UNIVERSIDADE ESTADUAL DE CAMPINAS

INSTITUTO DE GEOCIÊNCIAS

MARCUS VINÍCIUS THEODORO SOARES

# ARQUITETURA DEPOSICIONAL E DINÂMICA DE SISTEMAS FLUVIAIS DE AMBIENTE SEMI-ÁRIDO: O GRUPO BAURU NO TRIÂNGULO MINEIRO (CRETÁCEO SUPERIOR)

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**ORIENTADOR: PROF. DR. GIORGIO BASILICI**

**CO-ORIENTADOR: PROF. DR. THIAGO DA SILVA MARINHO**

ESTE EXEMPLAR CORRESPONDE À VERSÃO FINAL DA DISSERTAÇÃO DEFENDIDA PELO ALUNO MARCUS VINÍCIUS THEODORO SOARES E ORIENTADO PELO PROF. DR. GIORGIO BASILICI

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Aprovado em: 22 / 02 / 2018

**EXAMINADORES**:

Prof. Dr. Giorgio Basilici - Presidente

Prof. Dr. Alexandre Campane Vidal

Prof. Dr. Renato Paes de Almeida

***A Ata de Defesa assinada pelos membros da Comissão Examinadora, consta no processo de vida acadêmica do aluno.***

Campinas, 22 de fevereiro de 2018.

*Aos meus pais, Sonia e Marco,*

*à minha avó Olga,*

*pelo amor incondicional.*

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*“Science and everyday life cannot and should not be separated”*

* ROSALIND FRANKLIN

# BIOGRAFIA

## Marcus Vinícius Theodoro Soares

Bacharel em Geologia (2016) e Mestre (2018) em Geociências, Área de Geologia e Recursos Naturais, pela Universidade Estadual de Campinas, UNICAMP.

Foi bolsista junto ao Programa Institucional de Bolsas de Iniciação Científica - PIBIC/CNPq (2011-2012) na área de Geomorfologia Costeira. Em 2014 participou como bolsista do Programa Ciências sem Fronteiras na modalidade Graduação-Sanduíche na Inglaterra, vinculado ao curso de Geologia pela School of Earth Sciences - University of Bristol em nível acadêmico Bachelors Degrees with Honours. Foi contemplado com a bolsa Subaru Minority Student, concedida pela Geological Society of America - GSA por mérito acadêmico (2014).

Em seu mestrado (Fapesp 2016/06968-5), atuou com enfoque na arquitetura deposicional e dinâmica de sistemas fluviais distributivos áridos do Cretáceo Superior, Bacia Bauru. Em 2016 realizou estágio de pesquisa no Geological Studies Unit - Indian Statistical Institute, em Calcuta, Índia (Bolsa VRERI-BRICS) com enfoque na análise de sistemas áridos Proterozóicos. Iniciou seu doutorado em Geociências em 2018 pela Universidade Estadual de Campinas, focando na inter-relação entre sedimentação e pedogênese de sistemas fluviais distributivos áridos modernos e antigos.

Tem experiência na área de Sedimentologia e Estratigrafia, atuando principalmente na reconstrução da arquitetura deposicional e paleohidrologia de sistemas fluviais distributivos.

## RESUMO

Modelos de fácies empregados no entendimento de depósitos fluviais são atualmente construídos sobre uma perspectiva uniformitarista. Através desta perspectiva, rios tributários modernos, localizados em bacias sedimentares de baixo potencial de preservação, predominantemente de regiões úmidas, são utilizados como análogos para a compreensão de antigos sistemas fluviais. Tal abordagem estabelece um arcabouço empírico-teórico deficitário para o entendimento de antigos sistemas fluviais áridos e semi-áridos, negligenciando a elevada complexidade e variabilidade espaço-temporal associadas a estes sistemas, por consequência fornecendo modelos pouco precisos na organização do arranjo estratigráfico resultante. Pesquisas recentes realizadas em mais de 700 bacias sedimentares continentais modernas demonstram que a totalidade das bacias analisadas, endorréicas ou exorréicas, são compostas predominantemente por sistemas aluviais e fluviais distributários. Dessa maneira, a atual aplicação de modelos deposicionais uniformitarísticos, baseada principalmente em sistemas fluviais tributários e em bacias não-agradacionais, limita o entendimento de arquitetura de fácies no registro geológico. A margem nordeste da Bacia Bauru abriga depósitos fluviais desenvolvidos sobre contexto climático árido a semi-árido durante o Cretáceo Superior (Grupo Bauru). Estes depósitos oferecem as condições ideais para o desenvolvimento de sistemas fluviais distributários. Desta forma, este trabalho aplica o modelo de sistema fluvial distributário para explicar a organização estratigráfica e reconstruir o ambiente deposicional destes depósitos fluviais, priorizando os fatores controladores na dinâmica temporal e espacial de alta frequência observados nestes depósitos.

**Palavras-chave:** *sistemas fluviais distributários; semi-árido; paleohidrologia; Cretáceo Superior; Bacia Bauru.*

## ABSTRACT

Fluvial deposits are currently studied through a uniformitaristic facies model approach. This perspective considers modern tributaries, located in non-aggrading, humid settings as analogues for understanding ancient fluvial systems. The method stablishes insufficient empirical and theoretical background to the study of dryland (arid and semi-arid) fluvial systems, neglecting their highly complex spatio-temporal variability, consequently offering innacurate models for their stratigraphic framework. Current studies conducted on more than seven hundred modern continental sedimentary basins demonstrated that the totality of the analysed basins, endohreic or exohreic, are composed predominantly by alluvial and fluvial distributary systems. Consequently, current application of uniformitaristic depositional models, based primarily on tributary, non-aggrading basins, restricts the comprehension of facies architecture of fluvial succession in the geologic record. The northeastern margin of the Bauru Basin hosts fluvial deposits developed under dryland settings during the Upper Cretaceous (Bauru Group). The setting under which the deposits were formed offer ideal conditions to the development of distributary fluvial systems. Therefore, this work applies the distributary fluvial system model to explain the stratigraphic organization and reconstruct the depositional environment of the fluvial deposits, prioritizing the controlling factors on the high-frequency temporal and spatial dynamics observed in the ancient system.

**Keywords:** *distributary fluvial system; semi-arid; palaeohydrology; Upper Cretaceous; Bauru Basin.*

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## SUMÁRIO

# 1. INTRODUÇÃO E JUSTIFICATIVA

Estudos modernos em sedimentologia fluvial tiveram início em 1950, focados *a priori* no desenvolvimento de barras de pontal e na construção de ciclos de granodecrescência ascendentes, posteriormente aprimorados com o estabelecimento do modelo de fácies desenvolvido por Miall (1996). Por consequência da expansão da indústria do petróleo, modelos fluviais baseados em arquitetura deposicional contribuíram significativamente para o entendimento de depósitos fluviais em escala de afloramento (Miall, 2014). Atualmente, modelos de fácies empregados no entendimento de depósitos fluviais são construídos sobre uma perspectiva uniformitarista. Através desta perspectiva, rios tributários modernos, localizados em bacias sedimentares de baixo potencial de preservação, predominantemente de regiões úmidas, são utilizados como análogos para a compreensão de antigos sistemas fluviais (Bridge, 2006). Tal abordagem estabelece um arcabouço empírico-teórico deficitário para o entendimento de antigos sistemas fluviais áridos e semi-áridos, negligenciando a elevada complexidade e variabilidade espaço-temporal associadas a estes sistemas, por consequência fornecendo modelos pouco precisos na organização do arranjo estratigráfico resultante.

