & Fisher, 2007; Sáez *et al.*, 2007; Cain & Mountney, 2009). Os canais arenosos são uma pequena proporção do volume dos estratos (Alonzo Zarza *et al.*, 1993; Sadler & Kelly, 1993; Nichols & Fisher, 2007; Sáez *et al.*, 2007). Podem ocorrer canais meandrantes de alta sinuosidade (Tunbridge, 1984; Shukla *et al.*, 2001) ou canais anastomosados, de baixa mobilidade lateral (Stanistreet & McCarthy, 1993).

Em contextos onde existe um lago no centro da bacia, em momentos de nível de lago alto, se desenvolvem lobos deltaicos e finos lacustres (Friend, 1989; Fisher *et al.*, 2007). Em contextos mais áridos, podem ocorrer lamitos e evaporitos depositados em *playa lakes* (Tunbridge, 1984; Friend, 1989; Kelly & Olsen, 1993; Hampton & Horton, 2007; Sáez *et al.*, 2007).

Em contextos flúvio-eolicos, a zona distal é a área de dominância dos depósitos eólicos (Kelly & Olsen, 1993), chegando a desenvolver extensos campos de dunas (Cain & Mountney, 2009) com algum retrabalhamento por fluviais lobados (Ielpi & Ghinassi, 2016).

É a região que recebe o mais baixo suprimento sedimentar, mas possui alta acomodação (alta razão A/S), resultando numa arquitetura onde poucos corpos isolados de areia são envolvidos por extensos depósitos finos externos ao canal (Weissmann *et al.*, 2013; Figura 8).

2.2 Dimensões e acumulação dos sistemas fluviais distributivos

Apesar da quantidade considerável de trabalhos sobre sistemas fluviais distributivos, poucos deles estabelecem com certo grau de certeza o comprimento (distância radial entre o ápice e a borda do *DFS*) dos sistemas. Nesta compilação (Tabela 1) foram encontrados *DFS* variando de 5 a 720 km de comprimento.

Tabela 1. Lista de sistemas fluviais distributivos e suas dimensões.

Nome	*Bacia*	*Localização*	*Idade*	*Comprimento (entre ápice e borda distal)*	*Referência*
Pilcomayo DFS	Chaco	Chaco Plain, Argentina/Paraguai	Quaternário	720 km	Hartley *et al.* (2013)
Salt Wash DFS, Morrison Fm.	Morrison	SW dos EUA	Jurássico Superior	700 km	Owen *et al.* (2015)
Vários exemplos	-	-	-	30 km a >200km	Nichols & Fisher (2007)
Tista DFS	Foreland Himalaiano	Bangladesh e Índia	Quaternário	190 km	Hartley *et al.* (2013)
-	Munster	Irlanda	Devoniano Superior	160 km	Graham (1983)
Organ Fm.	Paradox	Utah, EUA	Permiano	160 km	Cain & Mountney (2009)
Okavango Fan	Okavango	Botswana, África Central	Quaternário	150 km	Stanistreet & McCarthy (1993)
Kosi Fan	Ganges	Nordeste da Índia	Quaternário	120 km	Stanistreet & McCarthy (1993)
Ganga Megafan	Indo-Ganges	N da Índia	Quaternário	120 km	Shukla *et al.* (2001)
Alderney Sandstone Fm.	-	Channel Islands, Reino Unido	Cambriano	75 km, inferida a partir de análogos recentes	Ielpi & Ghinassi (2016)
Sistema Huesca	Ebro	Aragão, Espanha	Mioceno	50 km	Friend (1989)
Cardona-Súria e Solsona-Sanaüja fans	Ebro	NE da Espanha	Paleógeno	45 km	Sáez *et al.* (2007)
Neales River	Lake Eire	Australia Central	Quaternário	45 km	Croke *et al.* (1996)

Smerwick Gr.	Munster	Irlanda	Devoniano Inferior	>30 km	Richmond & Williams (2000)
Trentishoe Fm.	Hangman	North Devon, Reino Unido	Devoniano Médio	20-30 km	Tunbridge (1984)
Gun Point Fm.	Munster	Sw da Irlanda	Devoniano Superior	~20 km	Sadler & Kelly (1993)
Jadraque	Madrid	Espanha	Neógeno	12 km	Alonzo Zarza *et al.* (1993)
La Alarilla	Madrid	Espanha	Neógeno	~10 km.	Alonzo Zarza *et al.* (1993)
Baides	Madrid	Espanha	Neógeno	10 km	Alonzo Zarza *et al.* (1993)
Tajuña	Madrid	Espanha	Neógeno	5 km	Alonzo Zarza *et al.* (1993)

Analisando os *DFS* do Quaternário, Weissmann *et al.* (2010) registram que o comprimento dos sistemas vai de <1 km a >700 km. Cabe destacar que neste trabalho os autores incluem os leques aluviais dominados por fluxos gravitacionais, que costumam ter os menores comprimentos.

Hartley *et al.* (2010) restringiu a amostragem para 415 DFS recentes, todos com comprimentos maiores do que 30 km. Da população analisada, 98 exemplos (28%) tem comprimento >100 km. Os dois maiores sistemas têm mais de 700 km. Conforme decresce o tamanho, aumenta o número de DFS: 3% estão entre 300 e 400 km de comprimento, 4% entre 200 e 300 km, 5% entre 150 e 200 km, 11% entre 100 e 150 km, 32% entre 50 e 100 km, e 44% entre 30 e 50 km. Os DFS gigantes, com dimensões em torno de 700 km são visivelmente mais raros no registro recente. No registro geológico, Owen *et al.* (2015) estimou o tamanho do sistema jurássico Salt Wash em aprox. 700 km (Tabela 1).

3 CONTEXTO GEOLÓGICO

3.1 Bacia do Paraná

A Bacia do Paraná constitui o registro sedimentar de vários períodos de subsidência e sedimentação separados por discordâncias regionais, num contexto geotectônico intracontinental, recobrindo partes do sul do Brasil, Paraguai, Uruguai e Argentina. Cada período de sedimentação corresponde a uma supersequência, compondo um registro estratigráfico que vai do Ordoviciano ao Cretáceo (Milani, 1997; Milani *et al.*, 1998).

O registro mesozoico da Bacia do Paraná pode ser dividido em 6 unidades litoestratigráficas, separadas por discordâncias regionais (Milani, 1997; Scherer *et al.*, 2000): (1) a Formação Sanga do Cabral (Triássico Inferior), composta de depósitos fluviais, lacustres e eólicos; (2) a Formação Santa Maria (Triássico Médio a Superior), que consiste em depósitos flúvio-lacustres; (3) o Arenito Mata (Triássico Superior), registro de um sistema fluvial entrelaçado; (4) A Formação Guará (Jurássico Superior), constituída por depósitos fluviais e flúvio-eólicos; (5) a Formação Botucatu (Cretáceo Inferior) composta por dunas de um sistema eólico seco, fossilizados sobre os derrames vulcânicos da Formação Serra Geral; e (6) os depósitos fluviais e eólicos do Grupo Bauru (Cretáceo Superior). As discordâncias estão relacionadas à tectônica das margens ativas do Gondwana Sul-Ocidental e ao início do processo de abertura do rifte Atlântico Sul (Milani, 1997; Zerfass *et al.*, 2003, 2004). Estes eventos tectônicos reativaram sistemas de falhas NW-SE e NE-SW do embasamento que exerceram o principal controle sobre a sedimentação e preservação das unidades estratigráficas (Milani, 1997; Milani *et al.*, 1998; Quintas *et al.*, 1999; Zerfass *et al.*, 2004, 2005).

2.3 Formação Guará

“Aloformação Guará” foi usado pela primeira vez em 1997 para designar um pacote arenoso com 200 metros de espessura máxima, aflorante no oeste do Rio Grande do Sul, posicionado estratigraficamente em discordância entre as Formações Sanga do Cabral e Botucatu (Scherer & Lavina, 1997). Nesta primeira abordagem, os mesmos autores propuseram a correlação da Aloformação Guará com o membro inferior da Formação Tacuarembó, no Uruguai, de idade neojurássica a eocretácea. Contudo, devido ao contato discordante com a Formação Botucatu, eocretácea, a idade mais provável seria neojurássica (Scherer & Lavina, 1997).

Mais tarde, os mesmos autores passaram a designar a unidade como Formação Guará, mostrando que essa formação apresenta uma distribuição lateral das fácies, variando de um sistema fluvial a norte, para um sistema flúvio-eólico a sul (Scherer & Lavina, 2005), apresentando padrão de paleocorrentes para SW. A idade neojurássica desta unidade foi confirmada por correlação com o Membro Batoví da Formação Tacuarembó, sua contraparte no Uruguai (Perea *et al.*, 2001, 2003; Soto & Perea, 2008; Perea *et al.*, 2009; Soto & Perea, 2010; Fortier *et al.*, 2011; Soto, Carvalho, *et al.*, 2012)e por associações de icnofósseis de dinossauros (Dentzien-Dias *et al.*, 2008, 2012; Francischini *et al.*, 2015, 2017). Reis (2016) trabalhando na região norte da área de afloramento da Formação Guará no Rio Grande do Sul demonstrou que a mesma é constituída pela alternância de sistemas fluviais efêmeros e perenes, resultantes de variações climáticas que promovem variações na descarga fluvial.

3.2 Formação Tacuarembó, Membro Batoví

A porção da Bacia do Paraná situada em território uruguaio é conhecida localmente como Bacia Norte. Contudo, a correlação entre as unidades Neo-mesozoicas da Bacia Norte e da Bacia do Paraná já está relativamente bem resolvida (Scherer & Lavina, 2005, 2006; Perea *et al.*, 2009; Francischini *et al.*, 2015; Amarante *et al.*, 2019). Portanto neste texto, se utilizará o nome Bacia do Paraná também para a porção uruguaia.

A definição litoestratigráfica formal da Formação Tacuarembó, constituída pelo Membro Batoví (inferior) e pelo Membro Rivera (superior), foi realizada por Perea *et al.* (2009). O Membro Batoví é interpretado como flúvio-eólico por Perea *et al.* (2009) e Amarante *et al.* (2019) define associações de fácies para a unidade: dunas eólicas, lençóis de areia eólicos, canais fluviais entrelaçados, canais fluviais efêmeros e *sheetfloods*, sendo correlacionado com a Formação Guará. O Membro Rivera, caracterizado por dunas eólicas de um sistema eólico seco, é correspondente a Formação Botucatu (Scherer & Lavina, 2006; Perea *et al.*, 2009; Amarante *et al.*, 2019).

O limite basal da Formação Tacuarembó se dá por discordância com as Formações permianas Yaguarí e Buena Vista. No topo, está em contato concordantes com as rochas vulcânicas básicas da Formação Arapey (Perea *et al.*, 2009), que no Brasil corresponde à Formação Serra Geral (Scherer & Lavina, 2006).

A idade atribuída à Formação Tacuarembó é Jurássica Superior (Kimmeridgiano-Tithoniano), datada pelo conteúdo fóssil bastante variado do Membro Batoví, entre répteis crocodilianos, tartarugas, saurópodes, ornitópodes, terópodes, megalossauros, pterossauros, tubarões, peixes pulmonados, celacantos, moluscos, conchostráceos e icnofósseis de dinossauros (Mones, 1980; Martinez *et al.*, 1993; Perea *et al.*, 2001, 2003, 2009, 2014, 2018; Yanbin *et al.*, 2004; Dentzien-Dias *et al.*, 2008; Soto & Perea, 2008, 2010; Fortier *et al.*, 2011; Francischini *et al.*, 2015, 2017; Mesa & Perea, 2015; Soto *et al.*, 2012a, b, 2020).

4 DADOS E MÉTODOS

Os dados foram coletados através da construção de perfis estratigráficos colunares, com especial atenção para a quantificação das fácies e para as relações entre as superfícies limítrofes com significado estratigráfico. No total, foram levantados 1.071,2 m de perfis colunares em 64 localidades (62 afloramentos e 2 poços). Os perfis estratigráficos foram interpretados por meio dos métodos clássicos da análise de fácies, onde grupos de fácies geneticamente relacionadas são classificadas como associações de fácies, representando depósitos ou sub ambientes que compõem sistemas deposicionais (Walker & James, 1992). Associações de fácies com morfologia definida foram classificadas como elementos arquiteturais, especialmente para os depósitos fluviais (Miall, 1985; James & Dalrymple, 2010).

Os dados de testemunhos de sondagem de poços e de afloramentos alimentaram planilhas digitais, classificados por código de fácies, espessura de camada, tamanho de grão, elemento arquitetural e associação de fácies. O tamanho de grão foi medido em milímetros, na escala Wentworth, e posteriormente convertido pra escala *phi*, com o objetivo de evitar o viés estatístico causado pelas diferenças de magnitude entre as classes de tamanho de grão da escala milimétrica. A média do tamanho de grão na escala *phi* foi ponderada pela espessura do corpo arenoso de canal (*channel body*), seguindo o método de Owen *et al.* (2015).

Para garantir a representatividade dos perfis estudados, ou seja, para que os perfis de afloramentos refletissem uma espessura mínima adequada em relação à espessura total da formação, as localidades que representavam menos de 25% da espessura total foram excluídas das análises estatísticas, embora sejam utilizados para interpretação faciológica e estratigráfica. Esta percentagem de corte foi escolhida com base nas espessuras medidas dos corpos arenosos de canal. Do banco de dados original permaneceram na análise 17 localidades, totalizando 718,9 m de perfis colunares (67,11% do total de dados levantados). Perfis com menos de 25% da espessura total da formação foram considerados apenas na análise de paleocorrentes.

A presença e a robustez das tendências estatísticas observadas estão indicadas pelo coeficiente de correlação de Spearman (ρ). Quando $\rho = 1$ existe uma correlação positiva perfeita e quando $\rho = -1$ existe uma correlação negativa perfeita.

Valores de ρ próximos de 0 indicam que os dois fatores são independentes, ou seja, não existe correlação (Davis, 2002). Um valor crítico (CV) foi calculado para definir um valor do coeficiente de correlação, indicando a probabilidade de os resultados ocorrerem por acaso (Davis, 2002). Resultados com valor de CV maiores do que 0,05 indicam uma fraca possiblidade de correlação entre os bancos de dados; valores de CV menores do que 0,05 indicam uma forte possibilidade de correlação, ou seja, menos de 5 % de chance de os resultados ocorrerem por acaso. O vetor médio das paleocorrentes foi calculado para os canais fluviais efêmeros e perenes e para os depósitos de dunas eólicas utilizando diagramas de roseta.

5 SÍNTESE DOS RESULTADOS E DISCUSSÕES

O Artigo 1 reconheceu pela primeira vez a ocorrência da Formação Guará na porção central do Estado do Paraná, distinguindo-a das Formações Pirambóia e Botucatu, expandindo a área coberta pela Formação Guará, até então restrita ao Rio Grande do Sul e Uruguai. As três unidades são caracterizadas por distintos sistemas deposicionais que refletem mudanças climáticas. A Formação Pirambóia é representada por um sistema eólico úmido com interação fluvial composto por dunas e interdunas eólicas, lençóis de areia úmidos e secos e depósitos fluviais efêmeros. Sobre ela, em contato discordante, a Formação Guará constitui um sistema fluvial entrelaçado, em corpos arenosos *multistorey* altamente amalgamados. Sobreposta à Fm. Guará, também em discordância, ocorre a Formação Botucatu como um sistema eólico seco. A correlação dos novos dados apresentados neste trabalho com os registros da Formação Guará no extremo sul permitiu a proposição do modelo de um vasto sistema fluvial com interação eólica de mais de 800 km de extensão, fluindo desde o estado do Paraná até o Uruguai. Corroborando o que foi sugerido por Amarante et al. (2019), é proposto que a Formação Guará constitua um sistema fluvial distributivo, que registra com a sua deposição os primeiros estágios de rifteamento que culminaram com a quebra do Gondwana.

No Artigo 2, foram processados em planilhas digitais aproximadamente 1070 m de perfis colunares, em 64 localidades, sendo 62 afloramentos e 2 poços. Destes, considerando a representatividade mínima de 25 % da espessura total da formação, foram selecionadas 17 localidades, totalizando aprox. 720 m de perfis colunares que foram quantificados para entendimento das variações espaciais do sistema com confiabilidade estatística. Foram identificadas 4 associações de fácies: canais fluviais perenes, canais fluviais efêmeros, depósitos de planícies de inundação e depósitos eólicos. Cada uma dessas associações de fácies é composta pela combinação de elementos arquiteturais. A disposição das localidades estudadas permitiu a análise de variações espaciais no sistema ao longo de uma seção NNE-SSW, paralela às paleocorrentes fluviais. Redução na profundidade dos canais, capacidade do fluxo e canalização para jusante, associada ao aumento na bifurcação, infiltração e evapotranspiração é indicada por reduções no tamanho de grão, espessura dos corpos arenosos de canal, número de *storeys* e espessura das barras. A interpretação destas variações espaciais confirmou que a Formação Guará constitui um sistema fluvial distributivo com interação eólica, de caráter terminal. A distribuição entre as proporções das associações de fácies permite dividir o Sistema Guará em 4 zonas: zona 1, onde dominam os canais fluviais perenes; zona 2, onde canais perenes e efêmeros se intercalam no registro; zona 3, onde a proporção de depósitos intercanais aumenta, representados principalmente por depósitos eólicos; e zona 4, onde os depósitos intercanais são dominados por planícies de inundação. O Formação Guará registra um dos maiores sistemas fluviais distributivos já descobertos, com extensão mínima de 1050 km. Foram registradas superfícies de incisão fluvial até 100 km a jusante do ápice do sistema, demonstrando um sistema dinâmico em que mudanças climáticas de alta frequência podem gerar erosão nas zonas mais proximais. A complexidade estratigráfica da Formação Guará não permite o reconhecimento de padrões de empilhamento correlacionáveis, sugerindo que flutuações de alta frequência na descarga geram expansão e retração das zonas do sistema distributivo, incisão nas zonas proximais e migração do ponto de intersecção para jusante. No contexto tectonossedimentar do Jurássico Superior, sua deposição já demonstra o controle estrutural da pluma Paraná-Etendeka sobre a Bacia do Paraná, com o transporte de sedimentos partindo da zona central para a borda sudoeste, indicando uma inversão da bacia.

6 CONCLUSÕES

- O reconhecimento da Formação Guará no estado do Paraná permitiu a expansão significativa da zona de ocorrência da unidade na Bacia do Paraná.
- A Formação Guará registra a sedimentação de um dos maiores sistemas fluviais distributivos entre antigos e recentes, com extensão mínima de 1050 km entre o sul do Brasil e o Uruguai.
- O sistema fluvial distributivo da Formação Guará também é o mais extenso já registrado com caráter terminal e interação com sistemas eólicos nas porções distais.
- O Sistema Guará é constituído pela interação de 4 associações de fácies: canais fluviais perenes, canais fluviais efêmeros, depósitos de planície de inundação e depósitos eólicos.
- A quantificação dos parâmetros sedimentológicos e das proporções entre as associações de fácies permitiu a identificação de variações espaciais do sistema na direção NNE-SSW. As variações espaciais demonstram a redução na profundidade dos canais, competência e canalização do sistema fluvial para jusante, associadas ao aumento da bifurcação dos canais, da infiltração e da evapotranspiração.
- O Sistema Guará pode ser dividido em 4 zonas, de acordo com as proporções das associações de fácies e com os parâmetros sedimentológicos. A zona 1 é dominada exclusivamente por canais fluviais perenes. Na zona 2 os canais perenes ainda são dominantes, mas ocorre a alternância vertical com canais fluviais efêmeros. A zona 3 é caracterizada por uma diminuição dos canais perenes aliada a um aumento dos efêmeros, com significativo retrabalhamento por atividade eólica. Finalmente, a zona 4 é dominada pelos fluviais efêmeros, mas os depósitos intercanais são na maioria depósitos de planície de inundação.
- Flutuações de alta frequências na descarga atribuídas a variações climáticas cíclicas causam recorrente expansão e retração das zonas do sistema fluvial distributivo, muitas vezes transferindo o ponto de intersecção para jusante o que resulta em incisão fluvial e erosão. Tais características geraram um registro estratigráfico bastante complexo para a Formação Guará, que não permite o reconhecimento de padrões de empilhamento regionalmente correlacionáveis.

- A Formação Guará constitui o registro da inversão tectônica e reciclagem da Bacia do Paraná durante o Kimmeridgiano-Tithoniano. A criação de espaço de acomodação para a deposição da Formação Guará, bem como sua posterior deformação e erosão, indicada por variações locais de espessura, são atribuídas à influência tectônica da pluma Paraná-Etendeka no Gondwana ocidental entre o Jurássico Superior e o Cretáceo Inferior.

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8 ARTIGOS

8.1 ARTIGO 1 – Sedimentology of the proximal portion of a large-scale, Upper Jurassic fluvial-aeolian system in Paraná Basin, southwestern Gondwana

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ABSTRACT

Upper Jurassic sedimentary rocks of Guará Formation record the environmental and geotectonic changes of the early break-up stages in the southwestern portion of Gondwana. Newly-described occurrences of this formation allow the expansion of its areal distribution to the central part of the Paraná Basin, Brazil. Four vertical sections are presently described in Paraná State, Brazil. Nineteen lithofacies were grouped in five facies associations, through the classical method of facies analysis. The facies analysis included Guará Formation and the adjacent portions of the underlying Pirambóia Formation and the overlying Botucatu Formation. The depositional system of Pirambóia Formation was wet aeolian fluvial-influenced and is composed by aeolian dunes, aeolian sandsheets/interdunes and ephemeral fluvial deposits facies associations. The Guará Formation is composed of multistorey fluvial facies association constituting a highly amalgamated perennial fluvial system. It is overlaid by the Botucatu Formation, characterized as a dry aeolian system formed by aeolian dune deposits. The stratigraphic units are separated by regional unconformities marked by a shift in facies and depositional systems that reflect climatic changes. The Guará Formation depositional model, established in correlation with southern sections, represents a broad fluvial system with aeolian interaction deposited in a wide basin with more than 800 km in extension. This large depositional paleoenvironment, together with other Upper Jurassic records in southwestern Gondwana, represents the early rift stage of Gondwana break-up.

KEYWORDS: Fluvial-aeolian interaction, braided fluvial, climatic changes, Upper Jurassic, southwestern Gondwana

INTRODUCTION

Understanding depositional systems are essential for palaeogeographic and palaeoclimatic reconstructions. The period between Late Jurassic and Early Cretaceous was marked by several palaeoenvironmental changes in Western Gondwana, promoted mainly by tectonic processes of continental break-up and opening of the South Atlantic Ocean (Kuchle et al., 2011; Seton et al., 2012; Salomon et al., 2017). Sedimentary basins are an essential record to in understanding the palaeoenvironmental evolution of a particular area, and the Paraná Basin, due to its large extension and location around the forming South Atlantic rift, is a key laboratory to study such evolution.

In the last years, different studies have identified Upper Jurassic fluvial-aeolian deposits in the southern portion of Paraná Basin, encompassed in the Guará (southern Brazil) and Tacuarembó (Uruguay) Formations (Scherer and Lavina, 2005, 2006; Perea et al., 2009; Reis, 2016; Amarante et al., 2019; Francischini et al. 2015). These formations represent the distal portion of a big distributive fluvial system that flowed to the southwest (Amarante et al., 2019). However, there are doubts about the extension of this system to the central part of the Paraná Basin, as well the possible faciologic variations in the proximal portions of the distributive system. We presently expand the areal distribution of the Guará Formation and evaluate the significance of this in terms of basin evolution inside the southwestern Gondwana context.

Facies analysis of four vertical profiles led to the identification of facies associations and depositional systems of Guará Formation, individualizing it from the adjacent Botucatu and Pirambóia Formations. Correlation of the profiles with previous occurrences allowed the establishment of Guará Formation as a record of a distinct paleoenvironmental and geotectonic setting in the evolution of Paraná Basin; a huge fluvial system interacting with aeolian systems in a wide endorheic basin.

GEOLOGICAL SETTING

The Paraná Basin is an intracratonic basin covering an area of 1,400,000 km² across Brazil, Argentina, Uruguay, Paraguay with a small remnant Huab Basin in Namibia (Milani et al., 2007; Fig. 1A and B). The basin records various periods of subsidence and sedimentation from Ordovician to Cretaceous (Milani, 1997; Milani et al., 1998, 2007). The Paleozoic basin fill was constructed by three second-order transgressive-regressive cycles (Milani, 1997; Milani et al., 1998, 2007). The Mesozoic record is composed of continental successions that comprise six lithostratigraphic units bounded by regional unconformities (Milani, 1997; Scherer et al., 2000; Fig. 2): (1) Sanga do Cabral Formation (Scitian), consisting of fluvial, lacustrine and aeolian deposits; (2) Santa Maria and Caturrita Formation (Ladiniam to Norian) composed of fluvial-lacustrine deposits; (3) Mata Sandstone (Norian) deposits of braided fluvial system; (4) Guará Formation (Upper Jurassic), constituted by fluvial and fluvial-aeolian systems; (5) Botucatu Formation (Lower Cretaceous), recording dunes of dry aeolian system fossilized under the Serra Geral Formation volcanic lavas; and (6) Bauru Group (Upper Cretaceous) composed of fluvial and aeolian deposits. The Pirambóia Formation occurs in the northwestern portion of the basin, with fluvial-aeolian deposits of undetermined age, possibly Permian to Eocretaceous (Giannini et al., 2004). The unconformities are related to active margin tectonics of southwestern Gondwana and to South Atlantic rifting process (Milani, 1997; Zerfass et al., 2003, 2004). These tectonic events activated and reactivated the NW-SE, NE-SW and E-W fault systems, main drivers of sedimentation and preservation of stratigraphic units (Milani, 1997; Milani et al., 1998, 2007; Quintas et al., 1999; Zerfass et al., 2004, 2005).