Friend (1978) foi pioneiro ao mencionar sistemas fluviais antigos cujas características observadas não se enquadravam em modelos uniformitaristas. Três características principais foram associadas a estes sistemas: (i) diminuição de espessura dos canais a jusante, (ii) ausência de incisões na superfície aluvial e (iii) arranjo estratigráfico do sistema fluvial organizado em geometria convexa para cima. Tais depósitos foram associados a sistemas fluviais distributivos desenvolvidos em ambientes áridos e semi-áridos, com dezenas de quilômetros de raio, denominados leques fluviais terminais (*terminal fluvial fans*). Variações deste modelo foram posteriormente aplicadas (Tunbridge, 1984; Olsen, 1987) e organizados em um modelo genérico através de comparações com análogos modernos das planícies fluviais Indo-Gangéicas (Mukerji, 1976; Parkash et al. 1983) e porções terminais do Rio Gash, no Sudão (Abdullatif, 1989). O modelo abrangia uma rede distributiva de canais simultaneamente ativos com diminuição de dimensão a jusante, progressivamente perdendo vazão hidráulica por evaporação e infiltração em razão do contexto climático árido a semi-árido (Kelly e Olsen, 1993). Devido à ausência de análogos modernos, este modelo foi considerado insuficiente (North e Warwick, 2007), sendo *a posteriori* modificado e refinado em dois modelos complementares. Nichols e Fisher (2007) introduziram o conceito de sistemas fluviais distributários (*distributary fluvial system*) enquanto Sáez et al. (2007) apresentaram um modelo de lobos terminais (*terminal lobes*).

O conceito de sistema fluvial distributário assume uma rede de canais que revelam progressiva perda em vazão hidráulica a jusante (*downstream*). Rios bifurcam em uma complexa rede de canais de menores dimensões culminando em um setor terminal descanalizado (Nichols e Fisher, 2007). Condições para o estabelecimento desta lógica hidráulica são associadas a drenagens endorréicas próximas a regiões mais elevadas em margens de bacia sedimentar. Estudo recente conduzido por Weissmann et al. (2010), em mais de setecentas bacias sedimentares continentais modernas, demonstrou que o registro geológico é composto predominantemente por sistemas fluviais distributários. Consequentemente, o modelo de fácies fluvial alicerçado sobre o princípio do uniformitarismo em rios tributários úmidos propaga um entendimento impreciso da arquitetura de depósitos fluviais presentes no registro geológico.

A margem nordeste da Bacia Bauru abriga depósitos fluviais desenvolvidos sobre contexto climático árido a semi-árido durante o Cretáceo Superior (Formação Marília, Grupo Bauru). Estes depósitos refletem as condições ideais para o desenvolvimento de sistemas fluviais distributários (drenagem endorréicas em climas áridos a semi-áridos, próximos a regiões elevadas). Desta forma, este trabalho é fundamentado na aplicação do modelo de sistema fluvial distributário para explicar a organização estratigráfica e reconstruir o ambiente deposicional destes depósitos fluviais, priorizando os fatores controladores da dinâmica temporal e lateral de alta frequência observados nestes depósitos.

# 2. CONTEXTUALIZAÇÃO REGIONAL

## 2.1. Generalidades da Bacia Bauru

A Bacia Bauru é caracteriza como bacia intracratônica, cuja gênese e evolução são atribuídas ao Cretáceo Superior (Coniaciano-Maastrichtiano). As datações relativas foram obtidas a partir de considerações bioestratigráficas (Dias-Brito et al., 2001) e intrusões ígneas alojadas às margens da bacia sedimentar (Coutinho et al., 1982). A formação da Bacia Bauru ocorreu numa área geográfica denominada “Zona do Cinturão Quente e Árido Sul” (Chumakov, 1995), que abrigou ambientes áridos e semi-áridos (Fernandes e Ribeiro, 2015). A bacia é preenchida por depósitos siliciclásticos areníticos, abrangendo uma área de 370.000 $km^2$ entre os estados de São Paulo, Paraná, Minas Gerais, Mato Grosso do Sul e Goiás e possui forma elíptica e assimétrica (Fig. 1).

A sedimentação da Bacia Bauru teve início durante a separação do Supercontinente Gondwana e abertura do proto-oceano Atlântico Sul, marcando o fim da sedimentação da Bacia do Paraná (Milani et al., 2007). Desta forma, a Supersequência Bauru (Cretáceo superior) se desenvolveu sobre os derrames basálticos da Formação Serra Geral, fruto do episódio de extravasamento intracontinental do Jurássico Superior, denominada Província Magmática Continental do Paraná-Etendeka.

A sucessão sedimentar da Bacia Bauru é separada por um contato localmente marcado por depósitos brechóides dos basaltos da Formação Serra Geral. Sua espessura alcança aproximativamente 400 m (Fernandes e Ribeiro, 2015) e é dividida em dois grupos (Caiuá e Bauru) (Fig. 2), depositados de forma cronocorrelata em contexto climático árido e semi-árido, segundo Fernandes e Ribeiro (2015), ou sobrepostos segundo Batezelli (2015).

A sucessão sedimentar do Grupo Caiuá é constituída por um complexo de dunas eólicas de cristas sinuosas (*draas*) desenvolvidas em zona central de um mar de areia (*sand sea*) (Formação Rio Paraná), cercado por depósitos periféricos de dunas eólicas de cristas sinuosas e interdunas úmidas e molhadas (Formação Goiô Erê), e planícies de lençóis de areia (*aeolian sand sheet)* estabelecidos sobre zona marginal (Formação Santo Anastácio) (Fernandes e Ribeiro (2015).

Na literatura, o Grupo Bauru apresenta relativa flexibilidade interpretativa quanto aos ambientes e processos sedimentares associados. Segundo Fernandes e Ribeiro (2015), a Formação Araçatuba corresponde a depósitos de pântanos, a Formação Vale do Rio do Peixe e o Membro Echaporã, pertencente à Formação Marília, compõem depósitos de lençóis de areia (*aeolian sand sheet*) e os membros Ponte Alta e Serra da Galga teriam sido depositados na zona distal de sistemas de leques aluviais. Contudo, segundo Batezelli (2015), a Formação Araçatuba é interpretada como sistemas lacustres, as formações Adamantina e Uberaba como sistemas fluviais e a Formação Marília como depósitos de leques aluviais (Fig. 2).

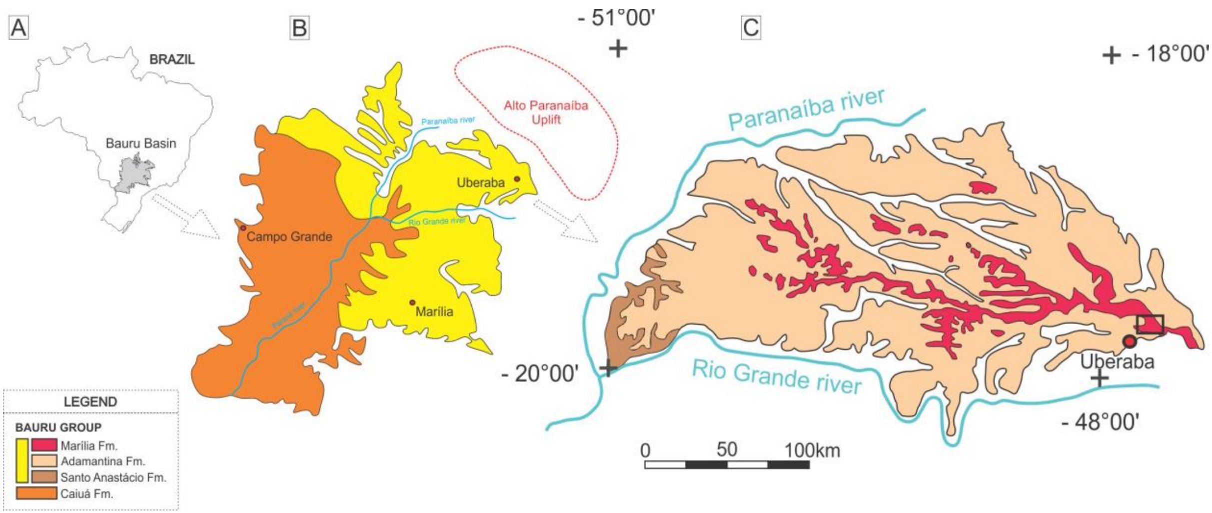


**Figura 1:** [A] Localização e [B] litoestratigrafia da Bacia Bauru. [C] Mapa Litoestratigráfico da Bacia Bauru no Triângulo Mineiro com detalhe para a área de estudo. (Modificado de Fernandes e Ribeiro, 2015).

## 2.2. Contextualização geológica e litoestratigráfica no Triângulo Mineiro

Devido à localização na borda da Bacia Bauru, a região do Triângulo Mineiro é marcada por reativações de diversas estruturas do embasamento Pré-Cambriano, responsáveis por intensos magmatismos alcalinos na forma de *plugs* vulcânicos, cuja concentração ao longo destas zonas de reativação deu origem ao principal alto estrutural observado no Triângulo Mineiro: o Soerguimento do Alto Paranaíba (Hasui et al., 1975) (Fig. 1B). Outras importantes estruturas que influenciaram a evolução geológica do Triângulo Mineiro são: a Sutura de Itumbiara e a Flexura de Goiânia, esta última delimitando a porção norte e nordeste da Bacia do Paraná (Pereira e Silva, 2014). Simultaneamente à formação dos altos estruturais, houve a formação da Depressão da Bacia Bauru (Hasui, 1990), a qual abrigaria os depósitos do grupo de mesmo nome, por volta de 85 Ma, depois de cessadas as últimas manifestações do magmatismo Serra Geral em 133 Ma (Fernandes, 2004).

No Triângulo Mineiro o Grupo Bauru é assentado sobre os basaltos da Formação Serra Geral, os arenitos da Formação Botucatu e as rochas do embasamento Pré-Cambriano (Etchebehere, 1988). Nesta área, o Grupo Bauru é composto pelas formações Adamantina, Uberaba e Marília (de forma ascendente), sendo a última subdividida entre os membros Ponte Alta, Serra da Galga e Echaporã (Fernandes e Ribeiro, 2015) (Fig. 1C).

A Formação Adamantina, depositada durante o Turoniano-Santoniano (Dias-Brito et al., 2001), apresenta espessura máxima aproximada de 200 m em contato erosivo com os basaltos da Formação Serra Geral, recobrindo a maior parte do Triângulo Mineiro. Esta unidade é composta por sedimentos eólicos, constituídos por arenito muito fino, bem selecionado de aspecto maciço e ainda com estratificações cruzadas acanaladas, associadas a laminações plano-paralelas incipientes (Etchebehere, 1988).

A Formação Uberaba ocorre restrita ao entorno da cidade homônima e passa lateralmente de forma interdigitada à Formação Adamantina. A Formação Uberaba é concentrada entre o Coniaciano e Santoniano (Dias-Brito et al., 2001). Sua espessura máxima alcança 140 m, apresentando nível conglomerático basal, arenitos médios a finos, siltitos e argilitos, além de nódulos e concreções carbonáticas (Etchebehere, 1988). Esta formação sobrepõe de forma discordante os basaltos da Formação Serra Geral, os arenitos da Formação Botucatu, o embasamento Pré-Cambriano e as rochas alcalinas cretáceas (Etchebehere, 1988).

A unidade mais nova do Grupo Bauru, a Formação Marília, é subdividida entre os membros Ponte Alta e Serra da Galga, possui idade Maastrichtiano Superior (Dias-Brito et al., 2001) e espessura aproximada de 180 m (Fernandes e Coimbra, 1996). O contato com a Formação Adamantina ocorre de forma interdigitada (Etchebehere, 1988). O Membro Ponte Alta é composto por arenitos grossos e conglomeráticos com cimentação calcítica. O Membro Serra da Galga, por sua vez, é composto por arenitos imaturos e conglomerados (Etchebehere, 1988). Os membros ocorrem complexamente associados e se diferenciam pelo grau de cimentação carbonática de origem freática (Fernandes e Ribeiro, 2015). Na literatura, são interpretados segundo os autores *op. cit.* como depósitos de leques aluviais associados a sistemas fluviais e ainda depósitos de esporádicos fluxos de elevada densidade.

Na região, o Grupo Bauru abriga um das biotas continentais brasileiras mais ricas do Cretáceo Superior, somando 73 *taxa*, incluindo vertebrados e invertebrados, mais expressivamente dinossauros, e de forma subordinada: quelônios, peixes, anfíbios, moluscos, crustáceos e plantas. O grupo na região apresenta idade constrita entre o Turoniano e o Maastrichtiano tardio (Candeiro, 2007).