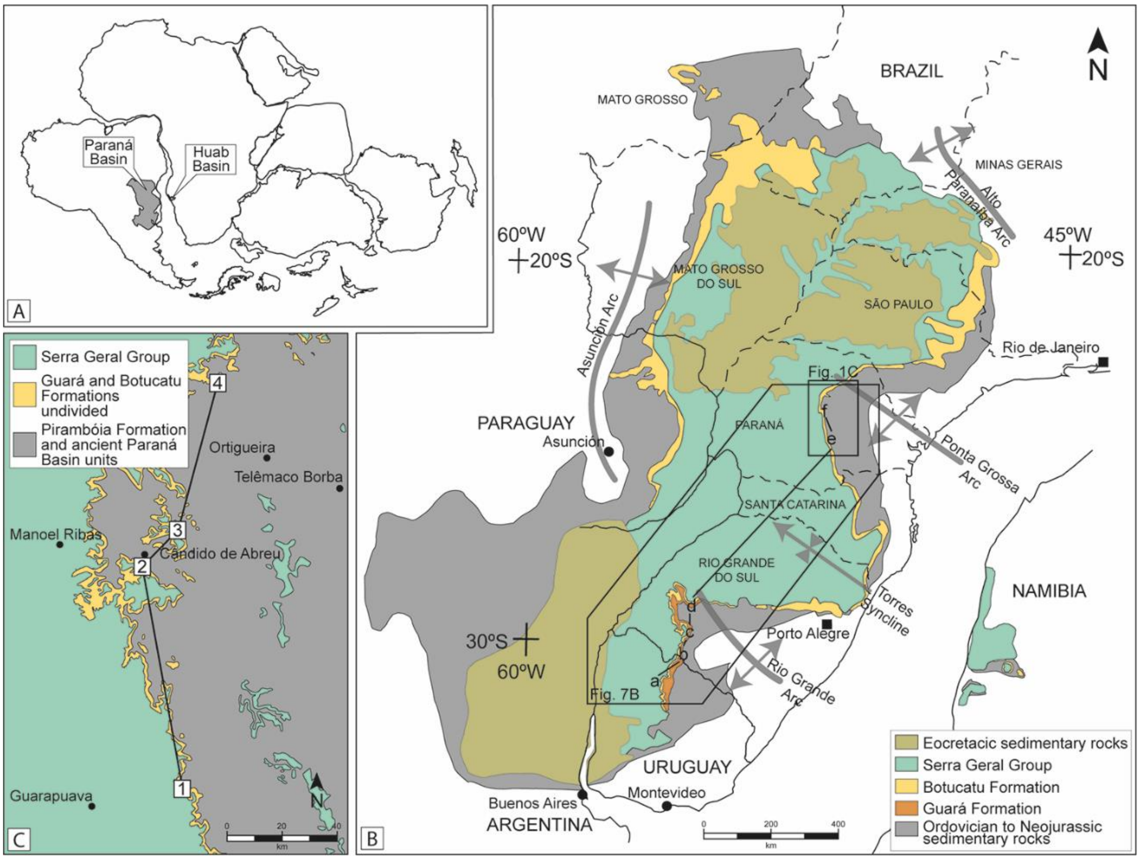

Figure 1. Location of the studied area and correlated sections in the contexts of Paraná Basin and Gondwana. A) Paraná Basin and its counterpart in southwestern Africa Huab Basin, positioned in Upper Jurassic Gondwana (based on Schmitt and Romeiro, 2017). B) Paraná and Huab Basins locations. The original occurrence of Guará Formation is in orange (small letters a, b, c and d). The newly discovered occurrences of Gará Formation are in the area with the letters f and e, highlighted in Fig. 1C (Modified from Zalán et al., 1987; Scherer and Lavina 2005, 2006; Scherer and Goldberg, 2007; Amarante 2017; Rossetti et al., 2017) C) Study area in central Paraná state, the numbers (1 to 4) are the logged sections where Guará Formation was recognized in this work.

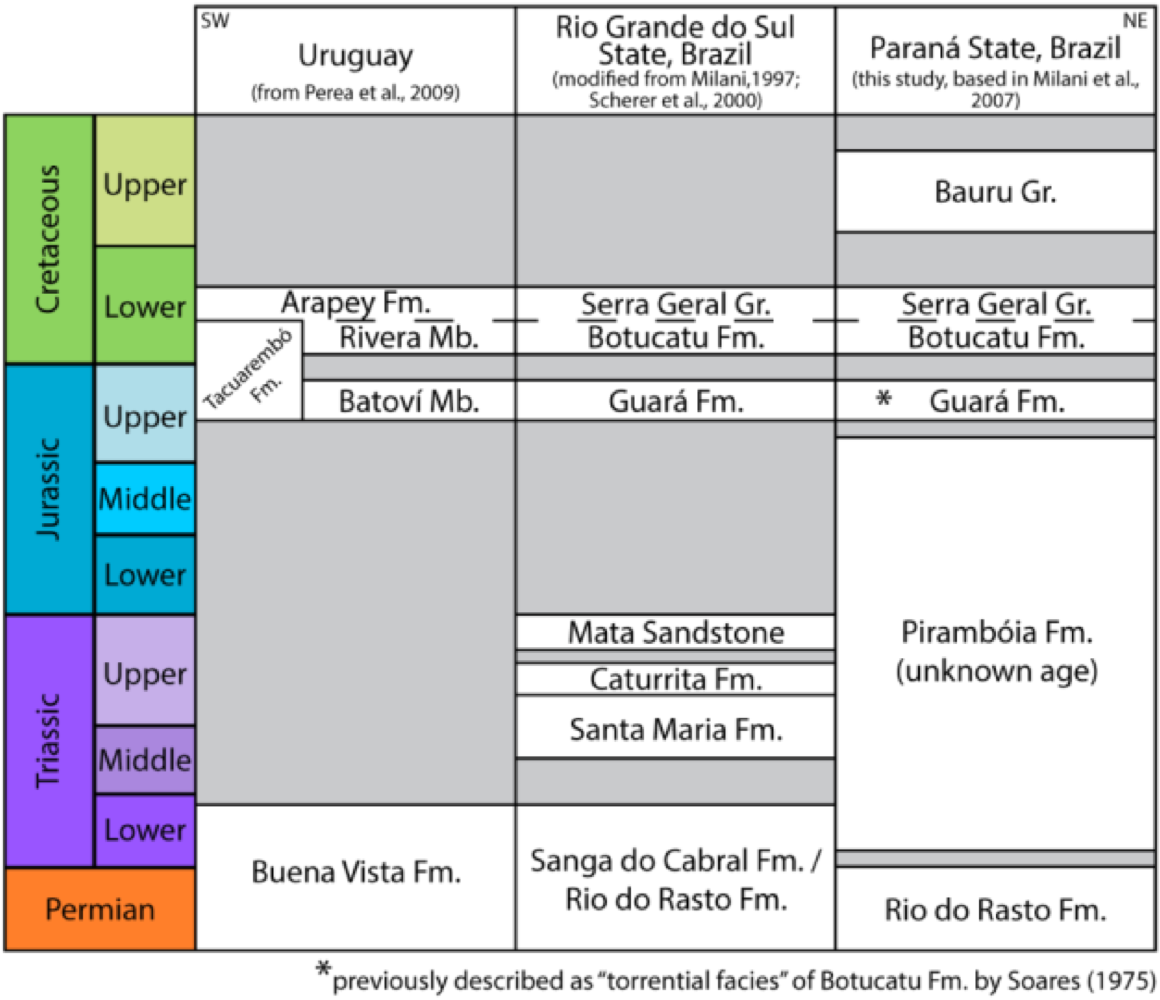

Figure 2. Stratigraphy of southern to central portions of Paraná Basin, from Upper Permian to Mesozoic, highlighting the stratigraphic position of Guará and Botucatu Formations, and the controversial age of Pirambóia Formation. Modified from Soares (1975), Milani (1997), Scherer et al. (2000), Milani et al. (2007) and Perea et al. (2009). SW - southwest; NE - northeast; Gr. - Group; Fm. - Formation; Mb. - Member.

The Pirambóia Formation is recognized in the study area as dunes and wet interdunes. Despite extensive and inconclusive discussion about nomenclature, age and areal distribution of Pirambóia Formation (Francischini et al., 2018), this work is restricted to the unit's definition on the study area, in Paraná States (Fig. 2). Firstly described by Pacheco (1927), the Pirambóia Formation was later detailed (Soares et al., 1973; Soares, 1975), allowing the recognition of an erosive unconformity between Pirambóia Formation and overlying Lower Cretaceous Botucatu Formation. Modern sedimentological concepts demonstrate that the Pirambóia Formation consists of aeolian dunes, wet and dry interdunes and ephemeral fluvial (wadis) deposits, composing a fluvial-aeolian system (Wu and Caetano-Chang, 1992; Caetano-Chang and Wu, 1994).

The Lower Cretaceous Botucatu Formation is considered a record of a palaeodesert that covered an area of more than 1,500,000 km² (Bigarella and Salamuni, 1961; Scherer and Goldberg, 2007), cropping out in the edges of Paraná Basin in Brazil, Uruguay, Argentina, Paraguay, and has correlative deposits in Namibia (e.g. Twyfelfontein Formation; Stanistreet and Stollhoffen, 1999; Fig. 1). Morphological reconstructions of aeolian dunes Performed in Botucatu Formation in southern Brazil demonstrated the occurrence of simple to compound crescentic aeolian dunes and complex linear draas (Scherer, 2000, 2002). Conglomerates and gravelly sandstones occur above its basal contact, brought by ephemeral streams (Bigarella and Salamuni, 1961; Soares, 1975; Almeida and Melo,1981; Scherer, 2002). Soares (1975) identified, in his Paraná State study area, a package of sandstones with fluvial origin overlain by aeolian dunes which he termed the “torrential facies” of the Botucatu Formation. These fluvial deposits are the main focus of our study, in which we present a different origin for them, as part of Guará Formation. Despite this, Botucatu Formation deposits are considered a dry aeolian system developed in a hyper-arid climate (Scherer and Lavina, 2006). The upper boundary of the unit is overlain by volcanic rocks of Serra Geral Group which are concordant and transitional, as indicated by the preservation of features of interactions between the lava flows and active aeolian dunes, as impressions of lava lobes in the entirely preserved topset of dunes, recording their whole morphologies under lava-flows (Scherer, 2002; Waichel at al., 2008). Due to absence of internal hiatuses in the aeolian succession (supersurfaces, Scherer, 2002) and the intimate relation between aeolian sandstones and lava-flows, the age of Botucatu Formation is close to the beginning of Serra Geral Group magmatism, dated between 134.1 and 134.8 Ma (Valanginian; Renne et al., 1992; Thiede and Vasconcelos, 2010; Rossetti et al., 2017).

Upper Jurassic rocks in Paraná Basin were recorded in Uruguay, where it is known as the Batoví Member of Tacuarembó Formation (Perea et al., 2009) and in its counterpart, the Guará Formation in the Rio Grande do Sul State, southern Brazil (Scherer and Lavina, 2005, Fig. 1). The relative ages are attributed to their respective fossil and ichnofossil assemblages (Scherer and Lavina, 2005; Perea et al., 2009; Francischini et al., 2015). The Batoví Member is a fluvial-aeolian system (Perea et al., 2009) composed by five facies associations: aeolian dunes, aeolian sandsheets, ephemeral fluvial channels, perennial braided fluvial channels and distal sheetfloods (Amarante et al., 2019). The paleocurrent pattern indicates paleowinds to the ENE, and fluvial paleoflows to the SSW (Amarante et al., 2019). The Guará Formation consists of fluvial (in its proximal northern portion) and fluvial-aeolian (in its distal southern portion) depositional systems, forming wetting-upward cycles (Scherer and Lavina, 2005). Paleocurrents of aeolian dunes in Guará Formation were to the NE and the fluvial paleocurrents were to the SSW (Scherer and Lavina, 2005).

METHODS

The Guará Formation crops out along escarpments that cross the central part of Paraná State in Brazil. The locations to study are identified looking for places where this escarpment are cut by roads, quarries or rivers, spots in which the vegetation cover was opened. Four outcrops distributed along an N-S belt in (Fig. 1B and C, Fig. 3) are logged in vertical sections. Section 1 (25°19'27" S; 51°11'43" W) is from vertical road cuts at kilometre 290 of BR-373 road, on the limit between Guarapuava and Prudentópolis municipalities. Section 2 (24°36'37" S; 51°20'59" W) is located 3 km to the south of Cândido de Abreu town, along a dirt road. Section 3 (24°29'24" S; 51°13'21" W) is situated 15 km to the northeast of Cândido de Abreu town, along a dirt road. Section 4 (23°59'50" S; 51°05'33" W) is located next to BR 373 between Mauá da Serra and Ortigueira, inside a farm.

Four vertical sections were constructed at a 1:50 scale, totalizing 88 m of rock succession (Fig. 3). Sedimentological data collected were classified with traditional methods of facies analysis (*sensu* Walker, 1992), in which the genetically-related lithofacies define facies associations corresponding to subenvironments within a depositional system. Lithofacies were codified by the principles of Miall (1977): the first capital letter represents the grain-size (G for gravel, S for and F for fine sediments, i.e. mud) and the second lower case letter indicates sedimentary structure. Letter (e) was used to distinguish facies formed by aeolian processes. Measures of dip azimuths of foresets present in cross-bedded sandstone sets indicate paleocurrent orientations.

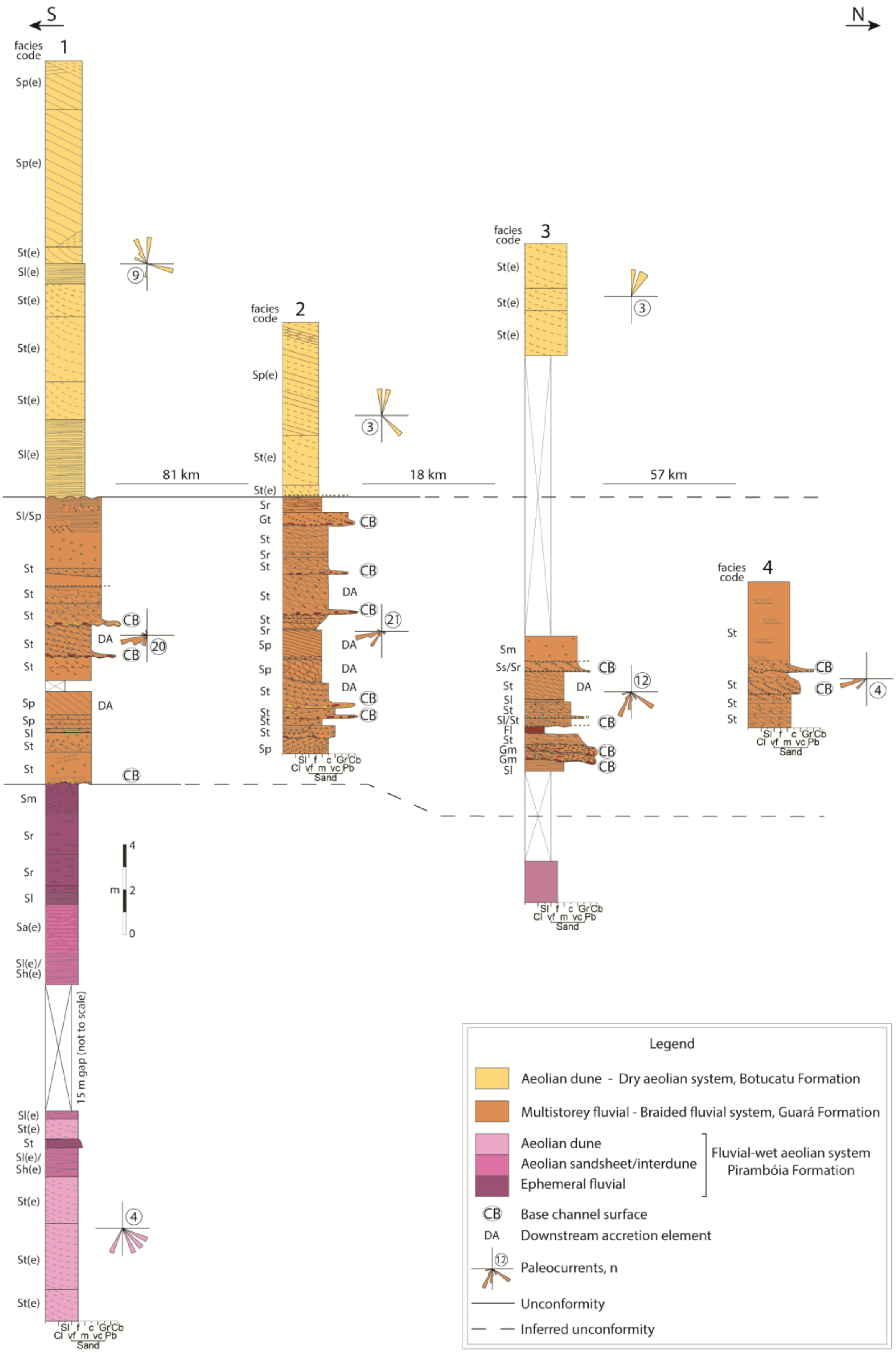

Figure 3. Logged vertical sections, divided by facies associations, depositional systems and stratigraphic units.. See Figure 1 for the location of logs. See Table 1 for facies code. The Pirambóia Formation show a diversity of aeolian facies associations and paleocurrents pattern to S. There is a 15 m gap on the logged section of Pirambóia Formation is Section 1 due to vegetation covering the outcrop. The Guará Formation is between two regional unconformities, showing a series of amalgamated channels with paleoflow to SW in all the 3 sections. Botucatu Formation, constituted by

aeolian dunes, show a variable range of paleocurrents. Where the unconformity surface was covered by vegetation, the surface is a dashed line and the top and base of Guará Formation is estimated.

LITHOFACIES

Here we present a brief summary of the general composition and texture of the sediments in each Formation recorded. Are stated here only features observable in macroscopic analysis in the field. The detailed descriptions and interpretations of each lithofacies are in Table 1.

The Pirambóia Formation succession presents a variety of lithofacies formed by subaqueous and wind-related processes (Fig. 3, Table 1). The macroscopic analysis in samples identified fine-grained sandstones with quartz and feldspar, indicating arkosic to sub-arkosic composition. The presence of argillaceous white material is notable, probably a diagenetic product. Sorting varies from well-sorted in the aeolian facies to poorly-sorted in subaqueous facies and the grains are well-rounded in general.

Lithofacies identified in Guará Formation are mainly cross-stratified medium- to very coarse-grained sandstones (rarely fine-grained), gravelly sandstones and conglomerates (Fig. 3, Table 1). Sand is poorly to very poorly-sorted with subrounded to rounded grains. The gravel fraction varies from rounded to subangular – normally the quartz clasts are more rounded while the mud clasts and lithoclasts are subrounded to subangular. Concerning the detrital composition, the sandstones and conglomerates of Guará Formation are very homogeneous. They are basically quartzarenites in sand fraction, while the gravel fraction is composed by quartz (granules to pebbles), mud clasts (granules to boulders) and sedimentary lithoclasts (pebbles to boulders). The presence of sedimentary lithoclasts is notable in gravel fraction, as it is composed of fine- to medium-grained sandstone clasts varying from pebble to boulder size classes (Fig. 4D and E, Fig. 5C and D), and granule to boulder-sized mud clasts (Fig. 4D). Fine sediments are restricted to mud clasts and one occurrence of laminated mudstone in Section 3 (Fig. 3).

Lithofacies of Botucatu Formation are sandstones deposited by aeolian processes, homogeneous in composition and texture (Table 1). They are basically fine- to medium-grained sub-arkosic sandstones, well-sorted and well-rounded sandstones.

Table 1. Summary of lithofacies, with description and interpretation of the forming process of each lithofacies. The Lithofacies are grouped by stratigraphic unit (e.g., Pirambóia, Guará and Botucatu Formations).

Code	Description	Interpretation
Pirambóia Formation		
St(e)	Fine-grained sandstones, well-sorted, trough cross-stratified in large scale sets (1.4-3.0 m thick, Fig. 4A). Foresets formed by millimetric pin stripe inversely-graded lamination.	Sinuous-crested (3D) aeolian dunes alternating grainflow and translatent subcritical wind ripple migration in the lee side (Hunter, 1977; Hunter and Rubin, 1983).
Sl(e)/S(h)	Fine-grained sandstone, well-sorted, horizontal to low-angle lamination formed by thin pinstripe inversely graded laminae.	Translatent subcritical wind ripple migration over a plane to quasi-plane surface (Kocurek, 1981).
Sa(e)	Fine-grained sandstone, well-sorted, with crenulated plane-parallel lamination (Fig. 4B).	Adhesion structures originated by adherence of dry sand grains that were carried by wind over wet surfaces (Kocurek, 1981; Kocurek and Fielder, 1982).
St	Fine- to medium-grained sandstone, moderately-sorted, in normal graded trough cross-stratified sets.	Migration of subaqueous sinuous-crested dunes in unidirectional flow (Allen 1963; Miall, 1977; Collinson et al, 2006).
Sr	Fine-grained sandstone, poorly-sorted, with ripple cross-lamination	Migration of unidirectional subaqueous ripples with subcritical climbing angle (Allen, 1963; Miall, 1977).
Sl	Fine-grained sandstone, poorly-sorted, low-angle cross-stratified.	Structures formed in unconfined high energy flows, in transitional flow regime between upper and lower (Harms et al., 1982; Bridge and Best, 1988).
Sm	Fine-grained massive sandstone, moderately-sorted.	Fast deposition of subaqueous unidirectional high energy flow, hyper-concentrated in sediments, fluidization or intensive bioturbation (Miall, 1978, 1996)
Guará Formation		
Gt	The clast-suported sandy conglomerate, quartz pebbles, trough cross-bedded. Green muddy cobbles at the set base.	Migration of subaqueous sinuous-crested gravel dunes in unidirectional flow (Todd, 1996).

Gm	The clast-supported conglomerate, pebble-sized quartz clasts, reddish muddy intraclasts and sandstone lithoclasts cobble to boulder-sized, massive (Fig. 6B). Frequently at the base of cross-strata sets. Resting upon erosive surfaces, filling scours.	Deposition of bedload as diffuse gravel sheets (Hein and Walker, 1997) in the channel bottom, resulting from erosion of previous gravelly sands (quartz pebbles), overbank deposits (mud clasts) and ancient sedimentary rocks (sandstone lithoclasts).
Sm	Very coarse-grained sandstone, massive. Muddy pebbles at the bed bottom.	Fast deposition of subaqueous unidirectional high energy flow, hyper-concentrated (Scherer et al., 2015) in sediments, fluidization or intensive bioturbation (Miall, 1978, 1996).
St	Medium to very coarse-grained gravelly sandstone, trough cross-stratified (Fig. 4D and F, 5B and E, 6C, E and F). Sets varying from 10-20 up to 40 cm thick. Foresets and sets normally graded. Quartz and muddy granules and pebbles dispersive, at the set base and marking the foresets. Frequently deposited above Gm facies bed. Compound cosets with set bases gently inclined downstream. Cosets and sets with plane or concave base.	Migration of subaqueous sinuous-crested dunes in unidirectional flow (Allen 1963; Miall, 1977; Collinson et al, 2006). Compound downstream accretion elements of mid-channel bars (Allen, 1983; Haszeldine, 1983; Wizevich, 1992; Miall, 1996).
Sp	Medium to coarse-grained sandstone, planar cross-stratified. Dispersive quartz granules. Mudclasts and quartz granules and pebbles at the set base. Sets varying from 10-20 up to 40 cm thick. Simple large scale sets (up to 1.25 m). Compound cosets with set bases gently inclined downstream.	Migration of subaqueous straight-crested dunes in unidirectional flow (Allen 1963; Miall, 1977; Collinson et al, 2006). Simple and compound downstream accretion elements of mid-channel bars (Allen, 1983; Haszeldine, 1983; Wizevich, 1992; Bridge, 1993; Miall, 1996; Jo and Choug, 2001).
Sl	Medium to coarse-grained sandstone, moderately to poorly-sorted, low-angle cross stratification, alternated with facies St (Fig. 6B and D).	Structures formed in transitional flow between subcritical and supercritical (Harms et al., 1982; Bridge and Best, 1988).
Sr	Fine to coarse sandstones with ripple cross-lamination (Fig. 5E and F).	Migration of unidirectional subaqueous 2D or 3D in lower flow regime (Allen, 1963; Miall, 1977).

Ss	Very coarse-grained sandstone with sigmoidal cross stratification.	Migration of subaqueous dunes with rapid aggradation combining traction and suspension in lower- to upper-flow regime (Wizevich, 1992).
Fl	Gray-purple, laminated mudstone (Fig. 6D).	Deposition of suspended load by settling in standing water (Miall, 1977; Turner, 1980; Jo and Chough, 2001).
Botucatu Formation		
St(e)	Fine- to medium-grained sandstone, moderately to well-sorted, trough cross-stratified in large scale sets (0.8-6 m thick, Fig. 5F and G) formed by inversely graded foresets with millimetric pin stripe lamination or massive strata (1.5 cm thick).	Sinuous-crested (3D) aeolian dunes, alternating grainflow and translatent subcritical wind ripple migration in the lee side (Hunter, 1977; Hunter and Rubin, 1983).
Sp(e)	Fine- to medium-grained sandstone, moderately to well-sorted, trough cross-stratified in large scale sets (2-6 m thick) formed by inversely graded foresets formed by millimetric pin stripe lamination or massive strata (1.5 cm thick).	Straight-crested (2D) aeolian dunes alternating grainflow and translatent subcritical wind ripple migration in the lee side (Hunter, 1977; Hunter and Rubin, 1983).
Sl(e)	Fine- to medium-grained sandstone, well-sorted, low-angle lamination formed by millimetric pin stripe inversely graded laminae (Fig. 4H).	Translatent subcritical wind ripple migration over a quasi-plane surface (Kocurek, 1981).