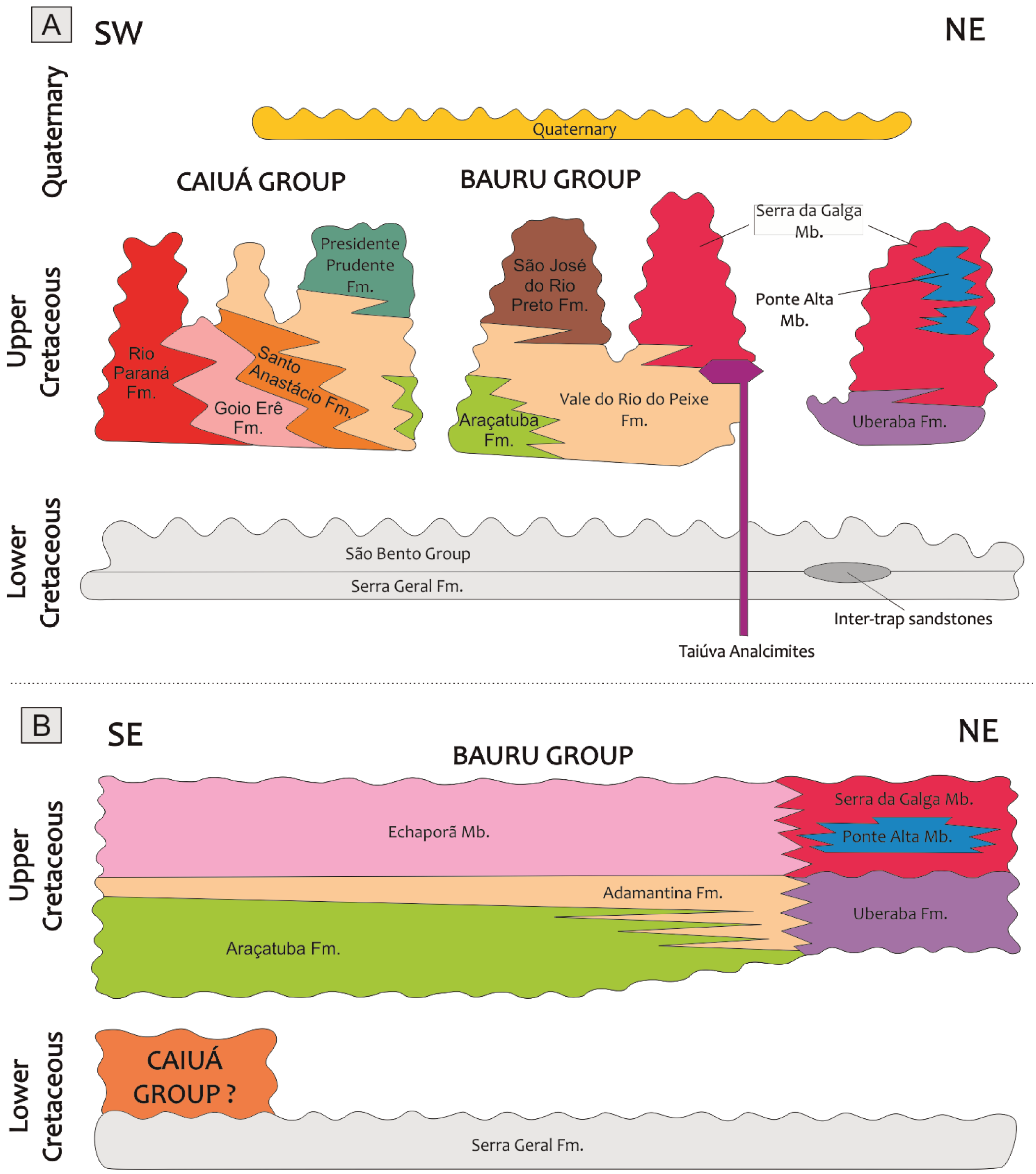


**Figura 2:** Diagrama comparativo da litoestratigrafia da Bacia Bauru modificado de [A] Fernandes e Ribeiro (2015) e [B] Batezelli (2015).

# 3. ESTADO DA ARTE: SISTEMAS FLUVIAIS ÁRIDOS

Observa-se uma dicotomia entre os padrões fluviais modernos e aqueles observados no registro estratigráfico. Estudos contemporâneos de sistemas fluviais são baseados em modelos de fácies a partir de rios tributários modernos alojados em bacias de baixo potencial de preservação (Bridge, 2006). Todavia, pesquisas recentes realizadas em mais de setecentas bacias sedimentares continentais modernas (Weissmann et. al, 2010) demonstram que a totalidade das bacias analisadas, endorréicas ou exorréicas, são compostas predominantemente por sistemas fluviais distributários. Dessa maneira, a atual aplicação de modelos deposicionais uniformitaristas, baseada principalmente em sistemas fluviais tributários de bacias não-agradacionais, limita o entendimento de arquitetura de fácies no registro geológico.

Modelos conceituais baseados em sistemas fluviais distributários não possuem análogos atuais completos e são espelhados em bacias endorréicas de clima árido e semi-árido adjacentes a altos estruturais com maior precipitação (Nichols e Fisher, 2007). Tais modelos são embasados acima de rios cuja dinâmica revela diminuição de aporte em sentido jusante com transições entre zonas proximal, intermediária e distal, ao longo das quais se constata: (1) diminuição na dimensão dos canais, (2) diminuição de granulometria nos sedimentos e (3) consequente aumento de fluxos não canalizados, culminando em um complexo de espraiamentos terminais em zona distal (Nichols e Fisher, 2007). Segundo estes autores, modelos de fácies em escala de bacia tendem a se concentrar em sistemas terminais em bacias endorréicas, dentre eles sistemas fluviais distributários (*distributary fluvial systems*) (Fig. 3).

Tais sistemas são baseados em análogos com ambientes modernos de sistemas fluviais das planícies Indo-Gangeicas do leque Markanda, Índia (Mukerji, 1976; Parkash et al. 1983), e ainda a porção terminal do rio Gash, Sudão (Abdullatif, 1989). O reconhecimento de sistemas fluviais distributários é baseado na identificação de uma série de alterações nas características das fácies que indiquem diminuição a jusante em: vazão hídrica, dimensões dos canais, fluxos canalizados, bem como aumento em fluxos não canalizados (*sheetflood)*, e ainda bifurcação de canais e ocorrência de depósitos eólicos ou de *playa-lake* (Cain e Mountney, 2009).

Análogos atuais para esses sistemas têm sido desenvolvidos em rios de zonas áridas e semi-áridas dos desertos australianos (Tooth, 1999), israelenses (Schick, 1993) e do sul da África (Tooth e Nanson, 1995). A literatura recente prioriza a caracterização destes sistemas segundo a dinâmica hidráulica, nos quais o controle de aporte hídrico é dominado pela precipitação, considerada altamente variável no tempo e no espaço, bem como pela dimensão das bacias de drenagem (Tooth, 2000). Fluxos normalmente ocorrem na forma de rápidas inundações (*flash floods)*, desencadeadas por chuvas com picos isolados, múltiplos ou sazonais (Graf, 1988). Embora rios de zonas áridas apresentem natureza efêmera, frequentemente relacionada a episódios isolados de elevada pluviosidade, eles são capazes de assumir natureza intermitente a perene se associados a chuvas sazonais ou ainda se alimentados por bacias hidrográficas fora da zona árida (rios alogenéticos) (Tooth, 2000).

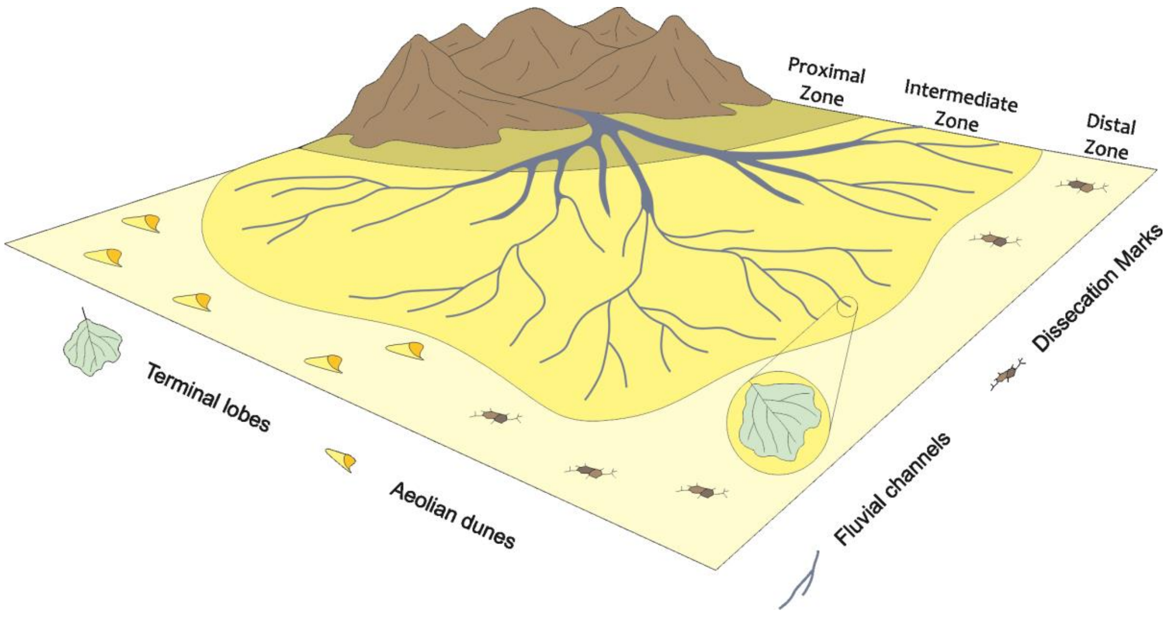


**Figura 3:** Modelo de sistema fluvial distributário estruturado em zonas proximal, intermediária e distal, segundo o modelo de Nichols e Fischer, 2007 (Modificado de Cain e Mountney, 2009).

Em consequência da dinâmica fluvial de elevada variabilidade espaço-temporal, regiões áridas são dominadas por ciclos episódicos de grandes inundações. Se somarmos essa característica ao fato dos canais serem compostos por bancos de sedimentos arenosos e vegetação esparsa, conclui-se que canais de sistemas áridos são altamente susceptíveis ao poder erosivo de inundações episódicas (Tooth, 2000), fenômenos que obrigam a constante readaptação dos canais frente às mudanças hidráulicas. Nesse sentido, rios desenvolvidos em contextos áridos e semi-áridos são caracterizados por elevada *sensibilidade*, termo amplamente empregado na literatura de geomorfologia fluvial relacionado à capacidade dos canais em readaptar sua morfologia frente a mudanças hidráulicas.

Embora exista um crescente desenvolvimento de pesquisas orientadas ao estudo de sistemas fluviais distributários de ambiente árido e semi-árido, diversas lacunas permanecem. O estado da arte em sistemas fluviais distributários é predominantemente fundamentado sobre a distribuição *downstream* de elementos arquiteturais, controlada pela dispersão radial de canais a partir das margens da bacia sedimentar. Esta abordagem foca na distribuição lateral de fácies e elementos arquiteturais ao longo da rede de canais fluviais, negligenciando importantes variações temporais e a organização vertical de elementos arquiteturais, bem como os fatores de controle.

# 4 . OBJETIVOS

## 4.1 Objetivo primário

O principal objetivo desta pesquisa é definir a arquitetura deposicional e a dinâmica do sistema fluvial do Membro Serra da Galga na região do Triângulo Mineiro, priorizando a organização vertical de fácies e elementos arquiteturais do sistema fluvial distributário bem como os fatores de controle da dinâmica temporal do sistema.

## 4.2 Objetivos secundários

i. Aquisição de um novo banco de dados de caráter sedimentar, estratigráfico e paleopedológico para o membro selecionado;

ii. Organização sequencial e descrição dos sedimentos, interpretação dos processos deposicionais e dos fatores de controle e definição das características estratigráficas do Membro Serra da Galga;

# 5. MATERIAIS E MÉTODOS

A pesquisa foi organizada em três etapas de elaboração: (i) análise de sedimentos, (ii) análise de paleossolos e (iii) integração dos dados de sedimentos e paleossolos.

## 5.1 Análise de sedimentos

### 5.1.1 Aquisição de dados em campo

Na região do Triângulo Mineiro, o Membro Serra da Galga exibe frequentes variações verticais e laterais, o que obriga uma análise bidimensional dos corpos sedimentares. A aquisição de dados sedimentológicos em campo foi conduzida através das seguintes etapas:

1. **Seleção de afloramentos adequados:** Inicialmente foram estabelecidos os afloramentos mais adequados à análise sedimentológica segundo a exposição, os tipos de rochas, a dimensão, a espessura, o grau de preservação dos litotipos e a correlação espacial entre os afloramentos.
2. **Descrição das fácies:** As fácies foram descritas através da análise dos seguintes atributos físicos: litologia, granulometria, seleção, trama (*fabric)*, aspectos petrográficos, espessura, geometria, tipos de contato e desenvolvimento horizontal das camadas, estruturas sedimentares, indicadores de paleocorrentes e bioturbações.
3. **Documentação fotográfica e construção de fotomosaicos:** Os afloramentos previamente selecionados foram documentados por meio de fotografias de alta resolução ($\geq$14 megapixels) obtidas a distâncias compatíveis com a observação das superfícies limitantes de menor ordem. O objetivo da documentação fotográfica foi promover as bases para análise por hierarquia de superfícies limitantes dos depósitos selecionados.
4. **Análise e hierarquização de superfícies de descontinuidade:** Sobre as imagens obtidas na etapa anterior foram gerados croquis com a identificação das principais fácies e superfícies de descontinuidade, observando suas relações de contato. Um segundo momento foi dedicado à hierarquização das superfícies,

iniciado sempre das superfícies de menor ordem (1ª e 2ª ordens) para as superfícies de maior ordem (4ª e 5ª ordens). Estas últimas frequentemente ocorrem no Membro Serra da Galga como superfícies erosivas ou paleopedológicas e funcionam como robustos indicadores estratigráficos na correlação espacial entre os afloramentos.