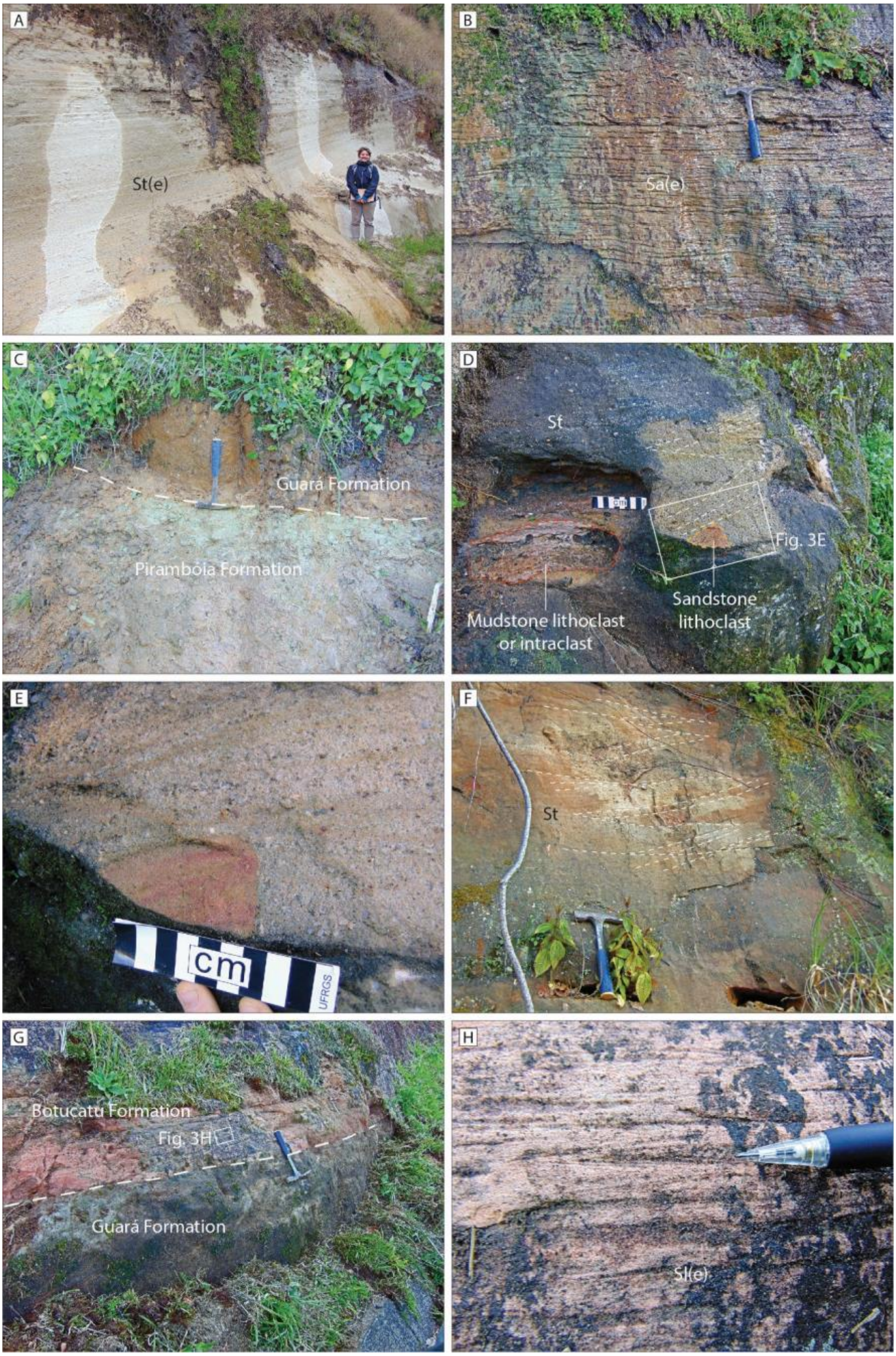

Figure 4. Details of Section 1 (Fig. 3). See Table 1 for facies code. A) Large scale cross strata of aeolian dune (facies St(e); person for scale 1.65 m high) and B) plane-parallel crenulated adhesion structures (facies Sa(e); hammer length = 28 cm) from Pirambóia Formation. C) Sharp bounding surface (dashed line) marking the unconformity between Pirambóia and Guará Formations. D) Very

coarse-grained cross-stratified sandstone (facies St, white dashed lines), with mudstone lithoclast or intraclast (limited by the red dashed line) and sandstone lithoclast (limited by the yellow dashed line) at the over an erosive surface representing the base of a fluvial channel. Each white or black bar on the scale has 1 cm. E) Detail of a medium-grained sandstone lithoclast at the base of a channel. F) Composite coset of trough cross stratification (facies St) compounding a downstream accretion element (DA). White dashed lines highlighting the sets and foresets. G) Sharp bounding surface (white dashed line) on the unconformity between Guará and Botucatu Formations. H) Detail of translatent wind ripple lamination (facies Sl(e); pencil tip = 2 cm).

FACIES ASSOCIATIONS

Pirambóia Formation

Aeolian dune facies association

This facies association comprises fine-grained, well-sorted, white sandstones that form large scale trough cross-stratified sets (St(e), Fig. 3, Section 1, Fig. 4A). Set thickness varies from 0.8 m to 3.0 m, and length around 2 m in outcrop, superimposed or in abrupt contact with aeolian sandsheet and ephemeral fluvial deposits. The stratification of foresets is constituted by millimetric laminae that exhibit an upward change from very fine- to fine-grained sandstone defining inverse grading, formed by the migration of translatent subcritical wind ripples. The measured azimuths of foresets indicate palaeowind to SSE (as show the rose diagram in Fig. 3).

Interpretation

Well-sorted, fine-grained sandstones arranged in large scale trough cross-stratified sets composed of wind ripple lamination suggest aeolian dune deposits (Hunter 1977, Kocurek, 1991, Scherer et al. 2007). The exclusive presence of wind ripple lamination may represent: (a) a severely truncated dune set, where the lee slipface is not preserved; (b) a dune type or portion of the dune where the slipface is absent; or (c) a low relief dune without slipface (Kocurek, 1991).

Aeolian sandsheet/interdune facies association

This facies association comprises fine-grained well-sorted white sandstones arranged into two distinct structures (Fig. 3, section 1): (1) Low-angle to horizontal millimetric lamination (Sl(e)/Sh(e)), with inversely graded laminae, formed by migration of translatent subcritical wind ripples over a plane or quasi-plane surface;

(2) crenulated plane-parallel lamination (Sa(e); Fig. 4B) originated by adhesion of dry sand transported by wind in a wet substrate. The upward transition from facies Sl(e)/Sh(e) to Sa(e) is gradual. These facies are disposed in tabular packages 0.4 m to 1.4 m thick when in abrupt contact with aeolian dune facies association, or in thicker packages (4.6 m), directly in contact with ephemeral fluvial deposits.

Interpretation

Tabular packages of wind ripples and adhesion structures are characteristic of deposits of aeolian origin (Kocurek and Nielson, 1986; Clemmensen and Dam, 1993; Chakraborty and Chakraborty, 2001; Scherer and Lavina, 2005). The low-angle to horizontal wind ripple lamination was generated when dry sand was not sufficiently available for aeolian dune formation (Kocurek and Nielson, 1986; Clemmensen and Dam, 1993). The high water table intercepting the depositional surface is a significant mechanism that restricts dry sand supply (Kocurek and Nielson, 1986). Presence of adhesion structures testifies a moisturized substrate. Capillarity moisture was responsible for “freezing” and preserving wind ripple lamination (Kocurek and Nielson, 1986). In the Pirambóia sedimentary succession, there is a gradual transition from low-angle/horizontal wind ripple lamination to adhesion lamination, suggesting an increase in the humidity and local rise of the water table (Fig. 3, Section 1).

Tabular packages with horizontal lamination of aeolian origin can be formed in two different depositional settings: (a) metasaturated interdune areas located between aeolian dunes (e.g. Herries, 1993; Mountney & Thompson, 2002; Uličný, 2004); or (b) aeolian sandsheets, in context of low dry sand availability, inhibiting the construction of aeolian dunes (e.g. Trewin, 1993; Veiga et al., 2002; Biswas, 2005). For Pirambóia Formation deposits, both interpretations are possible. Horizontally-laminated aeolian deposits occur separating dune deposits and isolated between ephemeral fluvial deposits (Fig. 3, Section 1).

The interference of fluvial deposition in an aeolian system is also an important mechanism that controls dry sand supply (Kocurek and Nielson, 1986). Pirambóia Formation deposits present an interaction between ephemeral fluvial deposits and aeolian deposits, which indicates that fluvial activity has critical importance in the generation of aeolian sand sheets (Clemmensen and Dam, 1993; Chakraborty and Chakraborty, 2001; Scherer and Lavina, 2005).

Ephemeral fluvial deposits facies association

These deposits congregate facies resulting from subaqueous processes. Fine- and fine- to medium-grained white sandstone, moderately- to poorly-sorted, represents the main lithology (Fig. 3, section 1). The most recurrent structure in these deposits is subaqueous ripple lamination (Sr)arranged in a 3.6 m thick bed. Low-angle lamination formed in transitional flow (Sl) and massive (Sm) sandstones also occur. These facies together constitute a tabular sandbody 5 m thick, succeeding an aeolian sandsheet deposit, with sharp abrupt contact (Fig. 3, Section 1). In an alternative context, a single normal graded trough cross-bedded sandstone bed, representing a 3D subaqueous dune, occurs over an aeolian sandsheet deposit, whit an erosive contact, and preceding aeolian dune strata (Fig. 3, Section 1).

Interpretation

Moderately to poorly-sorted sandstones displaying ripple lamination, low-angle cross-stratification, trough-cross stratification and massive structure suggest fluvial deposition in a highly variable energy flow context. Massive sandstones are generated by deposition under upper flow regime conditions hyper-concentrated in sediments (Miall, 1978, 1996). Low-angle cross-stratification represents accelerant or waning flow within a transitional stage between subcritical and supercritical flow regimes (Harms et al., 1982; Bridge and Best, 1988). On the other hand, ripple lamination and subaqueous 3D dunes can also be products of unidirectional current under lower flow regime conditions (Allen 1963; Miall, 1977; Collinson et al, 2006). Such variation in flow energy suggests deposition in poorly-confined to unconfined ephemeral streams. The relationship of these deposits with aeolian sheets and aeolian dunes demonstrates fluvial-aeolian interactions, where fluvial transport and deposition invade the interdune area or cover aeolian sandsheets in periods of flash discharge, possibly at the border of aeolian system (Langford & Chan, 1989; Mountney and Jagger, 2004; Scherer and Lavina, 2005).

Guará Formation

Multistorey fluvial facies association

The deposits of Guará Formation are significantly composed of lithofacies that represent dune migration (e.g. St and Sp isolated sets; Fig. 3, Fig. 4D, 6C and E) and bedload or residual deposits that are deposited upon erosive surfaces (i.e. Gm;

Fig. 3, Fig 4D, E and F). Simple and compound elements such as downstream accretion (DA, Fig. 3, 6F) are represented by large scale (0.8 to 1.9 m thick) cross-stratified sets and cosets (Sp and St). In compound elements, individual sets are bounded by low-angle inclined surfaces, dipping in the same direction of the intraset cross strata (Fig. 4F, Fig. 6F). In general, these facies are organized as fining upwards packages with massive conglomerates (facies Gm) at the base, composed by pebble to boulder sandstone clasts, granule to boulder mud clasts and granule to pebble quartz grains. The packages rest upon sharp erosive surfaces overlain by cross-stratified sets and cosets (Fig. 3, Fig. 4D, Fig. 5A, C and D, Fig. 6B). Foresets and cross-strata sets are commonly normally graded, with quartz granules and pebbles dispersive or marking the foresets and set bases (Fig. 5B).

Other sandstone lithofacies have very subordinated occurrence, including low-angle cross stratified sets (Sl), subaqueous ripple cross lamination (Sr; Fig. 5E), sigmoidal cross-stratified sets (Ss) and massive sandstones (Sm). The minor record of fine lithofacies (Fl) deserves special attention (Fig. 6D).

Paleocurrent measurements are concentrated in southwestern quadrant (Fig. 3). The mean vectors vary from 230° to 248°. Only in Section 3 there is a deviation to south, with mean vector to azimuth 179° (Fig. 3).

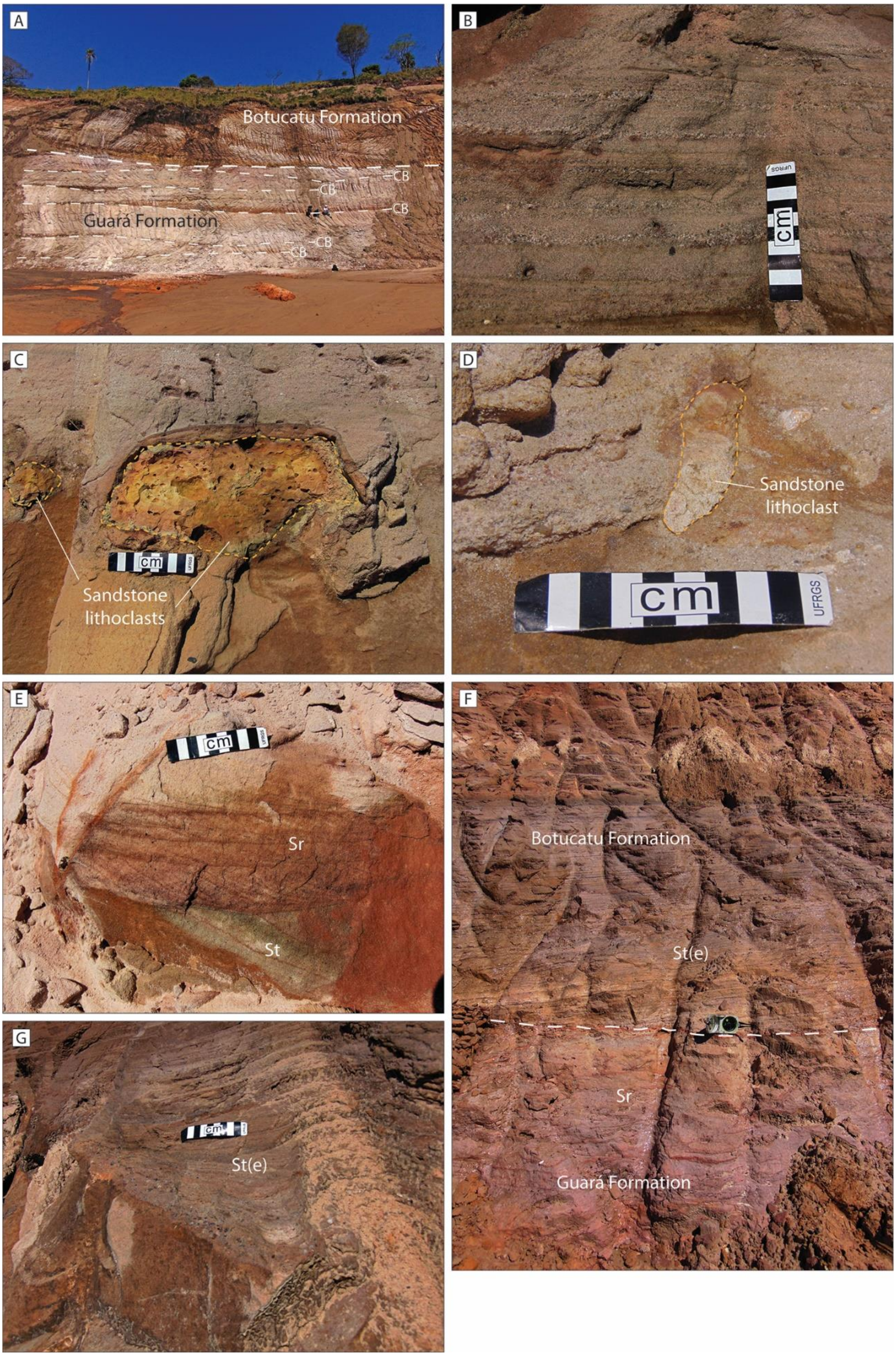

Figure 5. Details of Section 2 (Fig. 3). A) Photo of Section 2. Amalgamated channel bodies (thin white dashed lines) below unconformity (thick white dashed line) that separates Guará and Botucatu Formations, the latter represented by a large-scale cross-stratified set of aeolian dune. B) Normal-graded foresets that form the trough cross-stratification (facies St). C) Fine-grained sandstone

lithoclasts aligned over erosive surface and D) medium-grained sandstone lithoclast (highlighted by the yellow dashed line), at the channel bases. E) Coset of ripples cross-lamination (facies Sr) above cross-stratified set of subaqueous dune (facies St). F) Sharp surface boundary (white dashed line) between fluvial deposits of Guará Formation (facies Sr) and large scale trough cross strata of aeolian dunes of Botucatu Formation (facies St(e)). Compass for scale over the surface = 15 cm width. G) Detail of large-scale cross stratified set (facies St(e)) of aeolian dune, Botucatu Formation.

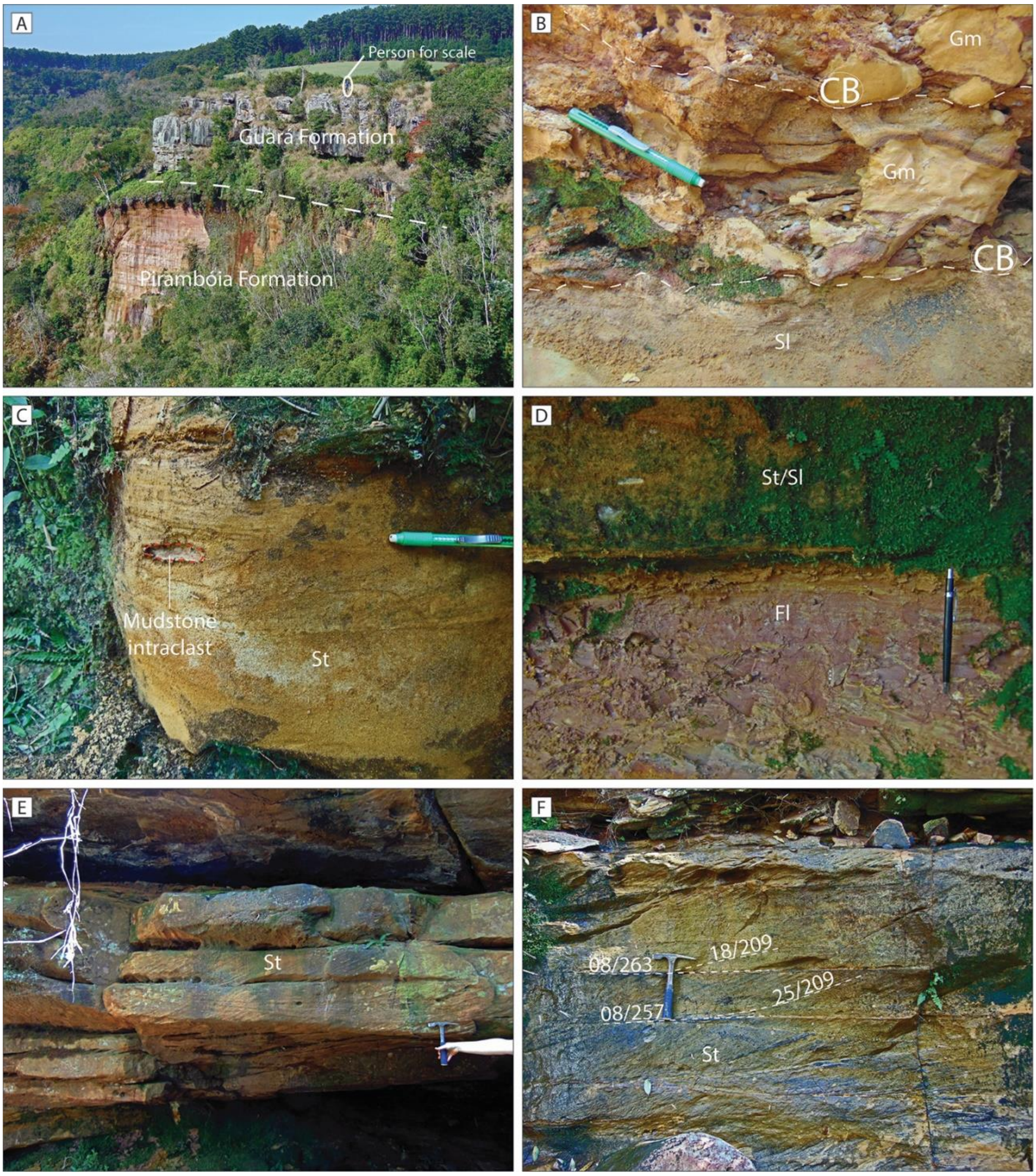

Figure 6. Details of Section 3 (Fig. 3). A) The unconformity between Pirambóia and Guará Formations, in a view of the landscape near Section 3. B) Intraformational massive conglomerates (facies Gm) over channel basal surfaces of two highly amalgamated channels. Pen length = 15 cm. C) Cross-stratified sandstone with mud clast (facies St). D) Sharp erosive surface of the channel base overlying the single floodplain mudstone (facies Fl) of the four sections studied. E) Cross-stratified isolated sets (facies St; hammer length = 28 cm). F) Composed coset (facies St) of a compound

downstream accretion element (DA). The basal surfaces of the sets represent the accretion surfaces, dipping gently downstream (measures in horizontal numbers). The inclined truncated lines are the dunes foresets migrating in the front side of the bar element (paleocurrent measures in inclined numbers).

Interpretation

The fining-upward packages, the normal grading in foresets and sets, the presence of mud clasts associated with numerous erosive surfaces are characteristics of fluvial deposits (Collinson, 1996). The predominance of cross-stratified sets representing subaqueous dunes suggests perennial fluvial channels (Miall, 1996; Allen et al., 2013). The occurrence of downstream accretion elements, representing mid-channel and transverse bars migration, together with narrow dispersion of paleocurrents, points to a low sinuosity perennial fluvial system with considerable channel depth (Miall, 1996; Chakraborty, 1999; Scherer et al., 2015). The near absence of mudstones representing overbank deposits (notable in the logs of Fig. 3) in contrast with recurrence of mud clasts over erosive surfaces indicates a highly amalgamated and strongly erosive system that cannibalized overbank deposits. This amalgamation is a signal of low accommodation/supply ratio (Martinsen et al. 1999). All these characteristics indicate that Guará Formation represents highly amalgamated multistorey fluvial deposits in braided-channel belts.

Botucatu Formation

Aeolian dune facies association

Aeolian deposits of Botucatu Formation comprises fine- to medium-grained, moderately to well-sorted sandstones, with well-rounded grains. These sandstones constitute three lithofacies (Fig. 3): large scale trough cross-stratified sets (St(e); Fig 5A, F and G), large-scale planar cross-stratified sets (Sp(e)) and low-angle cross-stratification (Sl(e), Fig. 4H).

Cross-stratification foresets are exclusively formed by translatent subcritical wind ripples in millimetric inversely graded lamination (see facies St(e) and Sp(e) in Table 1). In the studied area, 3 to 5 cm thick massive inversely graded strata were generated by grainflow in the lee side of the dunes (Fig. 5A, F and G); or in 15 cm thick cycles alternating both wind ripples and grainflow strata. Sets from 1.5 to 6 m thick occur superimposed, bounded by planar sharp truncating surfaces, or separated by packages of low-angle cross-stratified sandstones. Dip-direction of foresets of these cross-strata shows a large dispersion between NW and SE (rose diagrams in Fig. 3). Low-angle cross-stratified sets are constituted by the migration of translatent subcritical wind ripples resulting in millimetric inversely-graded lamination (Table 1, Fig. 4H).

Interpretation

The presence of fine to medium-grained sandstones, with well-sorted and well-rounded grains arranged in cross-strata sets composed of wind ripples and grainflow strata suggest aeolian dune deposits (Hunter, 1977; Kocurek, 1981, 1991, 1996; Uličný, 2004). Trough cross stratification allied to high dispersion in the direction of curved foresets indicates crescent dunes with a sinuous crestline (e.g. 3D dunes). However, expressive sets of planar cross stratification demonstrate the occurrence of straight-crested transversal dunes (2D dunes).

The presence of cycles alternating grainflow strata and ripple laminae indicates the occurrence of intervals during which the dunes had well-developed slipfaces that alternated with periods during which part of the lee face was covered by wind ripples (Kocurek, 1991). This cyclic strata pattern suggests to seasonal changes in wind direction (Loope et al., 2001; Scherer and Goldberg, 2010).

Horizontal to low-angle stratification characterizes both sandsheet and dune-plinth deposits (Fryberger et al., 1979; Kocurek and Nielson, 1986). In relation to sandsheets, dune plinths tend to be finer-grained and are more often associated with aeolian dune cross-stratified beds (Eriksson and Simpson, 1998). Due to the homogeneity in sedimentary structures (exclusively wind-ripple lamination, Fig. 4H), the absence of sedimentary structures that character moisture during deposition in addition to the relation with aeolian dune cross-strata suggest that the packages of low-angle stratification of Botucatu Formation are the record of aeolian dune plinths.