5. **Medição das direções de paleocorrentes:** As principais medições de paleocorrentes foram fornecidas por estratificações cruzadas acanaladas ou tabulares. Entretanto, quando não disponíveis, foram utilizados outros indicadores de paleocorrentes como marcas de corrente (*current ripples*) e imbricamento de seixos.
6. **Identificação de elementos arquiteturais e macroformas:** A sucessão fluvial hierarquizada na etapa 4 foi analisada, segundo os princípios de Miall (1985), de forma a identificar e descrever dimensão, geometria, razão largura/espessura e relações de contato dos corpos sedimentares, identificando os elementos arquiteturais que compõem a sucessão fluvial. A relação entre direção de paleocorrente e direção de mergulho das superfícies de descontinuidade foi utilizada para auxiliar na definição das macroformas que constituem o depósito.
7. **Amostragem:** Como etapa final da atividade de campo, amostras de sedimentos das fácies descritas foram coletadas para análise textural e mineralógica em lupa binocular.

### 5.1.2 Aquisição de dados em laboratório

Os sedimentos de origem fluvial dos depósitos estudados revelam baixa maturidade química, com presença de feldspatos, carbonatos, óxidos, minerais pesados e fragmentos fósseis (Soares, 2015). Nesse sentido, as amostras, cimentadas ou não, foram avaliadas através de:

- **Análise em lupas binoculares:** com o intuito de detalhar as descrições produzidas *in situ*, avaliando os sedimentos em termos de mineralogia, textura superficial dos grãos, grau de arredondamento, presença de restos vegetais e outros fragmentos fósseis.

### 5.1.3 Elaboração dos dados

A fase de elaboração dos dados focou na individualização dos mecanismos físicos que geraram os sedimentos. Os dados obtidos foram analisados segundo uma metodologia comparativa, equiparando dados obtidos em campo e laboratório com depósitos antigos e recentes descritos na literatura, bem como em ensaios de sedimentação. Não foi aplicado o modelo de código de fácies proposto por Miall (1985).

As superfícies limitantes identificadas e descritas em campo foram refinadas e melhor definidas segundo critérios adotados por Brookfield (1977), Allen (1983) e Ramos e Sopeña (1983) e ainda segundo conhecimentos específicos atrelados a sistemas fluviais áridos e semi-áridos estudados por Graf (1988), Schick (1993), Kelly e Olsen (1993), Tooth e Nanson (1995), Reid e Frostick (1997), Tooth (1999, 2000), Cain e Mountney (2009), Parsons e Abrahams (2009). A definição das litofácies e superfícies delimitantes resultou na construção e interpretação de elementos arquiteturais, segundo os princípios de Miall (1985), apoiando-se ainda sobre conhecimentos específicos de sistemas fluviais áridos descritos por Tooth (1999) e seguintes.

Os dados adquiridos foram apresentados em forma de seções estratigráficas e *sketches* bidimensionais. Os dados de paleocorrentes foram colocados em histogramas circulares, utilizando o software StereoNet, e então acoplados às seções estratigráficas produzidas. Esta abordagem de representação monodimensional permitiu identificar padrões de sequencialidade relacionados à dinâmica do sistema fluvial.

## 5.2 Análise de paleossolos

### 5.2.1 Aquisição de dados em campo

A análise dos paleossolos limitou-se a descrições macroscópicas *in situ* ou em amostras coletadas. Para tanto, as seguintes etapas foram executadas:

1 Reconhecimento de perfis de paleossolos nas sucessões estratigráficas analisadas, de forma a distingui-los e delimitá-los em relação aos depósitos sedimentares. Os dados coletados foram baseados nas seguintes características macroscópicas: ausência de estruturas sedimentares (*destratification*), marcas de raízes, agregados (*peds*), películas (*cutans*), níveis ou faixas com diferentes características cromáticas, concentração de minerais em nódulos ou pseudo-estratificações, mosqueamento (*mottles*), bioturbação e restos fósseis (Retallack, 1988; Catt, 1990).

2 Descrição e medição de perfis paleopedológicos de detalhe do topo para a base, extraindo informações a respeito de: granulometria; superfícies de *slickenside*; estruturas dos horizontes de perfis de paleossolos; presença, tipo, geometria e concentração de nódulos; bioturbações; marcas de raízes; espessura; tipos de contato e ainda o desenvolvimento lateral dos perfis de paleossolos.

### 5.2.2 Elaboração dos dados

Os dados obtidos foram aplicados na construção de perfis de paleossolos a fim de compreender sua distribuição vertical e lateral nos depósitos analisados. Esta distribuição foi utilizada para compreender a dinâmica temporal e espacial do sistema fluvial distributário.

## 5.3 Integração e elaboração dos dados de sedimentos e paleossolos

Através da integração entre os dados de sedimentos e paleossolos foi possível:

i. Definir a importância e relações entre depósitos e paleossolos como indicadores paleoambientais e estratigráficos;

ii. Interpretar os fatores que controlaram a interrupção dos processos sedimentares;

iii. Estabelecer um modelo sequencial para os depósitos do Membro Serra da Galga.

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# ANEXO I

Soares, M.V.T., Basilici, G., Dal' Bo, P. F. F, Marinho, T. S., Oliveira, E. F., Silva, K. E. B. *Climatic and geomorphologic cycles in a semi-arid fluvial distributary system (Upper Cretaceous, Bauru Group - SE Brazil)*. *Sedimentary Geology [submetido em jan/2018].*

*“To see a World in a Grain of Sand*
*And a Heaven in a Wild Flower*
*Hold Infinity in the palm of your hand*
*And Eternity in an hour”*

** WILLIAM BLAKE*

# Climatic and geomorphologic cycles in a semi-arid fluvial distributary system (Upper Cretaceous, Bauru Group - SE Brazil)

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**ABSTRACT**

Studies on fluvial distributary systems rely primarily on the lateral distribution of architectural elements, controlled by channels radiating outward from the basin margin. This approach is mainly based on the downstream dynamics of the fluvial network, not considering its temporal variations, vertical organisation of architectural elements and relative factors controlling its dynamics. In order to understand the vertical organisation of fluvial distributary systems, this work analyses the proximal deposits of an Upper Cretaceous, semi-arid, fluvial distributary system, localised at the northeastern margin of the Bauru Basin (Southeast Brazil). In order to unravel the internal architecture of the channel deposits, the relationships with flood plain deposits and the factors influencing its sequential organisation, five detailed stratigraphic sections, *c.*10 m thick each one, were measured and analysed. Three fining- and thinning-upward fluvial sequences were identified, separated at the top and the bottom by two palaeosol profiles. Each sequence is formed of channel and floodplain architectural elements. Two types of channels were identified. The first has been associated to fluvial activity during more humid climate periods, wherein river flows assumed more perennial behaviour. A second channel type has been related to drier climate periods wherein the channel assumed ephemeral hydraulic behaviour and was characterised by highly erosive and supersaturated flows operating near supercritical conditions. The vertical alternation of these channels unravelled a fluvial belt organisation brought out by high-frequency climate-induced cycles. The two palaeosol profiles that mark top and bottom of the sequence indicate temporary interruptions of the fluvial sedimentation, related to autogenic avulsion of the fluvial belt. Thereby the studied succession reveals high-frequency climate-induced allogenic sedimentary cycles encompassed by a long-period autogenic geomorphologic-induced sedimentary cycle. This work suggests how climate and geomorphology act jointly as remarkable factors that control the vertical organisation of fluvial distributary systems.

**Keywords:** Fluvial deposits; Palaeohydrology; Semi-arid climate; Bauru Basin; Upper Cretaceous.

## 1. INTRODUCTION

Facies models in fluvial deposits derive from the studies of modern tributary rivers located in sedimentary basins with low preservation potential (Miall, 1996; Bridge, 2006). However, recent studies, which considered more than seven hundred modern continental sedimentary basins, demonstrated that the majority of these basins are composed predominantly of fluvial distributary systems (Weissmann et al., 2010). Consequently, the prevailing application of the uniformitarian approach in depositional models, based mainly on tributary fluvial systems, provides a deficient understanding of the facies architecture in the geological record.

Conceptual models of fluvial distributary systems are based on rivers whose dynamics reveal a clear downstream reduction in water discharge from proximal to distal zone. Along these zones it is possible to observe decrease in channels dimension and grain size of the transported sediments, and increase in non-channelised flows, culminating in a terminal splay complex (Parkash et al., 1983; Abdullatif, 1989; Nichols and Fisher, 2007). These systems are divided in three zones (proximal, intermediate and distal) based on downstream changes of the architectural elements (Cain and Mountney, 2009, see their Fig. 1). Distally they can pass to playa-lakes, permanent water body, larger fluvial system, sand sea or sand sheet, depending on the general climatic conditions. In the geological record, the recognition of fluvial distributary systems is based on the characteristics of the facies that indicate downstream decrease in (1) hydraulic discharge, (2) channels dimension, (3) channelised flows, and an increase of (1) non-channelised flows (sheet floods), (2) channel bifurcation and (3) occurrence of aeolian, playa-lake, coastal, wetland or lacustrine deposits (Nichols and Fischer, 2007; Cain and Mountney, 2009). Most of these models are described in endorheic basins in arid to semi-arid climate conditions (Nichols and Fisher, 2007). The dynamics of dryland fluvial systems are scarcely represented in the literature and derive from studies of modern rivers in arid and semi-arid regions of Australia (Tooth, 1999), Israel (Schick, 1993) and South Africa (Tooth and Nanson, 1995). Current literature prioritizes the characterisation of dryland fluvial environments according to their hydraulic behaviour, controlled by highly variable rainfall in time and space (Tooth, 2000). These characteristics indicate the apparent highly spatiotemporal variability associated to fluvial distributary systems.

On the contrary, our current understanding of fluvial distributary systems relies primarily on the lateral distribution of architectural elements, controlled by the outward irradiation of the channels from the basin margin. This approach is based on the lateral variation of facies and architecture of the fluvial network, but it does not consider its temporal variations, vertical organisation of the architectural elements and its controlling factors. In this regard, the northeastern margin of the Bauru Basin (Upper Cretaceous, southeast Brazil), which hosts excellent exposures of deposits related to a semi-arid fluvial distributary system (Basilici et al., 2016a), offers ideal conditions for detailed study on the vertical stratigraphic organisation of fluvial distributary systems. The aim of this paper is to describe how the sedimentary facies and architectural elements of fluvial distributary system can vary vertically and define what and how controlling factors govern the temporal dynamics of the fluvial distributary system.

## 2. STUDY AREA, GEOLOGIC AND STRATIGRAPHIC SETTING OF THE BAURU GROUP

The Bauru Basin is classified as an endorheic sag basin whose origin and evolution range from Coniacian to Maastrichian, according to biostratigraphic considerations (Dias-Brito et al., 2001) and igneous intrusions bordering the limits of the basin (Coutinho et al., 1992). The Bauru Basin developed under the “Hot and Arid Southern Belt Zone” (Chumakov, 1995) and it hosted one of the most extensive dryland environments from the Cretaceous period, occupying an approximate area of 370,000 km$^2$, revealing an asymmetric elliptical shape in plan view (Fig. 1A). The sedimentation of the Bauru Basin started after the continental break-up between South America and Africa, when the opening of the Proto-Atlantic ocean established one the largest basalt effusions recorded on the Earth's history, the Paraná-Etendeka Continental Flood Basalt Province (Milani et al., 2007). The

Bauru Basin is composed of *c.*450 m thick siliciclastic interval that overlay the flood basalts. The lithostratigraphy of the Bauru Basin is extremely complex. The large dimension of the basin, the lithologic similarity of the units and the proliferation of lithostratigraphic names contributed to an intricate mosaic of lithostratigraphic units (Basilici et al., 2016a). Based on the work of Soares et al. (1980) and restricting the stratigraphic organisation to the central and south portions of the Bauru basin, the lithostratigraphy can be ordered in five units, from the base to the top: Caiuá Formation (aeolian systems), Santo Anastácio Formation (alluvial systems), Araçatuba Formation (playa-lake systems), Adamantina Formation (alluvial systems) and Marília Formation (alluvial system) (Fig. 2). The Marília Formation constitutes the top of the Bauru Basin, developed during the Upper Cretaceous (Dias-Brito et al., 2001).

The Marília Formation reveals 160 m thick deposits, primarily composed of chemically immature, poorly-sorted, coarse- to fine-grained sandstone, conglomerate and mudstone layers. A peculiar characteristic associated to this formation is the presence of well-defined horizons of carbonate concentrations, and the apparent structureless aspect of the sandstones (Soares et al., 1980). Lithostratigraphic reconstructions of the Bauru Basin have been conducted mainly on its central and southern parts, whereas the same lithostratigraphic model is barely suitable for the northernmost regions. Recent studies (Basilici et al., 2016a; 2016b) suggest a genetic association between the Araçatuba, Adamantina and Marília Formations at the southeast sector of the Bauru Basin, in which these units formed in a semi-arid, endorheic fluvial distributary system, but they have strong doubts on the use of the same lithostratigraphic model on the northern portion of Bauru Basin. The study area is located at the northeastern margin of the Bauru Basin, in the vicinity of Uberaba city, Minas Gerais State (Fig. 1B). At this location, a succession of c. 10 m of sandstone and, secondarily, pebbly sandstone and mudstone crops out. Although the geological map (CPRM - Geological Survey of Brazil, 2004) identifies this succession with the Marília Formation, the lithostratigraphic features are strongly contrasting with the characteristics of the cited formation, which is more typical of the southern part of the basin (Soares et al., 1980; Basilici et al., 2016b).