BOUNDING SURFACES

The contact between Pirambóia and Guará Formation in Paraná State is sharp contact with regional significance (Fig. 3, Fig. 4C, Fig. 6A), marking an abrupt lithological shift from arkose and subarkose fine-grained sandstone, massive, to quartzose coarse-grained gravelly sandstone with trough cross stratification (Fig. 4C). This surface represents a change from a wet aeolian system whit ephemeral fluvial influence to a perennial braided fluvial system (Fig. 3 and 4).

The transition from Guará Formation to Botucatu Formation is a regionally-correlated sharp surface (Fig. 3, Fig. 4G, Fig 5A and F) that represents the abrupt lithological transition between quartzose, coarse-grained gravelly sandstones, trough cross-stratified and arkose, fine to medium-grained sandstones, from a braided fluvial system to a dry aeolian depositional system.

DEPOSITIONAL SYSTEMS

The relation between aeolian dunes and aeolian sandsheets and interdunes under water table influence points to a wet aeolian system. Additionally, the influence of ephemeral fluvial deposits in aeolian sedimentation characterizes the Pirambóia Formation succession as a fluvial-wet aeolian depositional system. A similar interpretation was accomplished by Wu and Caetano-Chang (1992) and Caetano-Chang and Wu (1994) to Pirambóia Formation in São Paulo State.

The multistorey, unidirectional and highly erosive features of fluvial deposits of the Guará Formation indicate an amalgamated perennial braided fluvial system. The fluvial origin of Guará Formation deposits was identified in other regions of the basin (Scherer and Lavina, 2005, 2006; Reis, 2016)

The dominance of dune deposits, without interdune preservation, indicates that the deposits of Botucatu Formation are part of a dry aeolian system. This point of view is in accordance with previous (Bigarella and Salamuni, 1961; Soares, 1975; Scherer, 2000, 2002; Scherer and Lavina, 2006).

DISCUSSION

Stratigraphic Evolution

The regional stratigraphic logging and facies analysis allowed the recognition of five facies associations as part of three depositional systems, each corresponding to one independent stratigraphic unit. The units are: (i) a fluvial influenced wet aeolian depositional system in Pirambóia Formation; (ii) a perennial braided fluvial system in Guará Formation; and (iii) a dry aeolian system corresponding to Botucatu Formation.

Using sequence stratigraphy, large scale interpretations are limited. The volume of data recorded from Pirambóia and Botucatu Formation are not representative of their regional significance. These formations are not the main focus of this study, and although the collected data does not cover their full vertical successions, it is possible to make an evaluation of their stratigraphic evolution based on the herein described outcrops.

The record of Pirambóia Formation shows the interaction of aeolian dunes and interdunes or wet aeolian sandsheets with ephemeral fluvial processes. The studied succession has two portions separated by a gap of 15 m (Fig. 3, Section 1). In the first portion, a succession of cross-stratified sets of aeolian dunes is recognized, separated by low-angle to horizontally stratified strata of aeolian origin and a small subaqueous dune. The position of these horizontally stratified strata, between large scale aeolian cross strata, suggests the preservation of interdune deposits. The small scale subaqueous dunes demonstrate the invasion of interdune space by fluvial streams.

The second portion of Pirambóia Formation starts with 3 m of aeolian facies (low-angle strata formed by wind ripple migration and adhesion lamination), succeeded by facies of fluvial origin (low-angle cross stratification, current ripples and a massive bed), with no recurrence of aeolian facies up to the boundary with Guará Formation facies (Fig. 3, Section 1). Here, the aeolian portion demonstrates an increase of humidity influencing the aeolian transport, in the transition from wind ripples to adhesion lamination (Fig. 3, Section 1, Fig. 4B). The absence of aeolian dunes covering these beds suggests that these successions record a wet aeolian sandsheet.

The record of Pirambóia Formation in Section 1 (Fig. 3) shows a transition from facies of dry aeolian processes (aeolian dunes and dry aeolian sandsheets) passing through aeolian facies influenced for the water table (wet aeolian sandsheet, facies Sa(e)) and ending ephemeral fluvial deposits (facies St, Sl, Sm and Sr). This vertical facies succession represents the increase in humidity in the aeolian system along time, in a wetting-upward trend. The increase in humidity induced by the rise of the phreatic water table, reduced gradually the supply of dry sand, inhibiting the aeolian dune formation until the ephemeral fluvial processes prevailed.

The sharp bounding surface separating the units can be classified as an unconformity, marked by abrupt facies shift between Pirambóia and Guará Formations (Fig. 3, Fig. 4C, Fig. 6A), including color (from white yellowish to orange brownish), grain size (from fine- to coarse-grained), detrital composition (from arkose/subarkose to quartzarenite) and sedimentary structures (from massive to trough cross-stratified). This facies change represents an abrupt contact between ephemeral fluvial deposits of the Pirambóia Formation and multistorey fluvial channels of the Guará Formation, marking a major transition from a wet aeolian depositional system to a perennial braided fluvial system. Besides that, this surface has regional significance, correlated for nearly 100 km between Sections 1 and 3 (Fig. 3, Fig. 4C, Fig. 6A). The hiatus represented by this surface is unknown because the age of Pirambóia Formation is undetermined. The absence of pedogenic features below the unconformity may be explained by the erosive character of channelized fluvial deposits of Guará Formation, which probably caused the erosion of the superficial layer of pre-existent rocks. The presence of sandstone pebble to boulder lithoclasts concentrated over erosive surfaces in Guará Formation deposits (Fig. 4D and E, Fig. 5C and D) is diagnostic of the erosion of pre-existent consolidated sedimentary rocks. By context, these lithoclasts represent the original rocks of Pirambóia Formation. If the deposits of Pirambóia Formations were consolidated by diagenesis during the activity of Guará Formation fluvial channels, then a time hiatus would be assumed between the two units.

The composition and texture of the sandstones of the Guará Formation – well-rounded quartzarenites – are a strong characteristic of recycled sedimentary rocks, in other words, formed by sediment eroded from previous sedimentary rocks (Garzanti, 2016). The diagenesis and re-exposure to weathering, erosion and transport processes tend to concentrate quartz, a more resistant component in relation to feldspars and metamorphic/plutonic lithoclasts (Garzanti, 2016). The presence of gravel-sized sandstone clast, especially concentrated over scouring channel basal surfaces presumes the erosion of consolidated sandstones (Fig. 4D and E, Fig. 5C and D). This hypothesis is reinforced by the location of the study area and the paleocurrent patterns to SSW which suggest sediment transport from a source area located in northeastern Paraná Basin.

In the four studied sections, the Guará Formation is marked by the predominance of cross strata generated by subaqueous dune migration. In three of the sections studied (sections 1, 2 and 3, Fig. 3), the presence of large cross strata is notable, both simple and composed, representing downstream accretion elements (Fig. 3, 4F, 5F). These architectural elements are the typical unit of construction and migration of mid-channel fluvial bars (Miall, 1985; Wizevich, 1992; Bridge, 1993; Miall, 1996; Jo and Chough, 2001; Scherer et al., 2015). The mudstone bed (facies Fl, Fig. 3, section 3) represents overbank deposits in low energy floodplains and the recurrence of gravel-sized mud clasts over scour surfaces at the base of cross-stratified sets signal the low preservation potential of these deposits, frequently eroded by new channels (Miall, 1977; Ramos et al., 1986; Wizevich, 1992; Jo and Chough, 2001). The high number of channel boundaries (multistorey) identified in relatively thin successions, associated with low preservation of overbank deposits, is characteristic of braided rivers in the context of low vertical accommodation space (Shanley and McCabe, 1993; Wright and Marriot, 1993; Martinsen et al. 1999; Scherer et al., 2015).

The contact between Guará and Botucatu Formations is a sharp surface (Fig. 5A), marked by an abrupt facies shift where multistorey fluvial channel deposit of a perennial braided fluvial system of Guará Formation is overlain by superimposed sets of aeolian dunes of the Botucatu Formation. The Guará-Botucatu unconformity was described in detail in southern Paraná Basin (Scherer and Lavina 2006; Amarante et al., 2019). In the Rio Grande do Sul State, Scherer and Lavina (2006) mapped this unconformity for a 170 km long outcrop belt, identifying features of time hiatus as polygonal fractures and calcrete clasts at the base of Botucatu Formation. Amarante et al. (2019) recognized the surface in northwestern Uruguay, highlighting the shift of depositional systems trough it. The substantial climatic change necessary to recover a perennial river system by a hyper-arid aeolian deposit (Scherer, 2000; Scherer and Lavina, 2006, Amarante et al. 2019) is significant evidence of a sequence boundary. This change was also observed in this study in Paraná state.

The time of this boundary could be supposed by relative datation. Studies about the palaeofauna and palaeoichnofauna purpose Upper Jurassic age to Guará Formation (Scherer and Lavina, 2005; Dantzien Dias at al., 2007; Perea et al., 2009). Francischini et al. (2015) point to a significant difference in the dimensions in the dinosaur palaeofaunas between Guará and Botucatu Formation, suggesting that the Botucatu aridization reduced the size of the species. The age of Botucatu Formation final deposition is directly related with volcanic floods of Serra Geral Formation, dated in Valanginian (Renne et al., 1992; Thiede and Vasconcelos, 2010; Rossetti et al., 2017). In this sense, between Upper Jurassic and Valanginian we can attribute at least 5 million years of hiatus to the Guará-Botucatu unconformity, following the International Stratigraphic Chart (Cohen et al., 2013).

The Botucatu Formation succession shows large scale trough cross stratified sets with thicknesses varying from 1.5 to 6 m composed by wind ripple lamination and grainflow stratification. The sets dominated by wind ripples appear to be concentrated at the base, while the grain flow strata arise late in the vertical facies succession. This indicates upward increase in dune size, permitting the development of a slipface in the lee side of the dunes (Kokurek, 1991, 1996). The non-preservation of interdune deposits corroborates the interpretation of a dry aeolian system for the Botucatu Formation, in which the dunes climbed each other without the formation of interdune deposits due to lack of influence of phreatic water table (Mountney, 2012).

The Guará Formation in Gondwana context

The Guará Formation's braided fluvial deposits in Paraná state represents the proximal area of a wide depositional basin. Regional correlation integrating Scherer and Lavina (2006) and Amarante (2019) shows that Guará Formation constitutes the record of continental depositional systems in an area >800 km in north-south extension (Fig. 7). The facies and facies associations distribution also shows downstream shifting in depositional systems of Guará Formation, starting with fluvial systems, grading to fluvial-aeolian and ending in fluvial ephemeral and terminal distal sheetfloods. The paleocurrent patterns are similar in all sections, preferentially to SSW (see rose diagrams in Fig. 7). There is a reduction of general grain size of the deposits to the southwest direction, following the paleocurrent trend, starting with conglomeratic sandstones and conglomerates in Paraná up to fine-grained sandstones in Uruguay. The extension, the shifting depositional system and the reduction in grain size along the paleocurrent trend reinforce the proposition of Amarante et al. (2019) that Guará and Tacuarembó Formations constitute a big distributive fluvial system, following the models purposed by Hartley et al. (2010), Weissmann et al. (2010), Owen et al. (2015) and Owen et al. (2018).

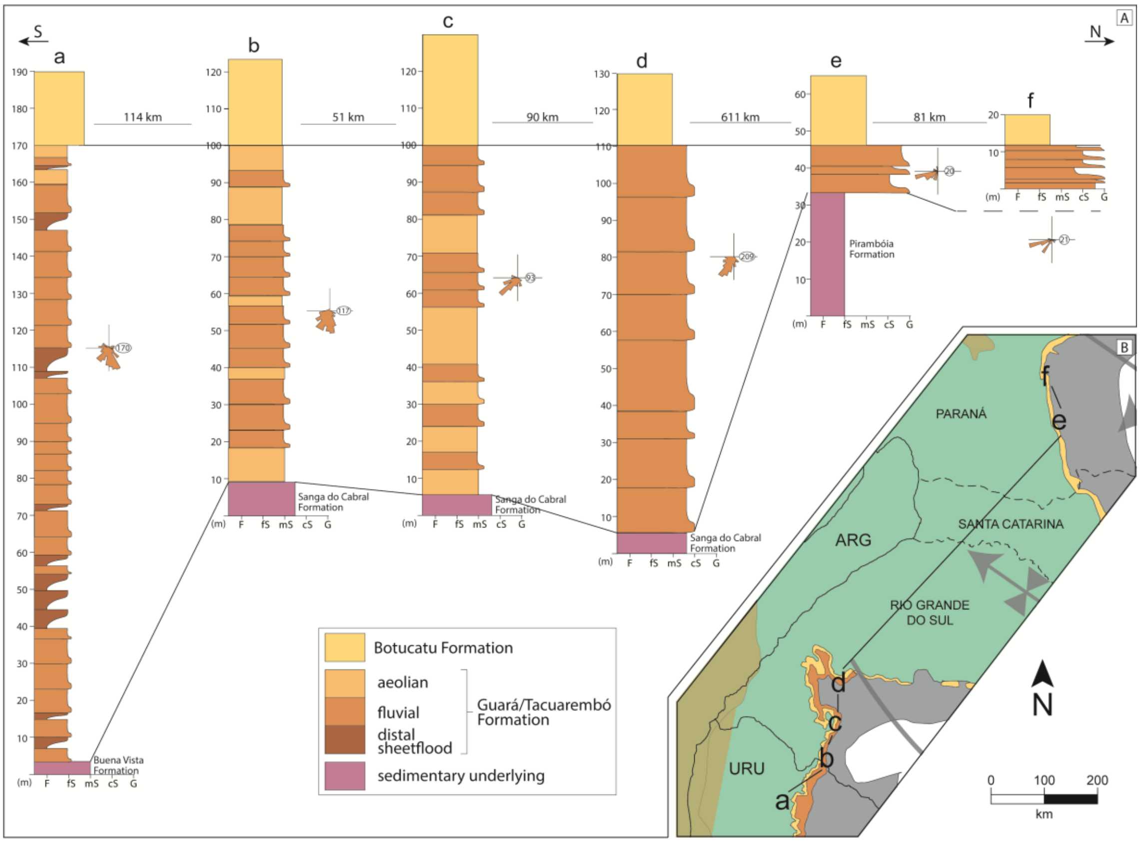

Figure 7. A) Regional correlation and cross-section through the Guará Formation occurrence area between the southern portion (section a) and the central portion (section f) of Paraná Basin. Section "a" has been adapted from Amarante et al. (2019). Sections "b" and "c" from Scherer and Lavina (2005, 2006). Section "d" from Scherer and Lavina (2006) and Reis (2016). Sections "e" and "f" from this study. B) Indicates the location map the cross-section, as a detail of Fig. 1B.

The Guará Formation as outlined by depositional model allows Southwestern Gondwana palaeoenvironmental reconstructions. The model suggests that Paraná Basin was dominated by fluvial and fluvial-aeolian systems in Upper Jurassic. The paleoflow points to a depocenter somewhere near the Argentina-Uruguay border, a unique condition in Paraná Basin history, in which the depocenter was located in the central portion of the basin. The distribution of the depositional systems points to an endorheic shallow basin.

The basal portion of the Twyfelfontein Formation in Namibia, southern Africa, is another example of an Upper Jurassic fluvial-aeolian succession (Fig. 8), designated by Mountney (1998) as Khrone Member (alluvial) and Mixed Unit (fluvial-aeolian)which precedes the Main Aeolian Unit (continuity of Botucatu Formation in African continent). Although the stratigraphic position of the Mixed Unit is the same as Guará Formation, below the Botucatu Formation, detailed studies were not done to understand the stratigraphic relation between the units.

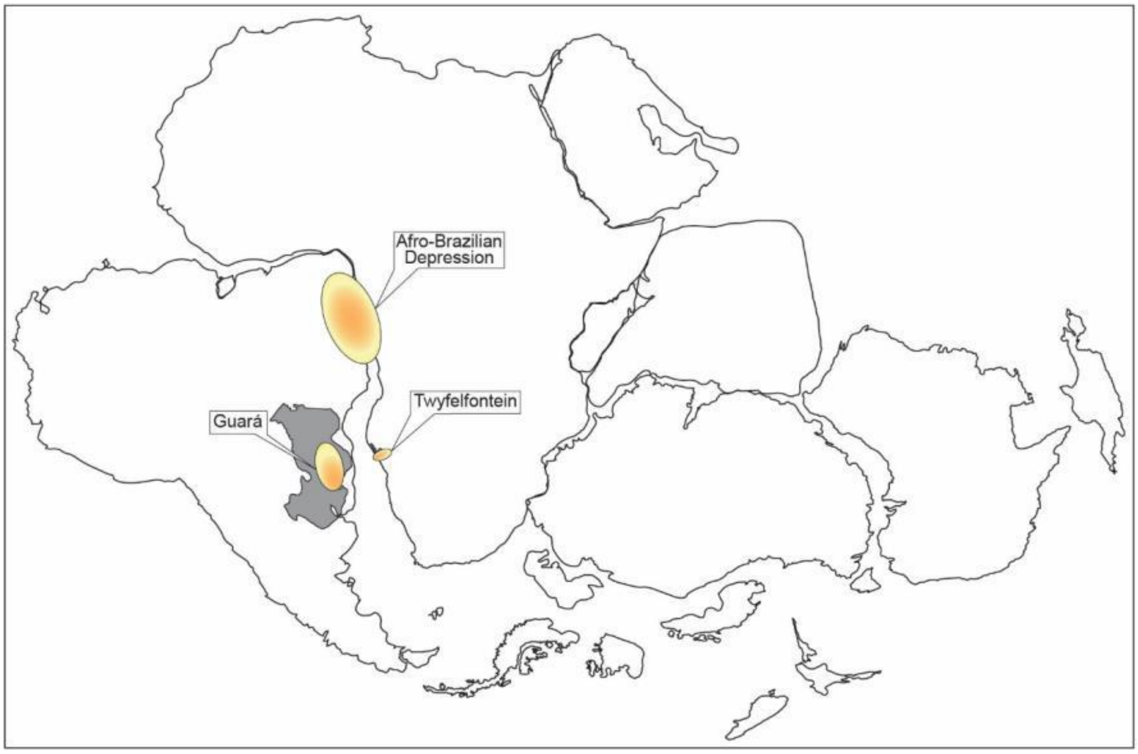

Figure 8. Upper Jurassic fluvial-aeolian occurrences in southwestern Gondwana: orange oval areas indicate the estimated extension and position inside Gondwana of the systems of Afro-Brazilian Depression, Guará Formation (Brazil) and Twyfelfontein Formation (Namibia). Gondwana reconstruction based on Schmitt and Romeiro (2017). Grey outlined areas = Paraná Basin and Huab Basin.

Similar depositional systems are found in reconstructions of Upper Jurassic Afro-Brazilian Depression setting (Fig. 8; Kuchle et al., 2011). These authors proposed that a fluvial, aeolian and lacustrine succession was deposited in a broad shallow endorheic basin occurring between Northeastern Brazil and Western Africa. These records and Guará model point to the existence of two Neo-Jurassic broad endorheic shallow basins in Gondwana (Fig. 8). Morley (2002) purposed the Early Rift Stage as a wide shallow basin formed by the aggregation of small slip faults in a region. This basin would occupy an area much bigger than the subsequent rift valleys (Morley, 2002). Kuchle and Scherer (2010) purposed a stratigraphic classification to this sedimentation: Rift Initiation Tectonic System Tract.

Different paleogeographic models predicted tectonism in the southwestern part of Gondwana in pre break up stages. The palaeomagnetism based model of Seton (2012) purposed transcurrent movements in the region of Chaco-Paraná around 150 Ma (Tithonian) that the authors attributed to the individualization of “Paraná subplate”. Salomon et al. (2017) analyzed the extensional structures of the conjugated margin of southern Brazil-Namibia and purposed a progressive rotation of southern South American Plate generated extension in a vast in a wide region around the future South Atlantic Rift. Is plausible to suppose that this tectonism promoted subsidence and sedimentation after the culmination of Gondwana break-up later in Lower Cretaceous.

CONCLUSIONS

The Upper Jurassic Guará Formation is recognized in the northern portion of Paraná Basin (Paraná state, Brazil). The formation records multistorey channels of a braided fluvial system. Sedimentological features and stratigraphic position allow the distinction of Guará Formation from Pirambóia and Botucatu formations (respectively underlying and overlying units). Fluvial paleocurrent pattern to SSW and detrital composition points to ancient stratigraphic units of Paraná Basin as sedimentary source area.

The spatial area covered by Guará Formation is thus expanded to a >800 km area with an overall north to south extension (Fig. 1, Fig. 7). This new fact points to a special geotectonic context for the Paraná Basin in Upper Jurassic, where a broad distributive fluvial system flowing from NE to SW interacted in distal portions with aeolian systems filling an endorheic basin. Fluvial-aeolian sedimentation is found in other parts of southwestern Gondwana in Upper Jurassic, as Huab Basin in Namibia and Afro-Brazilian Depression. These sedimentary successions are the record of the early stages of Gondwana break-up.

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8.2 ARTIGO 2 – A quantified depositional model of a large distributive fluvial system with terminal aeolian interaction: The Upper Jurassic of Southwestern Gondwana

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(A) RUNNING TITLE: **Quantified DFS aeolian interactions**

(A) ABSTRACT

Recent studies have shown that distributive fluvial systems are the dominant fluvial forms in modern sedimentary basins, thus composing a large portion of the geologic record. This study investigates if the Guará Formation, from the Upper Jurassic Southwestern Gondwana, complies with this hypothesis. This time is significative as it was a period of intense tectonic activity in the region related to Paraná-Etendeka plume and Gondwana break-up. Quantified stratigraphic sections were made at 17 locations located in southern Brazil and the Uruguayan border, totalling ~720 m of stratigraphy which sits within a wider dataset of ~1070 m of stratigraphy across 64 locations. Four facies associations are identified: perennial fluvial channels, ephemeral fluvial channels, floodplain deposits and aeolian deposits, indicating a dryland climate was present. Spatial trends were analysed in a downstream section (NNE-SSW). Grain size, channel body thickness, number of storeys and bar thickness decrease downstream, indicating a reduction in channel depth, flow capacity and channelisation of the fluvial deposits, interpreted to be associated with increasing bifurcation, infiltration and evapotranspiration. Based on spatial trends and facies association distributions, the Guará DFS depositional model is divided into four zones, from proximal to distal: Zone 1, dominated by perennial fluvial channels; Zone 2, a mixture of perennial and ephemeral channels; Zones 3 and 4, deposits outwith the fluvial channel environment dominate with aeolian and floodplain deposits prevailing in each zone, respectively. The Guará Formation confidently records one of the largest distributive fluvial systems recorded in both modern and ancient datasets and one of the first where the fluvial and aeolian interaction is quantified within this context. The Guará Formation DFS model here presented is key to understanding paleoenvironmental, paleoclimatic and geotectonic changes related to Gondwana fragmentation, as well as regional importance due to it being a relevant groundwater resource in South America.

(A) KEYWORDS: Distributive fluvial system, basin-scale, quantification, fluvial, Upper Jurassic, Southwestern Gondwana

(A) INTRODUCTION

An analysis on modern sedimentary basins by Hartley *et al.* (2010 and Weissmann *et al.* (2010, 2015) indicated that distributive fluvial system (DFS) covers a major part of sedimentary basins. These works suggest that DFS should therefore constitute the majority of the fluvial rock record in continental basins. However, large system to basin-scale studies are needed to determine the presence of DFS using criteria such as the spatial variations of facies associations, grain size and channel features (Davidson *et al.*, 2013; Owen *et al.*, 2015, 2019; Weissmann *et al.*, 2015). Basin-scale studies of ancient fluvial successions in comparison with modern continental settings are essential firstly in the development and refinement of facies models and secondly reconstruct the drainage basin in order to determine the distributive or tributary nature of the fluvial system (Ventra & Clarke, 2018). Several works describe DFS systems in the rock record (including Kelly & Olsen, 1993; Nichols & Hirst, 1998; DeCelles & Cavazza, 1999; Cain & Mountney, 2009; Çiftçi & Bozkurt, 2009; Galloway *et al.*, 2011; Owen *et al.*, 2015, 2019; Primm *et al.*, 2018; Ciccioli *et al.*, 2018; Aliyuda *et al.*, 2019; Burnham & Hodgetts, 2019; Dal' Bó *et al.*, 2019; Burnham *et al.*, 2020)). However, few basin-scale (more than 500 km extent) quantifications of deposits exist. Quantifying the depositional elements to determine they downstream distribution is essential to understand the morphological and morphodynamic diversity of distributive fluvial systems in the geological record.

Amarante *et al.* (2019) and Reis *et al.* (2019) suggested that the Guará Formation / Batoví Member of Paraná Basin (Brazil and Uruguay) are the deposits of a large distributive fluvial system flowing from NE to SW (Fig. 1) for at least 1050 km in Southwestern Gondwana. This study quantifies the fluvial characteristics of Guará Formation / Batoví Member along a downstream section to explore whether they are the deposits of DFS as well as help refine a depositional model for the formation based on a quantified facies analysis. This study confidently records one of the largest distributive fluvial systems recorded in both modern and ancient datasets. In comparison with other quantified DFS in the literature (Owen *et al.*, 2015; Burnham & Hodgetts, 2019; Wang & Plink-Björklund, 2019), this study of the Guará DFS also allows insights into DFS termination and interaction with aeolian systems, such as those provided at a facies level by Cain & Mountney (2009).

In addition to the reconstruction of a broad distributive fluvial system, the present study provides data that can be used for the paleogeographic and paleoclimatic reconstruction of Gondwana during the Late Jurassic. Few studies focus on facies and stratigraphic characterisation of Late Jurassic units present (Mountney *et al.*, 1998; Veiga & Spalletti, 2007; Francischini *et al.*, 2015; Linol *et al.*, 2015), despite this time interval being critical in understanding paleoenvironmental, paleoclimatic and geotectonic changes related to Gondwana fragmentation. The break-up of western Gondwana, together with the evolution of Paraná-Etendeka plume, controlled erosion and sedimentation in the Mesozoic period (Friedrich *et al.*, 2018; Krob *et al.*, 2020). This study therefore rectifies this knowledge gap through the study of the Guará Formation / Batoví Member that is present across a large portion of Paraná Basin, recording climate and palaeogeography of southwestern Gondwana in the Upper Jurassic (Scherer & Lavina, 2005, 2006; Perea *et al.*, 2009; Amarante *et al.*, 2019; Reis *et al.*, 2019). The quantification of the Guará Formation also helps robustly document the generation of sedimentary basins and their fills within a significant geological time period relating to continental crust evolution over an active plume.

The Guará Formation / Batoví Member outcrop belt also has important resource implications as it is an unconfined recharge and discharge zone of the Guarani Aquifer System, one of the largest transboundary groundwater reservoirs worldwide (Foster *et al.*, 2009; Sindico *et al.*, 2018). At the Brazil-Uruguay border, which resides in the study area, approximately 162,000 people are supplied with drinking water exclusively from this aquifer system (Foster *et al.*, 2009). Understanding the detailed stratigraphy of Guará Formation / Batoví Member is essential to the sustainable management of this strategic water resource.

(A) GEOLOGICAL SETTING

The Paraná Basin is an intracratonic basin covering an area of 1,400,000 km² across Brazil, Argentina, Uruguay, Paraguay with a small remnant present in the Huab Basin (Namibia) (Milani *et al.*, 2007;Fig. 1). The basin records various periods of subsidence and sedimentation from the Ordovician to Cretaceous (Milani, 1997; Milani *et al.*, 1998, 2007). The Upper Jurassic Guará Formation is bounded at both the base and top by unconformities, defining a distinct depositional sequence in the Paraná Basin (Scherer *et al.*, 2000; Fig. 2) The thickness of the Guará Formation varies from 12 to 110 m in Brazil, cropping out in the Paraná and the Rio Grande do Sul States (Scherer & Lavina, 2005, 2006; Reis *et al.*, 2019). In Uruguay, this stratigraphic unit is equivalent to the Batoví Member of Tacuarembó Formation, reaching up to 200 m thick (Amarante *et al.*, 2019). The Guará Formation unconformably covers the fluvial-aeolian deposits of Pirambóia Formation (Paraná State) and Sanga do Cabral Formation (Rio Grande do Sul State) (Scherer *et al.*, 2000; Reis *et al.*, 2019), while the Batoví Member unconformably overlies aeolian deposits of the Buena Vista Formation (Amarante *et al.*, 2019) in Uruguay. In both countries, the Guará Formation / Batoví Member is unconformably overlain by the aeolian dune deposits of the Lower Cretaceous Botucatu Formation (Brazil) and Rivera Member (Uruguay) (Scherer *et al.*, 2000; Scherer & Lavina, 2005, 2006; Amarante *et al.*, 2019; Reis *et al.*, 2019).

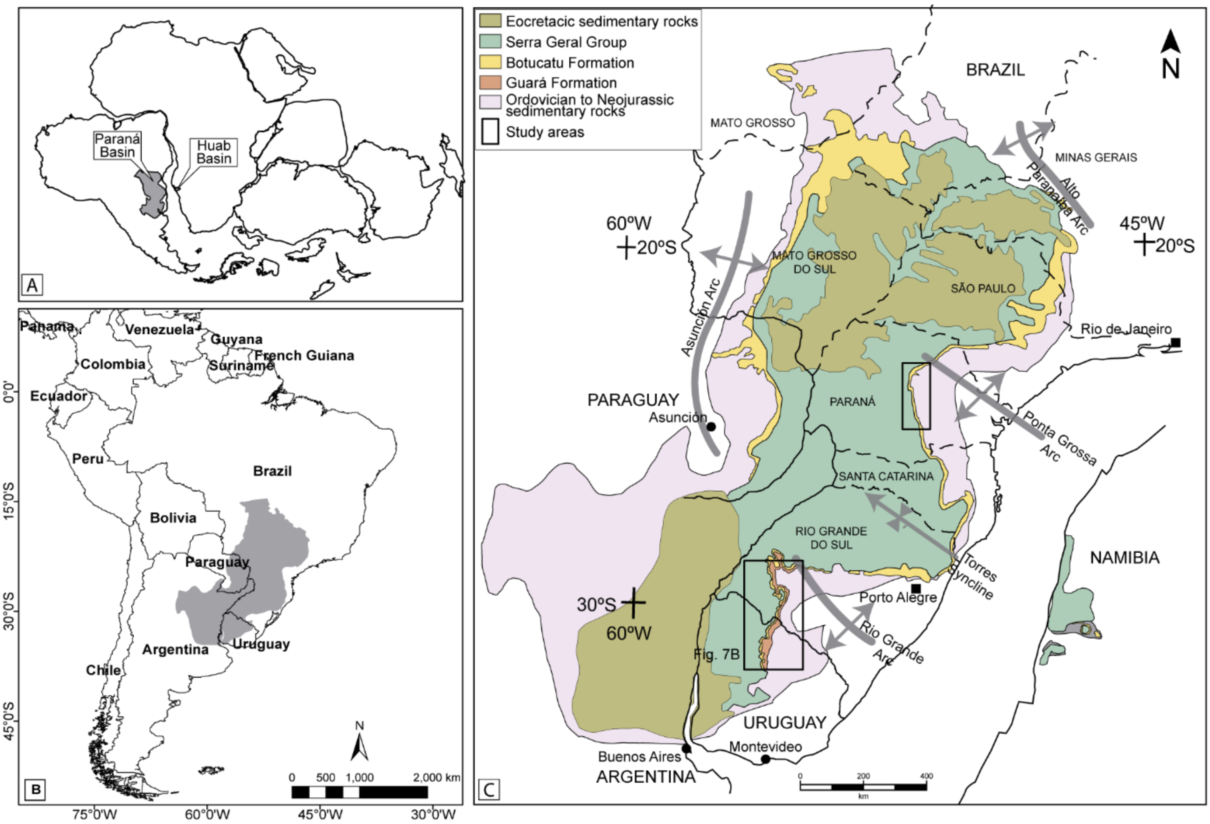


Figure 1. Location of the study areas in Paraná Basin and Gondwana contexts. A) Paraná Basin and its counterpart in southwestern Africa Huab Basin, positioned in Upper Jurassic Gondwana, based on Schmitt & Romeiro (2017) reconstruction. B) Paraná Basin position in South America. C) Paraná Basin map showing the study areas (modified from Zalán *et al.*, 1987; Scherer & Lavina, 2005, 2006; Scherer & Goldberg, 2007; Rossetti *et al.*, 2017; Amarante *et al.*, 2019).

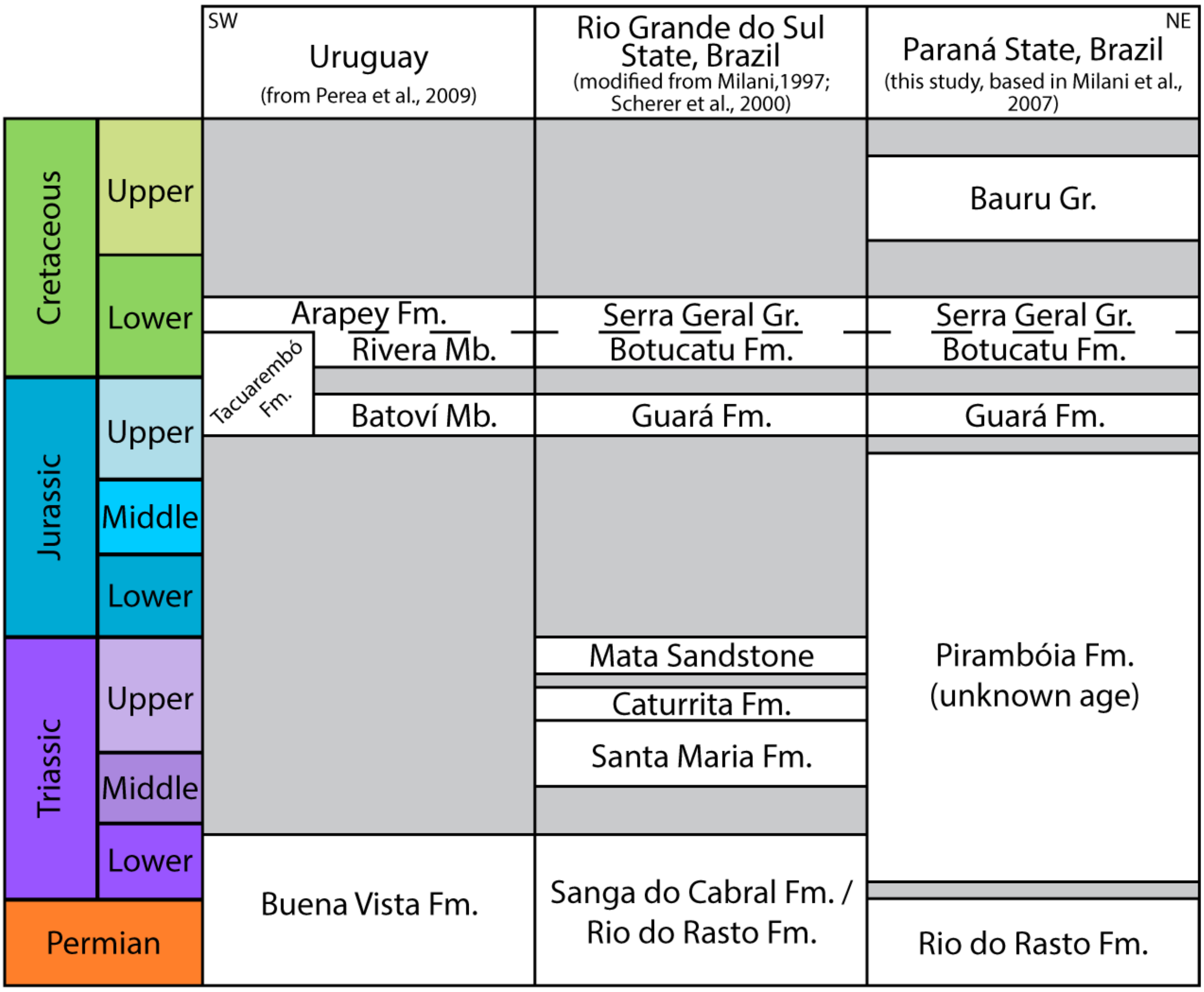


Figure 2. Summary of stratigraphic units of Paraná Basin. Modified from Reis *et al.* (2019) after Soares (1975), Milani (1997), Scherer *et al.* (2000), Milani *et al.* (2007) and Perea *et al.* (2009). SW - southwest; NE - northeast; Gr. - Group; Fm. - Formation; Mb. - Member.

The Guará Formation / Batoví Member is composed of fine to coarse-grained sandstones, and rare mudstones (Scherer *et al.*, 2000; Scherer & Lavina, 2005, 2006; Perea *et al.*, 2009; Amarante *et al.*, 2019; Reis *et al.*, 2019), with internal facies zonation. The northern portion (Paraná State and northern Rio Grande do Sul State) is composed of coarse- to medium-grained sandstones deposited by braided fluvial systems, which transitions southwards to medium- to fine-grained sandstones, deposited by fluvial channels, distal sheetfloods, aeolian dunes and aeolian sandsheets (southern Rio Grande do Sul State and Uruguay). Paleocurrents from aeolian dunes show a NE migration direction, while fluvial systems flowed SSW (Scherer & Lavina, 2005; Amarante *et al.*, 2019; Reis *et al.*, 2019).

A diverse fossil content is present in the Guará Formation/Batoví Member, with body part preservations of crocodilians, turtles, sauropods, ornithopods, theropods, megalosaurs, pterosaurs, sharks, lungfishes, coelacanths, molluscs and conchostrachans (Mones, 1980; Martinez *et al.*, 1993; Perea *et al.*, 2001, 2003, 2009, 2014, 2018; Yanbin *et al.*, 2004; Soto & Perea, 2008, 2010; Fortier *et al.*, 2011; Soto *et al.*, 2012b; a, 2020) and dinosaurs ichnofossils discovered (Dentzien-Dias *et al.*, 2008; Francischini *et al.*, 2015, 2017; Mesa & Perea, 2015). The paleoecologic interpretations of these confirm a fluvial environment within a continental semi-arid to arid climatic regime. The more restrictive biostratigraphic interpretations attribute Upper Jurassic (Kimmeridgian-Tithonian) ages to the Guará Formation (Fortier *et al.*, 2011; Francischini *et al.*, 2015, 2017; Soto *et al.*, 2020).

(A) METHODS AND DATASET

Data was collected through the construction of graphic sedimentary logs, with special attention to the quantification of facies and the relationship of bounding surfaces. In total, 1,071.2 m of section was logged across 64 locations (62 outcrops and 2 wells). The sedimentological logs were interpreted using the classical methods of facies analysis, where groups of genetically related facies are classified as facies associations, representing deposits or sub environments that compose the depositional systems (Walker & James, 1992). Facies associations with defined morphology were classified as architectural elements, especially for fluvial deposits (Miall, 1985; James & Dalrymple, 2010).

Data from both the wells and outcrops were input into digital spreadsheets and classified by facies code, bed thickness, grain size, architectural element, and facies association. Grain size was measured in Wentworth millimetric scale then converted to the phi scale, avoiding statistical bias caused by magnitude differences between grain size classes in millimetric scale. The weighted average of the phi grain size was considered to take into account the thickness of the channel body (following Owen *et al.*, 2015).

To ensure representative ‘snapshots’ at the system scale (i.e. using outcrop sections of adequate thickness in relation to total thickness of the formation), localities that were below 25% of the total thickness were discounted from statistical analysis. The cut off percentage was chosen based on the thicknesses measured for channel bodies. From the original dataset this left 17 locations totaling 718.9 m of logged sections (67.11 % of total data logged). Sections of less than 25 % of the total formation thickness were considered only for paleocurrent insights.

Presence and strength of observed trends was indicated by the Spearman’s rank correlation coefficient (ρ). Where ρ = a perfect positive correlation exists and ρ = -1 a perfect negative correlation exists, while ρ values near 0 indicate the two factor are independent, i. e., there is no correlation (Davis, 2002). A critical value (CV) was calculated to define a correlation coefficient value, indicating the likelihood of results occurring by chance (Davis, 2002). Results that have a CV value of more than 0.05 indicates a weak possibility of correlation between the datasets; CV value less than 0.05 indicates a strong possibility of correlation, i.e., less than 5% chance that the trends occurred by chance.

Mean paleocurrent direction was mapped from perennial or ephemeral fluvial channel and aeolian dunes deposits.

(A) RESULTS

(B) Facies and facies associations

Sandstones of the Guará Formation vary in grain size from fine- to very coarse-grained sandstones through to gravelly sandstones and conglomerates (Table 1). Fluvial facies are moderately to very poorly-sorted, dominantly poorly-sorted, with subrounded to rounded grains. In aeolian facies, the sand is fine to medium-grained, well-sorted and well-rounded. The gravel fraction varies from rounded to subangular – typically the quartz clasts are more rounded while the mud clasts and lithoclasts are subrounded to subangular. The sandstones and conglomerates of Guará Formation are compositionally very homogeneous. Sand fractions are classified to be quartzarenites, while the gravel fraction is composed of quartz (granules to pebbles), mud clasts (granules to boulders) and sedimentary lithoclasts (pebbles to boulders). The presence of sedimentary lithoclasts is notable in gravel fractions, as it is composed of fine-to medium-grained sandstone clasts varying from pebble to boulder size classes, and granule to boulder-sized mud clasts. Fine sediments occur as mudstones, siltstones, very fine-grained sandstones and rarely claystones, frequently in hetherolithic bedding. The reddish colours suggest oxidation and pedogenic features are common.

Table 2. Summary of lithofacies observed in Guará Formation (based on Scherer & Lavina (2005), Amarante *et al.* (2019), Reis *et al.* (2019) and data collected in this study).

Code	Description	Interpretation
Gm	Clast-supported sandy conglomerate, pebble-sized quartz clasts, reddish muddy intraclasts and sandstone lithoclasts cobble to boulder-sized, massive. The sandy fraction varies from fine- to very coarse-grained. Frequently at	Deposition of bedload as diffuse gravel sheets (Hein & Walker, 1977) in the channel bottom, resulting from hyperconcentrated flows eroding previous gravelly sands (quartz pebbles), overbank deposits (mud clasts) and

	the base of cross-strata sets. Resting upon erosive surfaces, filling scours.	ancient sedimentary rocks (sandstone lithoclasts).
Gh	Clast-supported conglomerate, quartz pebbles, crudely horizontally bedded	Migration of longitudinal gravel bars in unidirectional flow (Miall, 1996; Todd, 1996).
Gt	Clast-suported sandy conglomerate, quartz pebbles, trough cross-bedded. Green muddy cobbles at the set base.	Migration of subaqueous sinuous-crested gravel dunes in unidirectional flow (Todd, 1996).
Sm	Fine- to very coarse-grained sandstone, poorly to well-sorted, massive. Muddy pebbles at the base of the bed.	Fast deposition of subaqueous unidirectional high energy flow, hyper-concentrated (Scherer *et al.*, 2015) in sediments, fluidisation or intensive bioturbation (Miall, 1978, 1996).
Sh	Fine- to coarse-grained sandstones; well- to poorly-sorted, horizontal lamination.	Horizontally-bedded deposits originated via unidirectional supercritical flow (Miall, 1978; Bridge & Best, 1988).
Sl	Fine to coarse-grained sandstone, moderately to poorly-sorted, low-angle cross stratification. Quartz and muddy granules and pebbles dispersive, mark stratification and base of beds.	Structures formed in transitional flow between subcritical and supercritical (Harms *et al.*, 1982; Bridge & Best, 1988).
Ss	Fine- to very coarse-grained, moderately- sorted sandstone with sigmoidal cross stratification.	Migration of subaqueous dunes with rapid aggradation combining traction and suspension in lower- to upper-flow regime (Wizevich, 1992).
St	Fine- to very coarse-grained, well- to poorly- sorted gravelly sandstone, trough cross-stratified. Foresets and sets are normal graded. Quartz and muddy granules and pebbles dispersive, at the set base and marking the foresets. Frequently deposited above Gm facies bed.	Migration of subaqueous sinuous-crested dunes in unidirectional flow (Allen, 1963; Miall, 1978; Collinson *et al.*, 2006).
Sp	Fine to coarse-grained, moderately- to poorly-sorted sandstone, planar cross-stratified. Foresets and sets are normal graded. Dispersive quartz granules. Mudclasts and quartz granules and pebbles at the set base.	Migration of subaqueous straight-crested dunes in unidirectional flow (Allen, 1963; Miall, 1977; Collinson *et al.*, 2006).

Sr	Very fine- to coarse-grained, moderately- to well-sorted sandstone with ripple cross-lamination, subcritical to supercritical climbing angle.	Migration of unidirectional subaqueous 2D or 3D ripples in lower flow regime (Allen, 1963; Miall, 1977).
Sd	Fine- to medium-grained sandstones with deformed undefined lamination; occasionally containing mudclasts.	Deformation of primary structures by liquefaction in unconsolidated layers (Owen & Moretti, 2011).
S	Fine- to very coarse-grained sandstones in which in not possible to recognise the primary structure.	Sandstones with structures obliterated by diagenetic or weathering action.
Ht	Millimetric to centimetric heterolytic lenticular to flaser bedding; intercalations of very fine to fine sandstones (massive, sometimes with ripples), mudstones, claystones and siltstones, laminated or massive; commonly presenting bioturbation and plastic deformation structures, which breaks the lamination	Deposition by decantation of suspended load alternating with bed load or rapid deposition of hyperpycnal flow in a flow regime very close to zero. Plastic deformation due to fluidisation and overloading (Amarante *et al.*, 2019).
Fl /Fd	Mudstones (claystones, siltstones and very fine-grained sandstones), with millimeter-sized horizontal lamination. Structures of plastic deformation are common, breaking lamination (facies Fd). Gray, purple, red to reddish-brown. Mottling, blocky cleavage and root marks occur occasionally.	Deposition of suspended load by settling in standing water (Miall, 1977; Turner, 1980; Jo & Chough, 2001). Purple, red and brown colours associated with mottling, blocky cleavage and root marks indicates pedogenic alteration (Retallack, 1988).
Fm	Mudstones to (claystones, siltstones and very fine-grained sandstones), massive; sometimes fissile in weathered surfaces. Gray, purple, red to reddish-brown. Mottling, blocky cleavage and root marks occur occasionally.	Deposition of suspended load by settling in standing water (Miall, 1977; Turner, 1980; Jo & Chough, 2001). Lack of lamination due to (i) flocculation of clay suspension, or (ii) loss of lamination associated with fluidisation or intensive bioturbation. Purple, red and brown colours associated with mottling, blocky cleavage and root marks indicates pedogenic alteration (Retallack, 1988).
Sl(e)/Sh(e)	Fine- to medium-grained sandstones, well-sorted, with	Translatent subcritical wind ripple migration over a plane to

	well-rounded and highly spherical grains, horizontal to low-angle lamination formed by thin pin-stripe inversely graded laminae.	quasi-plane surface (Kocurek, 1981).
St(e)	Fine- to medium-grained sandstones, well-sorted, with well-rounded and highly spherical grains, large-scale trough cross-bedding. The base of the foresets consists of millimetrically spaced pin-stripe laminations with inverse grading, which interdigitates with wedges of massive sandstones up to 4 cm thick towards the top of the foresets; frequent presence of reactivation surfaces.	Sinuous-crested (3D) aeolian dunes alternating grainflow and translatent subcritical wind ripple migration in the lee side (Hunter, 1977; Hunter & Rubin, 1983).
Sa(e)	Dominantly fine-grained sandstone, rarely medium-grained, well-sorted, with crenulated plane-parallel lamination, defining a crinkled texture.	Adhesion structures originated by adherence of dry sand grains that were carried by wind over wet surfaces (Kocurek, 1981; Kocurek & Fielder, 1982).

Three primary facies associations were determined based on the facies analysis, namely fluvial channel, floodplain and aeolian deposits. The fluvial channels are subdivided in two types, respecting architectural and facies peculiarities: perennial and ephemeral, based on Fielding *et al.* (2018). Floodplain facies association encompasses all the sedimentation resultant of fluvial transport deposited outside of the channel environment, including muddy floodplain, crevasse splays and channels and terminal sheetfloods. The aeolian facies associations includes aeolian dunes, interdunes and aeolian sandsheets.

Within fluvial channel deposits, erosive bounding surfaces are interpreted as storey surfaces, with each storey representing the infill of individual channel locations within a broader channel body. Each change in channel position defines deposition of a new storey. The amalgamation of 2 or more storeys constitutes multistorey channel bodies. Single-storey channel bodies are when no internal reworking or connectivity between individual storey is observed with floodplain and aeolian deposits separating channel bodies.

(C) Perennial fluvial deposits

(D) Description

Channel bodies vary from 1.2 to 15.3 m thick. The deposits are predominately composed of trough (St, 81.2%) and planar (Sp, 8.6%) cross strata (Fig. 3). Around 7% of total facies described are distributed in massive (Sm, 1.7%) and ripple cross-laminated (Sr, 1.6%) sandstones, thin beds of massive conglomerates with mud clasts (Gm, 1.5%), sigmoidal cross-bedded sets (Ss, 0.9%), low angle cross-stratified (Sl, 0.6%) sandstones, trough cross-stratified conglomerates (Gt, 0.3%) and sandstones where the primary structure is deformed (Sd, 0.2%) (Fig. 3). For the remaining 3.3% of the facies described it was not possible to identify primary structures (S) (Fig. 3). Storey successions from 0.5 to 9.5 m thick are poorly defined fining upward packages bounded at the base by undulated to concave-up surfaces. The bounding surfaces are commonly lined by gravel facies (Gm and GT). Each storey is filled within architectural elements, distinguished by facies and geometry. Three architectural elements are identified for perennial fluvial deposits: large simple cross set, down current dipping compound coset and amalgamated cross-bedded sets.

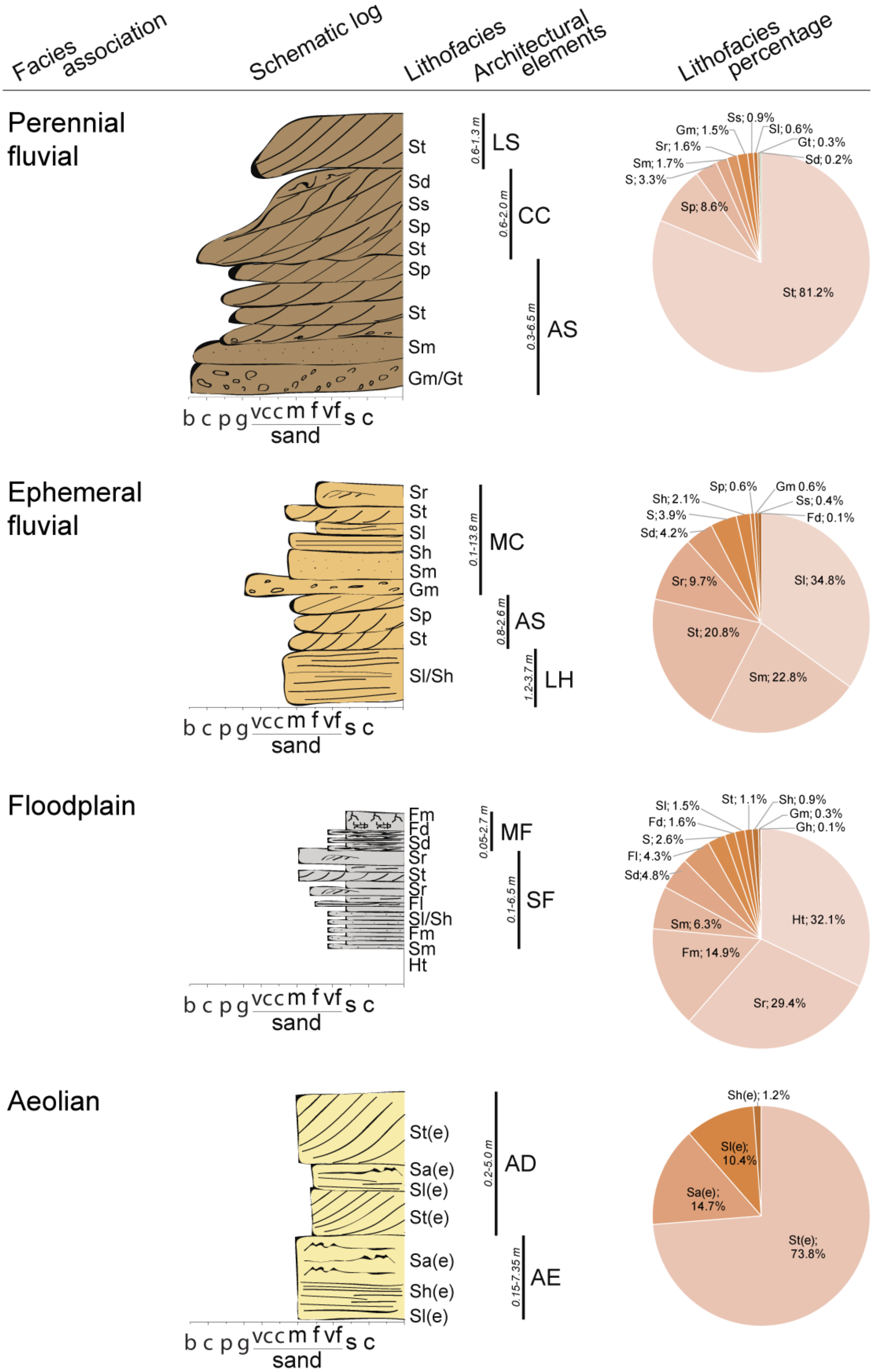


Figure 3. Schematic logs of facies associations, architectural elements and respective facies distributions.

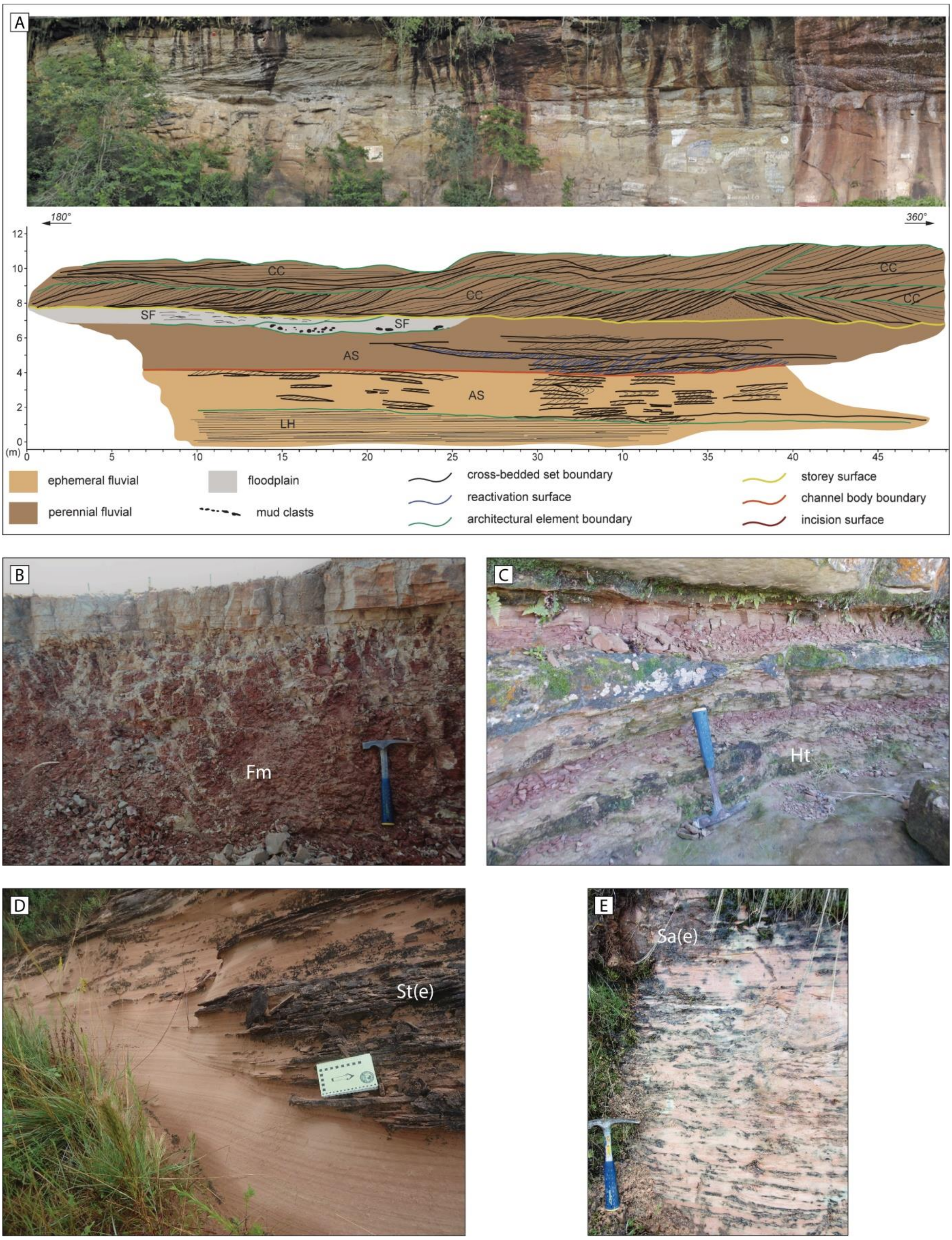
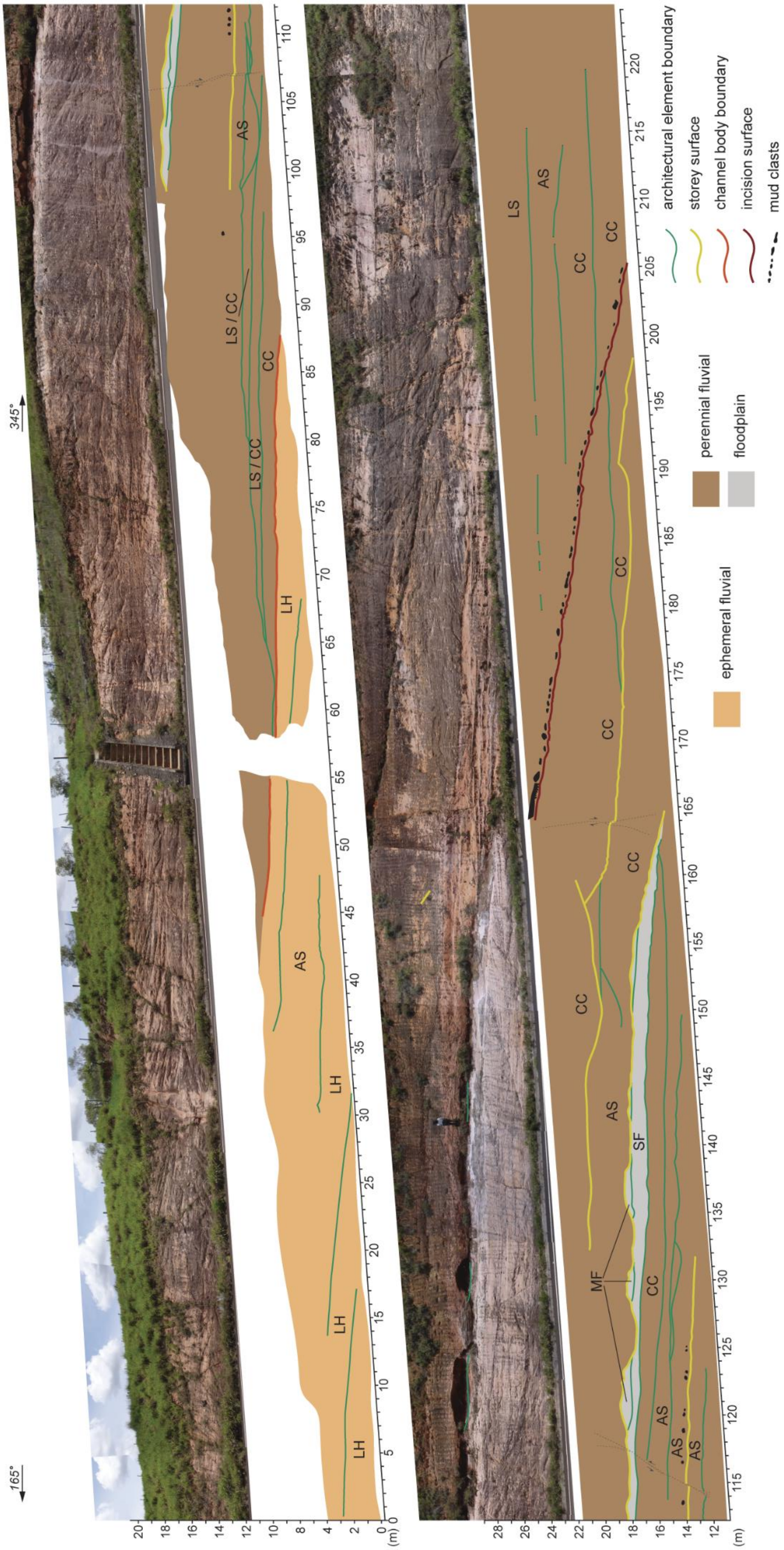


Figure 4. Facies associations examples. A) Interpreted panel showing the architectural elements of floodplain and fluvial channel deposits. Architectural elements: AS - Amalgamated cross-bedded sets; LH - Low angle to horizontally stratified sand sheets; CC - Downcurrent dipping compound coset; SF - Sandy floodplain deposits. B) Transcritical to supercritical structures of ephemeral fluvial channel deposits. B) Muddy floodplain with pedogenetic features. C) Thickening upward heterolytic succession of sandy floodplain. D) Large-scale trough cross stratification in aeolian dunes deposit. E) Adhesion structures in aeolian sandsheet deposit.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(m)
ephemeral fluvial
perennial fluvial
floodplain
architectural element boundary
storey surface
channel body boundary
incision surface
mud clasts

Figure 5. GA002 location, ~700 km downstream, show the amalgamated architecture of the alternation between perennial and ephemeral channel bodies. Floodplain deposits have highly eroded lenticular geometry. Note the high relief erosive surface (red line) that truncates the entire channel body package.

Large simple cross set (LS): Isolated, planar or tangential cross stratified sets (Sp and St) varying from 0.6 to 1.3 m thick and average thickness of 0.8 m, extending laterally up to 20 m (limited to outcrop expositions). Frequently the forests are truncated by regularly spaced (15 to 20 cm) concave-up, convex-up or concave-convex (sigmoidal) erosive surfaces, overlain by down-lapping foresets.

Downcurrent dipping compound coset (CC): cross stratified sets (facies St and Sp), 10-25 cm thick, bounded by surfaces dipping in the same direction of the crossbedding foresets, but in a lower angle (4°-20°). The compound cosets are 0.6 to 2.0 m thick (average thickness of 1.2 m), limited by erosive surfaces. Foresets and sets are frequently normal graded.

Amalgamated cross-bedded sets (AS): Cross stratified sets (St, Sp and rarely Ss) with average thickness of 20 cm (range of 10-50 cm), amalgamated in tabular packages from 0.3 to 6.5 m thick (average thickness of 1.9 m) extend laterally for tens of meters over erosive surfaces. The boundaries between sets are undulated to concave up in transversal or oblique sections to the paleoflow and tend to lightly undulated to gently inclined in the opposite direction to the crossbedding foresets in parallel sections to the paleoflow. Normal grading in foresets and sets is common.

(D) Interpretation

Sand bodies amalgamating poorly defined fining upward packages bounded by erosive surfaces and composed of poorly sorted and normal graded sandstones in cross-stratified medium and large-scale sets are typical of multistorey fluvial channel deposits. Large, simple cross sets are interpreted as unit bars with well-developed slipface (Wizevich, 1993; Scherer *et al.*, 2015; Amarante *et al.*, 2019; Herbert *et al.*, 2019). Cosets formed by sets dipping in the direction of the current typify compound unit bars where dunes superimposed over the bars migrate along the lightly inclined lee face of the bar (Scherer *et al.*, 2015). The presence of simple and compound unit bars represents variations in discharge, depth and continuity of flow through time (Herbert *et al.*, 2019). Unit bars could represent mid-channel bars in smaller rivers or be the more mobile portion of much larger and long lived mid-channel bars in larger river channels (Herbert *et al.*, 2019). Smaller amalgamated sets are interpreted as fields of migration and climbing of individual subaqueous dunes that accumulate by vertical aggradation, similar to sand bedforms of Miall (1985, 1996). These elements probably accumulate between mid-channel bars in the deepest portion of fluvial channels (Bristow, 1987; Jo & Chough, 2001). Migration of individual bedforms could occurs over the stoss side of mid-channel bars, during bankfull periods (Miall, 1996).

The association between unit bars and subaqueous dunes suggest the channels experienced low variability of interannual discharge (Fielding *et al.*, 2018), referred as perennial channels by Miall (1996). While the bedforms and macroforms suggest regularity in inter-annual discharge variation, the reactivation surfaces inside unit bars could demonstrate a highly variable seasonal discharge inside each year (Allen *et al.*, 2014; Scherer *et al.*, 2015; Fielding *et al.*, 2018; Herbert *et al.*, 2019).

(C) Ephemeral fluvial deposits

(D) Description

This facies association is composed of tabular channel sandbodies varying between 0.25 and 12 m thick, and one anomalous 25.2 m thick unit. The sandstone bodies are multi or single storey. Storey thickness varies from 0.25 to 10.2 m, are bounded by sharp and erosive basal surfaces, flat to concave-up, reaching more than 1.5 m of relief. This facies association is composed of fine to medium-grained sandstones and rarely fine sediments. Beds of massive conglomerate (Gm) are common, deposited over the basal erosive surfaces of the storeys. Almost 35 % of the facies described in this facies association are sandstones with low angle stratification (Sl), 22.8 % of massive sandstones (Sm), 20.8% of trough cross-stratified sets (St), 9.7% of current ripples (Sr) (Fig. 3). Deformed sandstones (Sd) are more common (4.2%) than in perennial fluvial channels (Fig. 3). Horizontally stratified sandstones (Sh, 2.1%), planar cross-bedding (Sp, 0.6%), massive conglomerates (Gm, 0.6%), sigmoidal cross-bedded sandstones (Ss, 0.4%) and rare, deformed and discontinuous thin layers of fine mudstones deposited between the sandstone beds can also occur (Fd, 0.1%; Fig. 3). In 3.9% of the sandstones described it was not possible to recognise any primary structure (S). Each storey is filled by one or more architectural elements, identified based on geometry and lithofacies assemblage: low angle to horizontally stratified sand sheets, amalgamated cross-bedded sets and massive to cross-bedded sand sheets (Fig. 4, Fig. 5)

Low angle to horizontally stratified sand sheets (LH): Tabular packages varying from 1.2 to 3.7 m (average thickness of 2.5) thick and 20 m of lateral extension, formed almost exclusively by low angle (Sl) and horizontally (Sh) stratified sandstones. Rarely, cross stratified sets (St) occur in isolated lenses. Quartz granules and pebbles occur sparsely in the sandstone beds.

Amalgamated cross-bedded sets (AS): This element is similar to perennial fluvial deposits, with differences in size and geometry. Within ephemeral channels the individual cross-stratified sets (St, but sometimes Sp and Ss) are smaller (from 0.05 to 0.9 m thick, average thickness 0.23 m) and the architectural elements are less thick, stacked in tabular packages varying from 0.8 to 2.65 m (average thickness of 1.5 m) and 15 m of lateral extension.

Massive to cross-bedded sand sheets (MC): The element is commonly composed from base to top of: massive intraformational conglomerates (Gm), massive sandstones (Sm), horizontally and low angle stratified sandstones (Sh and Sl), trough cross-stratified sandstones (St) and ripple cross-laminated sandstones (Sr). The successions described combine two or more of these facies, very rarely all of them, but the stacking order is maintained. These elements present well to poorly developed fining and thinning upward trends. The external morphology could be tabular or lenticular with sharp erosive concave-up base. Average thickness is 2 m, ranging between 0.1 and 13.8 m, extending laterally up to 17 m, limited for the outcrop exposition.

(D) Interpretation

The erosive bounding surfaces and the presence of structures of unidirectional flow demonstrate deposition occured in fluvial channels. Sand sheets formed by transcritical to upper flow structures in alternation with amalgamation of cross stratified sets suggest alternation between discharge regimes (Allen *et al.*, 2014). Nevertheless, this alternation could represent periods of slight confinement of flow and migration of dunes followed by unconfinement and splaying of the stream generating transcritical structures (Bromley, 1991). Facies successions representative of waning flows amalgamated in sandbodies demonstrate the multiepisodic filling of a channel by successive flood episodes (Hampton & Horton, 2007). The occurrence of the massive sandstones indicates hyperconcentrated flows in which the concentration of sandy sediment was high, and deposition occurs instantaneously during the deceleration of the flow (Allen & Leeder, 1980). The facies assemblage mixing dune elements, sandsheets of transcritical to supercritical structures and the waning flow indicates flow deceleration are characteristic of fluvial deposits of intermediate discharge variability (Fielding *et al.*, 2018) or ephemeral channels (Scherer *et al.*, 2007; Allen *et al.*, 2014).

(C) Floodplain deposits

(D) Description

Deposits have tabular geometries, varying in thickness from 0.2 up to 9 m. Sometimes the geometry is lenticular, due to erosion of overlying channels (Fig. 4, Fig. 5). The general facies distribution of these deposits is (Fig. 3): (Ht) Heterolithic bedding composed by massive or laminated mudstones thinly intercalated with fine or very fine massive or ripple laminated sandstones (32.1%); (Sr) ripple cross-laminated, very fine to medium sandstones (29.4); (Fm) massive mudstones (14.9%); (Sm) massive sandstones (6.3%); (Sd) sandstones with the primary structure deformed (4.8%); and (Fl) laminated mudstones (4.3%). 6.1% of the facies are distributed between sandstones with low angle stratification (Sl), with trough cross stratification (St), horizontally stratified (Sh) and some which were not possible to identify the structure (S). Deformed mudstones (Fd) are 1.6%, and 0.4% are massive and horizontally stratified conglomerates (Gm and Gh, respectively). This facies association is divided into two architectural elements, according to the lithofaciological features and the sand/mud ratio: sandy floodplain deposits and muddy floodplain deposits.

Sandy floodplain deposits (SF): This element occurs as tabular packages extending for tens of meters and is composed of sandstone beds with ripple cross lamination (Sr), massive (Sm) or with a variety of current structures (Sl, St, Sh) in alternation with beds of massive and laminated mudstones (Fm and Fl), varying in size since millimetric up to metric heterolithic bedding. Intraformational conglomerates (Gm) are rarely present. Lenticular geometries (0.5 m thick and 5 to 10 m long) are observed, always truncated at the top by erosive surfaces. This succession frequently shows thickening- and coarsening-upward trends of the sandstone beds in packages varying from 0.1 to 6.05 m thick (average thickness of 1.2 m).

Muddy floodplain deposits (MF): This element has a lenticular geometry with a plane base but as with others its form is due to the presence of eroded top. The thickness varies from 0.05 to 2.7 m (average of 0.5 m), and lateral extension is generally discontinuous, not exceeding 2 m. The alignment of these non-eroded residual lenses over the same basal surface allows the estimation of a minimal extension for the deposit of around 25 m long. Deposits are predominantly composed of Ht and Fl facies, with frequent plastic deformational structures (flame structures and convolute folding). Deposits are red and reddish-brown, but also purple, brown, black, grey and yellow colours can be present. The muddy packages sometimes show blocky structure and root marks.

(D) Interpretation

The floodplain facies association are the combined deposits of unconfined flows, i.e., deposited outside of channels environments. Sandy intraformational conglomerates over erosive surfaces are interpreted as crevasse channels crosscutting the floodplain fines. Tabular and laterally continuous packages, with no erosional features, comprising an alternation of mudstones and fine-grained sandstones, presenting unidirectional tractive structures suggests unconfined flows as terminal splays, that represent the distal portion of ephemeral channels or overbank flooding resulting from unconfined flow originated from overtopped adjacent channels (Hampton & Horton, 2007; Scherer *et al.*, 2015). Coarsening- and thickening-upward facies succession can be interpreted as progradation of splay complexes developed downslope of confined channels. (Morozova & Smith, 1999; Spalletti & Piñol, 2005; Hampton & Horton, 2007). The muddy tabular deposits are representing floodplain deposition mainly by decantation of fines after bankfull events. The blocky structure and the root marks suggest pedogenic and plant development over the floodplain deposits (Retallack, 1988).

(C) Aeolian Deposits

(D) Description

The basic lithology composing this facies association is fine- to coarse-grained sandstones with well-sorted and well-rounded quartz grains. Structures observed include small to large scale, cross-bedded sets (St(e), 73.8%), corrugated and crenulated horizontal lamination (Sa(e), 14.7%), low angle and horizontal lamination (Sl(e) and Sh(e), 11.5%) (Fig. 3, Fig. 4). The laminations at a millimeter scale and are sharply defined. This facies association is divided into two architectural elements: aeolian dunes and aeolian sandsheets.

Aeolian dunes and interdunes (AD): The cross-bedded sets (St(e)) are composed of grain flow and wind ripple laminations, being bounded by sharp and sub-horizontal upper and lower surfaces. Individual sets range in thickness from 0.2 to 2.8 m (average of 0.9 m), with multiple sets forming tabular packages of up to 5 m thick. Tabular beds ranging from 0.1 to 1 m thick of crenulated horizontal lamination (Sa(e)) and low angle lamination (Sl(e)) are sometimes recorded between cross-bedded sets.

Aeolian sand sheets (AE): Tabular packages with thickness from 0.15 m to 7.35 m (average thickness 1.35 m) of low angle to horizontally wind ripple laminated sandstones (Sl(e)) and horizontal crenulated adhesion structures (Sa(e)). The limits between these facies are sometimes abrupt and sometimes gradational.

(D) Interpretation

Small to large scale trough cross-bedded sets compounded by grain flow and wind ripple lamination are interpreted as 3D crescent aeolian dunes. The tabular beds of horizontal crenulated adhesion structures or low angle wind rippled lamination between cross sets represent respectively wet and dry interdunes (Mountney & Thompson, 2002; Jones *et al.*, 2016). The tabular packages composed of adhesion structures or low angle wind ripple lamination are interpreted as aeolian sandsheets (Fryberger *et al.*, 1979; Scherer & Lavina, 2005).

(B) Spatial Analysis

(C) Paleocurrents

Paleocurrent data from fluvial channels indicates a general flow direction to SSW from the northern point in Paraná State to Uruguay in the south (Fig. 6 B, B1, C, C1, C2). This pattern indicates that the northern and southern outcrop (Fig. 6 A) belts are oriented almost parallel to the dip direction of the entire system, thereby, the orientation of outcrop belt allows insights into spatial trends for a long distance in the downstream direction. Within the broad SSW direction local variations between west and southeast are presented and are attributed to frequent avulsion of the fluvial channel.

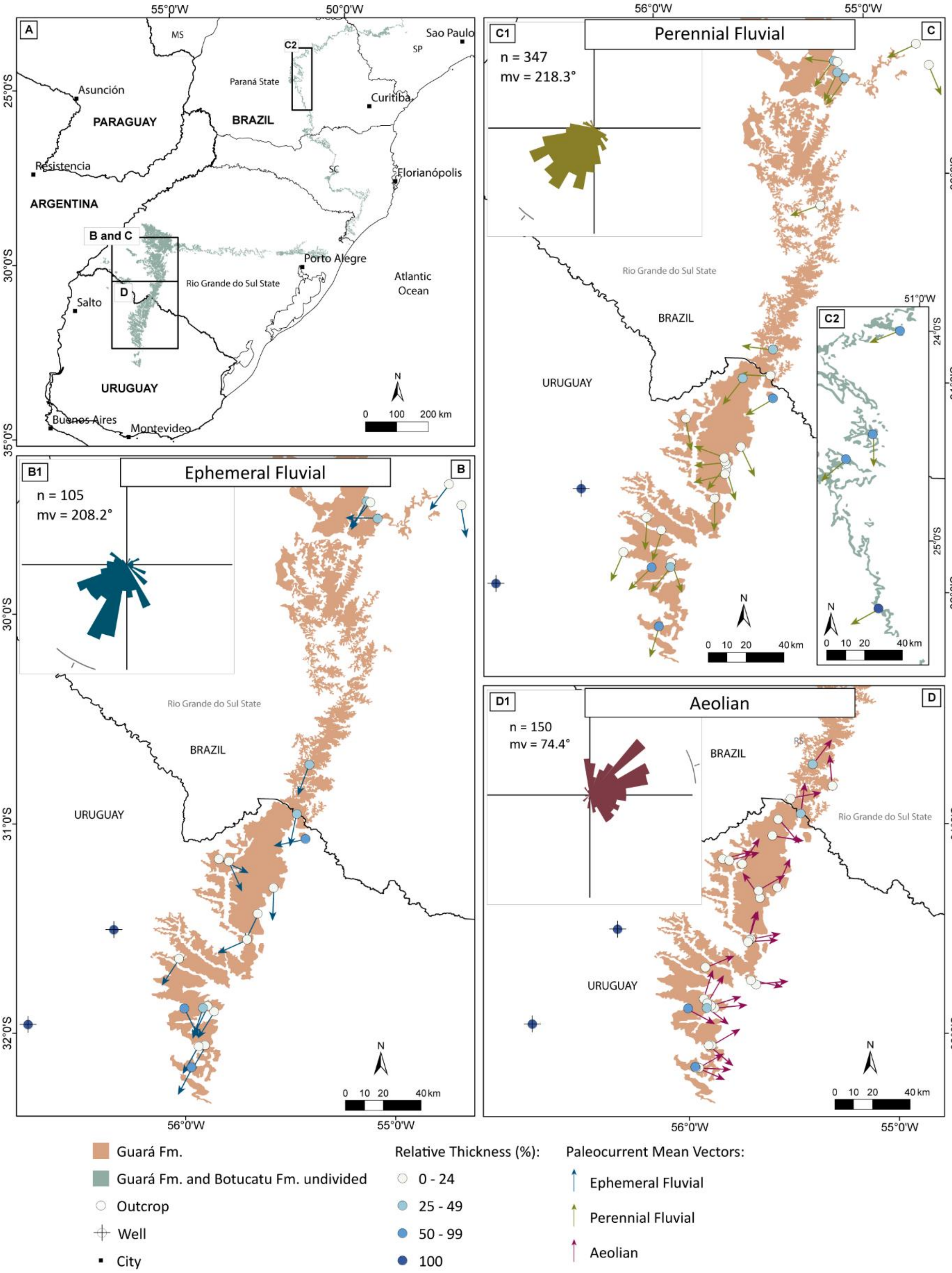

Figure 6. Maps of the paleocurrents distributions separated by facies associations. A) Location of the study areas. B and C) Fluvial facies associations have similar patterns to SSW (B1, C1), while D) aeolian paleoflow are in NE direction (D1).

The distribution of aeolian paleocurrents shows a mean vector to NE with a wide variation of almost 180° (Fig 6 D, D1). This pattern confirms the model of westerly winds that were present in mid latitudes in the west side of Gondwana over the Mesozoic (Scherer & Lavina, 2006; Scherer & Goldberg, 2007). The wide variation of the paleocurrent distribution (almost 180°, Fig. 6) is attributed to the sinuosity of the crestline of crescent dunes.

(C) Guará Formation thickness

The total thickness of Guará Formation is regionally variable across the study area (Fig. 8A). Figure 8A shows the difference between the total thickness to the logged thickness in each location. In the northeastern area (Paraná State) the thinnest sections are present (around 12 m), and the logged thickness is near the total thickness of the formation. Along the NE-SW dip section, the total thickness varies, not following a linear trend. Even when sections are close, the total thickness varies abruptly, as shown between the wells (CAÑADA DEL CHARRUA, 202.30 m thick, and CERRO PADILLA, 174.15 m thick) and the closest outcrops (UY014, 80 m thick; UY055, 80 m thick; and UY061, 70 m thick) (Fig. 8A).

(C) Stratigraphic architecture

The Guará Formation shows downstream differences in architecture. In northeastern region (Paraná State) there is high channel amalgamation of perennial fluvial facies association (Fig. 9, log PR004). In the central to the southern portion of the transect (Rio Grande do Sul State) an alternation between perennial and ephemeral facies associations is present with still a high degree of amalgamation of channels (Fig. 9, log GA002; Fig. 5). The channel amalgamation decreases to the SW, where the channels bodies are interbedded with aeolian and floodplain deposits (Fig. 9, logs UY065, CAÑADA DEL CHARRUA and CERRO PADILLA). The stacking of the deposits does not obey well defined sedimentary cycles of facies associations that can be correlated between the logs, and thus no the regular cyclicity, as suggested in Scherer & Lavina (2005), is observed. Therefore, the facies associations succession does not allow progradational or retrogradational trends at the formation scale. High relief erosive surface cutting fluvial channel bodies was observed around 700 km downstream of the system, in GA002 outcrop, Rio Grande do Sul State (Fig. 5). This surface is steep, with more than 10 m of relief, truncating the channel bodies. The storeys and architectural elements onlap over the surface.

(C) Facies association percentage

The percentage of facies associations varies along the NE-SW dip section. Perennial fluvial facies association is the major facies association present, varying from 95 % to 100 %, in the northeastern portion of the study area (Paraná State, Brazil) with a minor occurrence (5 % in PR010) of floodplain facies association (Fig. 7B, Fig. 8B), until 890 km downstream (near the Brazil-Uruguay border, UY047 log, Fig. 7C, Fig. 8B). From ~890 km the percentage of perennial fluvial decreases, reaching less than 3% of facies recorded in the southern log (CERRO PADILLA well, Fig. 7C, Fig. 8B). The ephemeral fluvial facies association start to appear at 700 km representing around 30% in the GA003 log (Fig. 7C, Fig. 8B). Ephemeral fluvial facies association increases in presence to the south in inverse proportion of perennial fluvial, passing through 38% of ephemeral versus 18% of perennial fluvial in CAÑADA DEL CHARRUA well and reaching 56% versus 2.5% in CERRO PADILLA well (Fig. 7C, Fig. 8B).

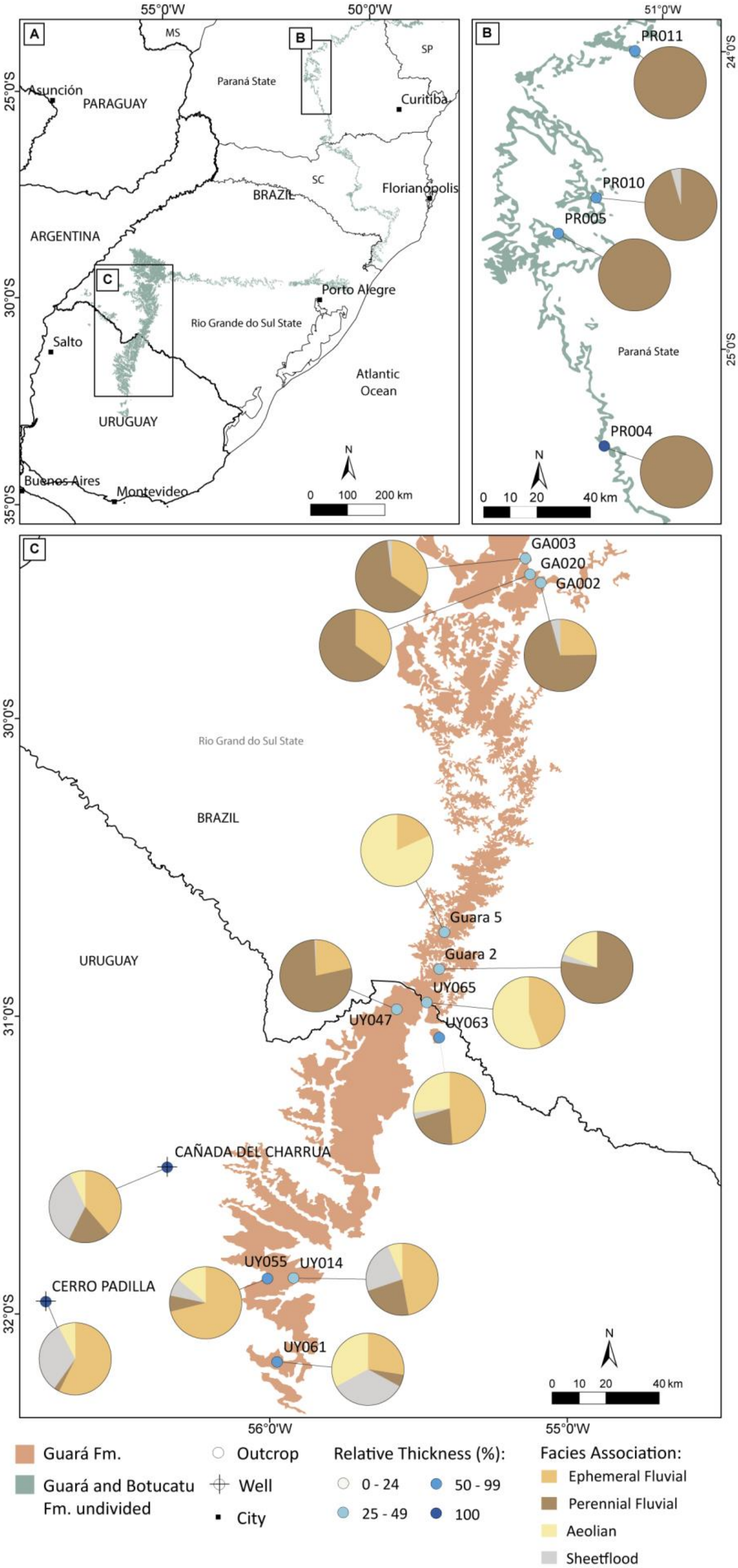

Figure 7. Distribution of the percentage of the facies associations. A) Location of the study areas. B) Paraná State area. C) Rio Grande do Sul and Uruguay area.

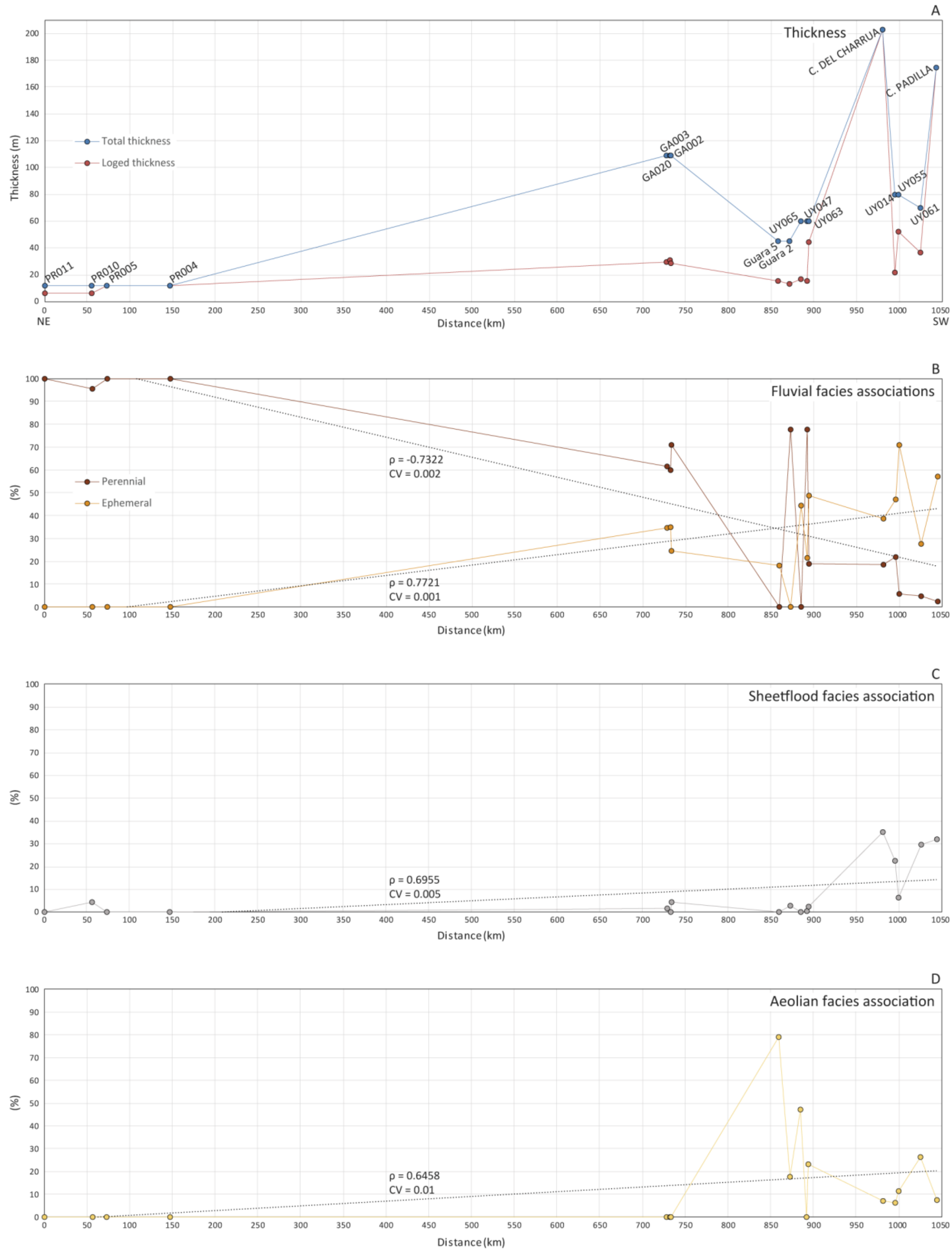

Figure 8. Charts of percentages distributed plotted against distance downstream. A) Comparison of the total thickness of the Guará Formation / Batoví Member and the thickness of each logged section used in quantification. B) Perennial versus ephemeral fluvial facies associations. C) Floodplain facies association. D) Aeolian facies association.

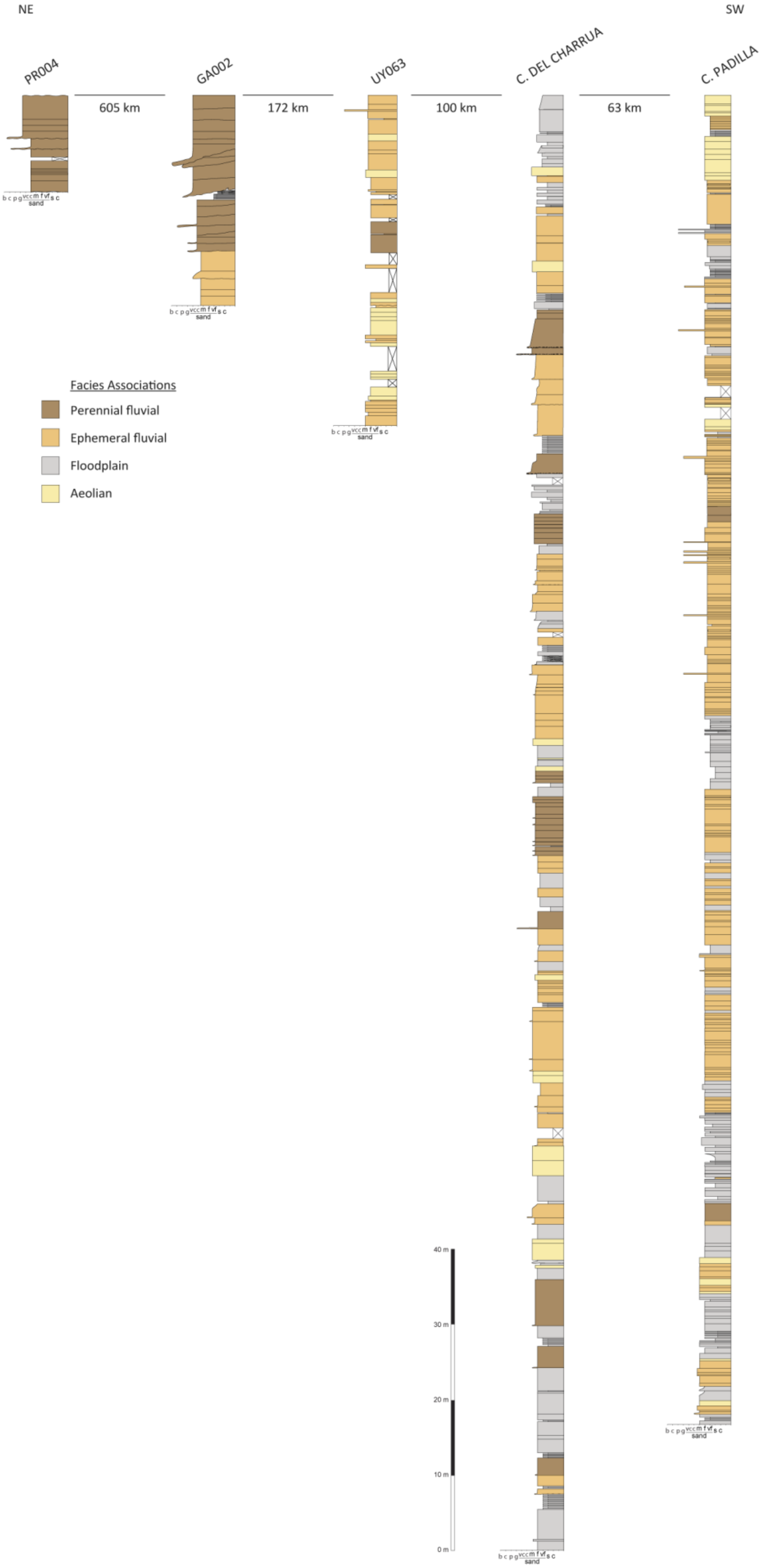

Figure 9. Selected logs exemplifying the lack of vertical stacking patterns of Guará Formation. Location of the logs is in Fig. 7.

Aeolian facies association are most prevalent between 850 and 890 km of distance downstream (17 % to 19%), becoming constant but less present (7 % to 26 %) in the southwest direction (Fig. 7C, Fig. 8D). Floodplain facies appear around 980 km on downstream direction, constituting between 25-30% in the southern portion of the study area (Fig. 7C, Fig. 8C).

(C) Weighted average grain size of fluvial channels

In the northern portion (Paraná State) of the study area, coarse sand dominates. In western Rio Grande do Sul State, medium sand dominates. In the most southern sections (Uruguay) fine sand dominates (Fig. 10, Fig. 11A). The ρ value (0.88, Fig. 11A) indicates a strong fining correlation between distance downstream and grain size, the low CV (0.001, Fig. 11A) demonstrates that this correlation is statistically strong. The distribution suggests a zonation from proximal to distal portions, with downstream grain size reduction from northeast to southwest of Guará System.

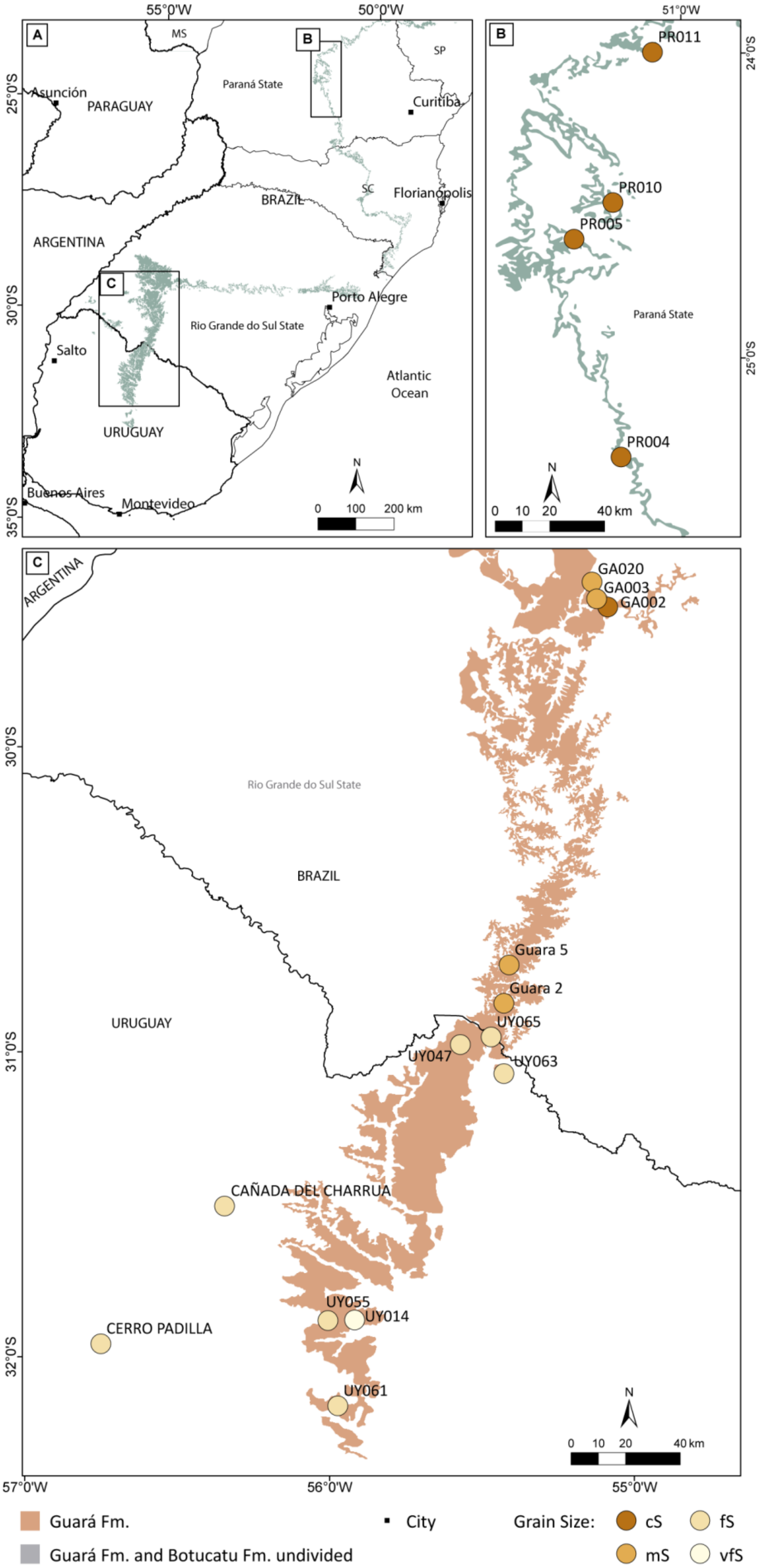

Figure 10. Map of the weighted average grain size of fluvial channels. A) Location of the study areas. B) Paraná State area. C) Rio Grande do Sul and Uruguay area.

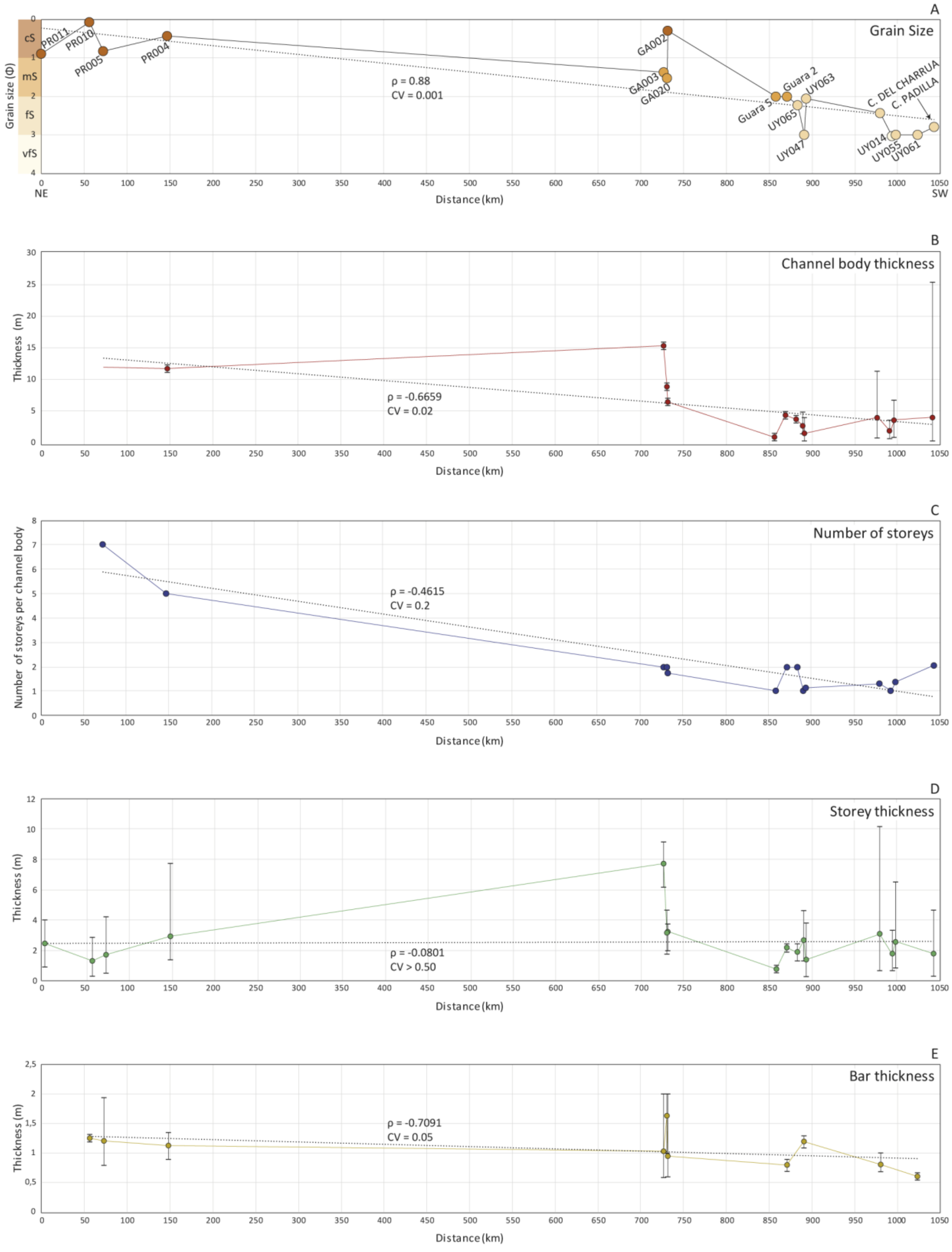

Figure 11. Fluvial features plotted against distance downstream. A) Weighted average grain size of the channel bodies. B) Channel body thickness. C) Number of storeys per channel body. D) Storey thickness. E) Bar thickness.

(C) Channel body thickness

Average channel body thicknesses were only calculated for channel bodies where the base and top boundaries were visible (i.e. total thickness was able to be observed). Along the NE-SW dip section a general decrease in channel body thickness is present, although the correlation is not totally linear, as shown by ρ and CV (Fig. 11B). For the first 750 km the channel bodies have an average thickness of > 6 m, however, in the last third of the section the channel body thickness decreases to < 5 m and these averages are maintained to the most distal locations.

(C) Number of storeys per channel body

The number of storeys decreases downstream from between 5 and 7 in northeastern portion to variations between 1 and 2 in the southern area (Fig. 11C). The trend calculated has a weak negative correlation between the number of storeys per channel body distance (ρ = -0.4615). A CV of 0.2 suggests the correlation is not reliable. This weak correlation could be a result of a random distribution with small variation in the distal portion, a major part of the data. Despite this, it is evident that the number of storeys differs substantially between the proximal and the distal areas, decreasing downstream (Fig. 11C).

(C) Average Storey thickness

The average storey thickness in the Guará system varies from 0.75 m to 3.25 m, with an outlier of 7.65 in GA003 location (Fig. 11D). The variation is distributed randomly along the NE-SW dip section, also demonstrated by a ρ value of -0.0801 and CV > 0.50, indicating that there is no correlation between storey thickness and distance downstream.

(C) Average Bar thickness

The average bar thickness was measured only in perennial fluvial facies association because barforms are not present in ephemeral deposits in Guará Formation. The distribution of bar thickness varies from 0.6 m to 1.25 m with an outlier of 1.64 m, showing no significant or abrupt changes in the size of preserved channels bars along the NE-SW dip section (Fig. 11E). However, ρ (-0.7091) demonstrates that statistically, there is a negative correlation between bar thickness and distance, supported by a reliable CV of 0.05.

(A) DISCUSSION

(B) Depositional model: the Guará Distributive Fluvial System

The facies analysis integrated with the spatial distribution of quantified properties of facies association along a downstream section across the basin suggests the Guará Formation System is the deposit of a distributive fluvial system (DFS) interacting with aeolian dune field, with attributes of a terminal fluvial megafan. Similar interpretations were previously suggested by Amarante *et al.* (2019) and Reis *et al.* (2019).

Due to the nature of the outcrop pattern (i.e. downstream section) the radial pattern of the paleocurrents, characteristic of ancient and modern distributive fluvial systems (Hartley *et al.*, 2010; Weissmann *et al.*, 2010, 2015) cannot be recognised in this study. On the other hand, the analysis of the cross-bedding dip direction distribution allows the quantification of the downstream trends, fundamental to recognise the spatial variations of the distributive fluvial system along the basin, from proximal to distal (Owen *et al.*, 2015). The perennial and ephemeral fluvial facies associations show a paleocurrent general trend to SSW, suggesting that the proximal portions of the Guará distributive fluvial system were located in the Paraná State (Brazil) and the most distal portions found in Uruguayan territory within this study. It is possible that the system extended further south, as the terminal limit of Guará megafan is not precisely determined. However, the increase of aeolian and floodplain deposits in the distal portion suggest the system should not extend much further south than the limit of the study area.

The gradual transition of facies associations distribution from proximal to distal portions suggest a zonation for the Guará system, suitable with facies zonation of distributive fluvial systems (Kelly & Olsen, 1993; Nichols & Fisher, 2007; Cain & Mountney, 2009; Weissmann *et al.*, 2010, 2015; Davidson *et al.*, 2013; Owen *et al.*, 2015). Perennial fluvial facies association is exclusive in the proximal portion and decrease gradually, while ephemeral fluvial deposits appear in the medial to distal zone and increase in presence to the end of the system (Fig. 7, Fig. 8B). This transition coincides with the record of aeolian deposits and the increase in floodplain deposits downstream. It is suggested that only a small portion of the proximal zone of the DFS is present in the study area (four locations in Paraná State); the most distal fringe of the medial zone, where there are only fluvial deposition and the ephemeral fluvial starts to be recorded (GA003, GA020, GA002, western portion of Rio Grande do Sul State); while nearly the entire distal zone is present, where there is variety of facies associations (perennial and ephemeral fluvial, aeolian and floodplain, from the areas close to the Brazil-Uruguay border to the end of the dip section). The distal zone can be further subdivided into areas where non-channel deposits are mainly aeolian and a southern area in which floodplain deposits dominate over aeolian.

The Guará DFS zonation is indicated by the other quantified parameters. The average grain size and the average bar thickness of the fluvial channels decrease linearly downstream. These reductions can be attributed to loss in discharge due to bifurcation of the channel in distributary pattern, infiltration in the substrate and evapotranspiration (Nichols & Fisher, 2007; Weissmann *et al.*, 2010, 2013, 2015), causing a decrease in depth and competence of the fluvial channels downstream. Downstream reduction in grain size is stated by Weissmann *et al.* (2015) as one of the criteria to recognise distributive fluvial system in the rock record. A similar pattern was found in the quantified Salt Wash DFS by Owen *et al.* (2015) as well as in the Huesca System by Hirst (1991). In comparison, tributary river systems tend to not maintain a regular grain size reduction, due to input of different grain sizes from affluent rivers, or yet show an increase in grain size following the rise of discharge expected to downstream (Davidson *et al.*, 2013; Weissmann *et al.*, 2015).

Downstream decreases of both channel body thickness and number of storeys are again features consistent with DFS deposits, suggesting reductions in channel belt width due to bifurcation and lost in discharge from proximal to distal portions of the distributive system. Hartley *et al.* (2010) purpose the reduction of discharge to downstream, resulting in a reduction of channel depth and width of the channels as a definitive characteristic of DFS, arguing that the loss of discharge by evapotranspiration and infiltration along the system cannot be compensated due to the lack of tributaries channels to feed the main channel belt. This argument is contested by Fielding *et al.* (2012) invoking one of the most cited modern DFS, the Kosi Fan to affirm that the discharge and size of the channel are not reducing along the 120 km of that system. However, Weissmann *et al.* (2015) using modern LANDSAT orbital images of Kosi Fan show that although the discharge and channel depth do not decrease downstream, the width and complexity of the Kosi river channel belts constantly reduce from the proximal to distal portions.

Interestingly, storey thickness shows no strong downstream trends (Fig. 11D). However, it is important to note that this may be due to preservation potential in the proximal region. It is well documented that avulsions occur over a small area in the proximal region compared to more distal realms (Owen *et al.*, 2015). It is therefore entirely possible that storey (channel depth) is not regularly preserved upstream, with preservation potential increasing downstream. However, more studies on modern DFS are needed to clarify this. The reduction in channel body thickness and number of storeys alongside an increase in non-channel facies associations is related to a decrease in channel reworking and amalgamation of the fluvial channels, downstream on a distributive fluvial system (Weissmann *et al.*, 2013; Owen *et al.*, 2015).

Paleocurrent pattern and associated facies characteristics from aeolian deposits, indicates the presence of sinuous transversal chains of dunes with NW-SE orientation, and migration in a NE direction. Comparing fluvial and aeolian dune paleocurrent distributions (Fig. 6), in the majority of locations, fluvial and aeolian show opposing directions, suggesting no deflection and reorientation of the channels in the interdune space. This suggest no coalescence between big dunes and fluvial channels, confirming Scherer & Lavina (2005) theory of alternating fluvial and aeolian activity. Exceptions could be made in the southern locations, where the paleocurrents of perennial fluvial and aeolian dunes are perpendicular (Fig. X, B and D). However, the aeolian facies association is less abundant in this region, in comparison with ephemeral fluvial and floodplain (Fig 7, Fig. 8C, D), which points to no causal relationship of this specific paleocurrent distribution.

The facies zonation of the Guará DFS, with a tendency to less channelisation of the fluvial systems, interaction with aeolian systems and occurrence of terminal splays and waning flow deposits in the distal portions points to a terminal DFS, with similarities with some DFS described from the rock record (Kelly & Olsen, 1993; Nichols & Fisher, 2007; Cain & Mountney, 2009). Terminal fans in modern systems are typical of endorheic basin under dry climates (Hartley *et al.*, 2010).

Davidson *et al.* (2013) classify DFS in dryland climates, in which extensive amalgamation is present in the proximal zone due to frequent nodal avulsion, and the distal portion is represented by a termination of the system into an aeolian dune field and terminal splay deposits as *braided bifurcating DFS*. This study shows that Guará DFS has several features of this type of system. The authors suggest that the occurrence of widespread nodal avulsion along the entire system contribute to distinguishing discrete events or series of events in the evolution of the DFS. However, the braided character is not clearly defined in the Guará DFS as river planforms are not easily distinguished in rock record, as pointed by Fielding *et al.* (2018).

Based on the spatial quantification, we divide the Guará DFS into four zones, from proximal to distal regions (Fig. 12):

a. Zone 1: This is the most proximal portion of the system, permanently covered by active and inactive perennial channels. The intense avulsion in which sedimentation rate is high in relation to accommodation produces intense amalgamation generating wide channel belts recorded as multistorey channel bodies and very low preservation of floodplain deposits. Channel belt incision an coarse-grained size is found in this zone.
b. Zone 2: Perennial channel belts start to bifurcate and although intense avulsion is still present, vast areas here remain exposed for a longer time. Intense and episodic flood events promote widespread expansion and unconfinement of channel belts, recording ephemeral fluvial deposits as the aggradation of upper flow tabular sandsheets. The recurrence of perennial and ephemeral fluvial do not allow floodplain preservation, except for lenses of well-drained paleosols over heteroliths. Coarse to medium sand is deposited in this area.
c. Zone 3: High dispersion and bifurcation of the perennial channel belts, recorded through channel bodies with less amalgamated storeys. Larger areas are exposed for more time as the system expands, with some areas reached only occasionally by ephemeral fluvial channels. This allows aeolian reworking and transportation of sandy material to form aeolian sand sheets and the climbing of aeolian dunes. The dry sand source is interrupted by new floods and migration and erosion of fluvial belts. Medium to fine-grained sand dominates this zone.
d. Zone 4: The terminal zone of the DFS. Perennial channels disperse in terminal splays, and only the distal fringes of ephemeral floods reach this zone as fine-grained waning flow deposits, so the fluvial channel bodies are single- or at a maximum two-stories. Aeolian systems are active here too. Only fine and very fine sand is present in the terminal portion of the DFS.

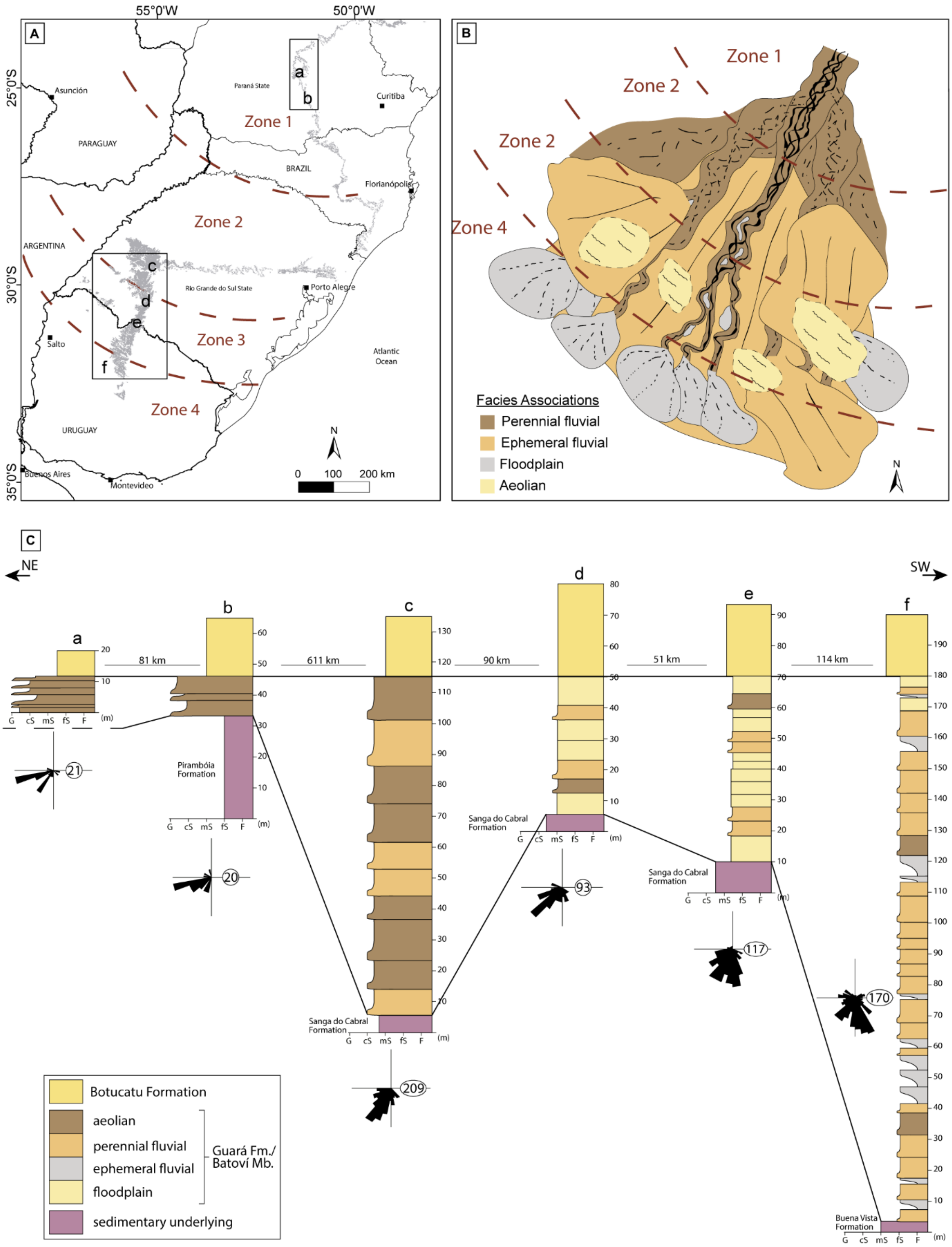

Figure 12. Depositional model of Guará distributive fluvial system. A) Estimated area of the zones in study areas. B) Schematic model of the Guará DFS showing the facies associations relations in each zone. Not to scale. C) Schematic composed logs of different regions in Guará DFS, showing the relative distribution of facies associations, the stratigraphic architecture interpreted and the variations in grain size. Location of the logs is on the map of Fig. 12A.

The occurrence of aeolian deposits in distal zones of terminal fans (DFS) is interpreted by Kelly & Olsen (1993) as a common characteristic of terminal fans with low suspended load of muddy sediments, in which the aeolian deposits replace floodplain fines as the interchannel deposits. Additionally, the aeolian deposits are related to ephemeral fluvial activity, that expose vast areas of the fan, that are only occasionally reached by floods, allowing aeolian reworking (Kelly & Olsen, 1993). Priddy & Clarke (2020) describe a similar setting where the ephemeral fluvial and aeolian activity are related in a system with a lack of mud grade sediments in the Lower Jurassic Kayenta Formation, USA. The authors attribute the lack of mud grade sediments to the reworking of aeolian deposits by the fluvial channels. The little occurrence of muddy sediments is peculiar in Guará Formation. Even in the floodplain facies associations, mud grade sediments account for less than 38% of the facies described (Fig. 7, Fig. 8). In Guará DFS, the aeolian deposits occur concentrated in distal zones (zones 3 and 4, Fig. 12) where the ephemeral fluvial facies association dominates over perennial fluvial. A modern example of DFS with aeolian interaction are in Tarim Basin (China). More than 80 % percent of the actual area of Tarim Basin is covered by aeolian dune fields, but the analysis of LANDSAT images show the traces of fluvial paleochannels over the dunes (Weissmann et al., 2015), probably record of past expansion of the DFS that are present in the southern border of the basin.

The presence of a high relief truncating surface up to 700 km downstream of the system (Fig. 5) is interpreted to be the result of fluvial incision over previous deposits. Incision and the occurrence of perennial fluvial channel in the most distal zones of Guará System, normally reached only by ephemeral fluvial and terminal splays, indicate rearrangements in the DFS river profile generating changes in the distribution of the depositional zones. It suggests advance of the intersection point downstream the system, creating a zone of low accommodation and incision upstream and a zone of aggradation downstream the intersection point (Weissmann *et al.*, 2002). Incision in the proximal portion of a DFS could be caused by climatic-driven discharge fluctuations (Weissmann *et al.*, 2002, 2005; Gibling *et al.*, 2005; Fontana *et al.*, 2008) or tectonic activity (Gawthorpe & Leeder, 2000). Incision promoted by climatic cyclicity is common in modern DFS, such as the Taquari River, Brazil (Assine, 2005; Weissmann *et al.*, 2015) and the western Ganges Plain, India (Gibling *et al.*, 2005; Tandon *et al.*, 2006; Kale, 2007; Roy *et al.*, 2012; Weissmann *et al.*, 2015). Vertical trends in Guará Formation are not observed within logs making it difficult to decipher a tectonic or climatic control. However, the alternations of perennial and ephemeral fluvial and aeolian deposits can suggest high-frequency climatic variations. On the other hand, tectonic controls cannot be discounted, although indirect sedimentologic evidence (e.g., abrupt vertical shifts in the sediment calibre) are absent in Guará Formation.

Interestingly, this study does not recognised vertical trends that suggest extension of Guará Formation, as suggested by Scherer & Lavina (2005). It has been documented that progradational or retrogradational trends can be present in the deposits of DFS (e.g. Cain & Mountney, 2009; Weissmann *et al.*, 2013; Owen *et al.*, 2017; Wang & Plink-Björklund, 2019). Although overall trends are not observed it is possible that high frequency low magnitude climatic variations are present, as suggested by the interfingering of perennial and ephemeral fluvial facies with aeolian deposits (e.g. Zone 3). Owen *et al.* (2017b) and Wang & Plink-Björklund (2019) demonstrated that high stratigraphic complexity can occur in fluvial fan rock record. We purpose that high-frequency variations in discharge that are possibly climatic-driven could cause high erosive events (e.g. incision and changing intensity of avulsion), that complicates the stratigraphic record.

The Guará Formation therefore confidently records one of the largest DFS recorded in both modern and ancient datasets as the minimum extent of the Guará DFS is 1050 km (Fig. 12). This size exceeds the biggest distributive fluvial systems recorded in modern basins, with the Pilcomayo DFS (Bolivian) Chaco basin, having an apex to toe length of ~720 km (Hartley *et al.*, 2010; Weissmann *et al.*, 2010). The longest DFS estimated in the rock record is the Late Jurassic Salt Wash DFS, with ~700 km of extension (Owen *et al.*, 2015). Nonetheless, Latrubesse (2015) estimated that the megafan system to the Miocene Solimões Formation covered an area 7,000,000 km² but the extent from proximal to distal is not known.

The source area for Guará Formation is located at the northeast of the Paraná State outcrops (Brazil). Additionally, the absence of Guará Formation to the north of Paraná State (Reis at al., 2019), suggest these areas, covered by the ancient sequences of Paraná Basin, were exposed to erosion during Upper Jurassic. The homogeneity the quartzarenite composition along the entire formation, the lack of mud grade material and the occurrence of gravel lags of ancient sedimentary rocks clasts reinforce this recycling hypothesis.

This study presents a basin-scale predictive model to reservoir studies on Guará Formation / Batoví Member. Medici *et al.* (2019) study demonstrated that heterogeneity of the reservoir in fluvial-aeolian settings tend to increase downstream, particularly in the non-channel (floodplain and aeolian) deposits. Something similar should happen in Guará DFS system. However, the dominance of aeolian and sandy floodplain in the distal zone of Guará DFS reduces the grade of the heterogeneity between channel and non-channel bodies, sustaining high reservoir connectivity even in distal regions. The Guará DFS model here presented confirms the high potential of Guará Formation / Batoví Member as a good reservoir, especially its groundwater potential as part of the Guarani Aquifer System (Foster *et al.*, 2009; Sindico *et al.*, 2018), since significative accumulation of hydrocarbon are not yet discovered in the Paraná Basin. Reservoir heterogeneity studies in minor scales associating facies and structural frameworks are needed to better understand the internal intra-reservoir properties of Guará Formation / Batoví Member.

(B) Geodynamic setting of Guará Formation

The importance of Upper Jurassic Guará Formation and Batoví Member in Paraná Basin have been highlighted in several paleontological (Mones, 1980; Martinez *et al.*, 1993; Perea *et al.*, 2018, 2001, 2003, 2014; Yanbin *et al.*, 2004; Dentzien-Dias *et al.*, 2008; Soto & Perea, 2008, 2010; Fortier *et al.*, 2011; Soto *et al.*, 2012a; b, 2020; Francischini *et al.*, 2015, 2017; Mesa & Perea, 2015) and sedimentological studies (Scherer & Lavina, 2005, 2006; Soares *et al.*, 2008; Perea *et al.*, 2009; Reis, 2016; Amarante *et al.*, 2019; Reis *et al.*, 2019) in Uruguayan and Brazilian territories. Nonetheless, none of these works tries to explore the geodynamic significance of the Upper Jurassic units. To investigate the tectonic setting of this sedimentation systematic structural and seismostratigraphic analysis is necessary, which is beyond the scope of this work. However, based on our quantified model, we purpose some points to open discussion about tectono-sedimentary relevance of Guará System to Western Gondwana.

Paleocurrent directions and the recycled detrital composition suggest that Guará Formation / Batoví Member records a tectonic inversion of Paraná Basin, with the uplift of the central portion and accommodation creation in the southwestern border of this basin. The depositional model points to deposition in a wide intracratonic basin, related to the break-up of Gondwana (Reis *et al.*, 2019).

The total thickness of Guará Formation shows variations across studied regions (Fig. 8 A). The section shows a general increase of the general thickness to downstream, but this increase is not linear, and thickness varies largely at a local scale in the most distal zone. The deformation responsible for the thickness variation across Guará Formation could have occurred after deposition and consolidation of the Guará Formation. Scherer & Lavina (2006) have pointed out that the far eastern portionof Guará Formation is controlled by a NW-SE fault system. There is an abrupt interruption of the Guará Formation to the east beyond this fault system, where the overlying Botucatu Formation (Early Cretaceous) continues eastward. This suggests that the unconformity between the Late Jurassic Guará Formation and the Early Cretaceous Botucatu Formation records ruptile deformation and erosion (Scherer and Lavina, 2006, Amarante 2019). Rosselo *et al.* (2006, Fig. 6) display a seismic interpretation to the Uruguayan Paraná Basin, where they recognised differences in the thickness of the Juro-Cretacic sandstones attributed to Mesozoic fault activity and erosion.

Recent models incorporating stratigraphic and thermochronologic data (Friedrich *et al.*, 2018; Krob *et al.*, 2020) relate tectonic subsidence and uplift movements in the entire Paraná Basin region to the Paraná-Etendeka plume activity which started around 220 Ma and continued up to the opening of South Atlantic Ocean in lower Cretaceous. These tectonic movements could be the triggers of accommodation creation as the posterior ruptile deformation of Guará Formation deposits. Unfortunately, the stratigraphic charts compiled by Krob *et al.* (2020) are from Milani *et al.* (2007), where the Guará Formation is not formally yet recognised as the depositional record of Upper Jurassic sedimentation in Paraná Basin. This fact highlights the urgent necessity for the revision of the stratigraphic chart of Paraná Basin to include this interval as it is fundamental for new interpretations of the evolution of western Gondwana.

(A) CONCLUSIONS

- The Guará Formation / Batoví Member was deposited by a large terminal megafan, with a minimum length of 1,050 km between the southern Brazil and Uruguay. This system is similar to the braided bifurcating distributive fluvial system of Davidson et al. (2013).
- Four facies associations are recognised in Guará Formation distributive fluvial system (DFS): perennial fluvial, ephemeral fluvial, floodplain and aeolian deposits indicating a dryland climatic regime.
- Quantification of sedimentologic parameters allowed the recognition of spatial trends in NNE-SSW (downstream) direction. Spatial trends suggest

a downstream reduction in channel depth, competence and channelisation of the fluvial deposits, associated with increasing bifurcation, infiltration and evapotranspiration.

- The large Guará DFS is divided into four zones, defined from quantified spatial variations. Perennial fluvial channels dominate zone 1; in zone 2 an alternation of ephemeral and perennial deposits is present, with predominance of perennial; in zone 3 perennial facies decrease while ephemeral facies increase in presence, and aeolian interchannel reworking is significative; and in zone 4 ephemeral fluvial dominate with associated floodplain facies also present.
- The stratigraphic complexity of the Guará Formation suggests high-frequency fluctuation in discharge causing recurrent expansion and retreat of DFS zones, transferring the intersection point downstream resulting in fluvial incision and erosion. This fluctuation in discharge is attributed to cyclic climatic variations affecting the southwestern Gondwana in Upper Jurassic.
- The creation of accommodation for the deposition of the Guará Formation / Batoví Member and the later deformation and erosion of the unit, indicated by local thickness variations, are attributed to the tectonic influence of the Paraná-Etendeka plume in the Paraná Basin region during the Upper Jurassic-Lower Cretaceous.

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