## 3. METHODS

An abandoned quarry, displaying excellent three-dimensional exposures, allowed a detailed study of the sedimentary succession (Fig. 1C). Five detailed stratigraphic sections, each one *c.*10 m thick, were measured and analysed with centimetre detail. Thirty-four small other outcrops distributed close to the study area were used to better define the facies and palaeosols that constitute the studied interval. Two palaeosol profiles, which delimit the fluvial deposits at the base and the top, were identified and described. Palaeosols were recognised in the field by the presence of destratification, root marks, nodules, mottles, colour patterns and bioturbation (Retallack, 1988; Catt, 1990). The fluvial deposits were subdivided in nine facies with genetic meaning (*sensu* Harms et al., 1982) regarding grain size, sorting, fabric, mineralogy, beds thickness, geometry, bounding surfaces, sedimentary structures, palaeocurrent indicators and bioturbations (Tab 1). Genetic facies, their boundaries and sequential organisation were the fundamental approach in this work to reconstruct the depositional environment of the studied succession. Three sedimentary sequences were identified and further subdivided in two architectural elements: channel-fill and floodplain deposits. The architectural elements within sequences were reconstructed through the identification of hierarchical bounding surfaces based on Miall (2006).

## 4. SEQUENTIAL ORGANISATION OF THE STUDY SUCCESSION

The studied sedimentary succession is limited at the base and the top by 1.25 m and 0.3 m thick palaeosol profiles, respectively (Fig. 3). The succession shows three depositional bodies, which are separated by erosional surfaces. Each body is characterised by a fining- and thinning-upward sequence, 1.6 to 2.35 m thick and can be subdivided in two portions: the lower portion is composed of pebbly sandstone and sandstone and the upper portion of very fine-grained sandstone and mudstone (Fig. 3) The erosional surfaces at the bottom of each sequence are laterally continuous for more than 110 m and characterised by undulated shape with scours up to 0.3 m deep and 0.5 m wide. The two portions of each sequence may be identified as channel-fill and flood plain architectural elements. Nine sedimentary facies were identified; description and interpretation is reported in Table 1. Above the analysed succession, similar depositional bodies overlay the uppermost palaeosol, however they are not considered in this study due to poor exposition.

**4.1. FIRST SEQUENCE**

The first sequence overlies a palaeosol and is constituted by 2.3 m thick, laterally extensive (110 m), tabular layer, marked at the base by an erosive surface, locally displaying asymmetrical, concave-up shape (0.3 m deep and 0.5 m wide) marks (Fig. 4A). From the base to the top, this sequence is formed by channel-fill and floodplain deposits, respectively (Fig. 3).

The lower palaeosol profile occurs in a 1.25 m thick tabular layer, more than 110 m laterally extended, showing homogeneous aspect. The top of the profile is marked by erosional surface whereas the bottom shows diffuse transition to underlying pebbly sandstone. The colour varies gradually from reddish pink (10YR 7.0/2.5) at the top to light pink (10YR 8.0/1.5) at the bottom of the profile (Fig. 4B). Parent material shows fining-upward trend and is constituted of coarse-grained sandstone at the bottom and medium-grained sandstone at the top. Sediments are composed of quartz, feldspar and lithic fragments (quartzite, chalcedony and gneiss). Bioturbation is present at the top of the profile and is characterised by vertical to subvertical tubes showing circular sections up to 8 mm in diameter. The vertical colour intensification towards the top of the profile indicates rubification, caused by oxidation of the parent material near the palaeosurface (Fenwick, 1985). Bioturbation and rubification indicate exposure to the atmosphere. However, the absence of horizons relates to an incipient palaeopedogenesis.

#### 4.1.1. Channel-fill deposits

*Description.* Channel-fill deposits are composed of sandstone beds showing fining-upward trend, associated to upward increase in sorting. This architectural element is divided in two portions (Fig. 3, 5; 6). The lowermost portion is constituted of pebbly sandstone, organised in trough cross-stratified sets, 0.2 to 0.6 m thick and 0.2 to 3 m wide (Fig. 7A), showing uniform palaeocurrent direction toward northwest (Fig. 3). Each trough cross-stratified set displays normal grading, evidenced by accumulation of cobble to granules of extraformational and intraformational clasts at the base. Extraformational clasts are rounded to well-rounded, and constituted of quartzite, chalcedony and gneiss; intraformational clasts are sub-rounded to angular and composed of mudstone and pedogenic calcareous nodules. The foresets of the cross stratifications are composed by alternating gravel and coarse- to medium-grained sandstone (Fig. 7B) and the sets are bounded at the top by alignments of sandy gravel layers. The transition to the upper portion is gradual and consists of medium-grained sandstone with barely visible trough cross beddings, underlined by alignment of granules and small pebbles along the foresets and the set boundaries (Fig. 5; 6; 7A).

*Interpretation.* The erosive surface at the bottom of the sequence, which cuts the top of a lower palaeosol profile, indicates the transition from a phase of stability and pedogenesis of the topographic surface to a phase of active erosion, transport and deposition of clastic material (Kraus and Wells, 1999). Asymmetrical marks are interpreted as obstacle scours produced by protruding objects (*e.g.* vegetation or large clasts) during initial erosion conditions. The obstacles act as hydrodynamic barriers, locally intensifying the turbulence around them and increasing the erosive power, producing scours at the channel floor (Sanz-Montero et al., 2014). Lenticular beds of though cross-beds (facies Stc – Tab. 1) indicate migration and deposition of three-dimensional subaqueous dunes with sinuous and/or linguoid crests (Collinson and Thompson, 1982; Miall, 2006). The bimodal sediment distribution along the foresets results from the migration of superimposed bedforms of different grain size and dimensions above the dune stoss side: sandy gravel material is related to smaller bedforms whereas gravel material to larger bedforms (Lunt et al., 2007). The alignment of sandy gravel material at the top of the sets result from difference of mobility between grain size fractions, by an effect referred to as kinetic sorting. During higher discharge, coarser particles are set in motion and temporary voids are created between moving gravel clasts, allowing the downward percolation of finer particles. When discharge decreases, coarser particles cease their movement, producing sandy gravel layers at the top of the dunes (Bacchi et al., 2014). The erosional surface at the bottom of this element and the coarse-grained concave-up geometry of the deposit suggest that this element constitute the filling of river channel. The overall fining-upward trend of its fill reveals the waning nature of the flow into the channel. The structureless character observed at the uppermost part (S) relates to the increase in sorting upwards, associated to smaller three-dimensional dunes produced by a low energy flow, obliterating the visualization of foresets.

**4.1.2. Floodplain deposits**

*Description.* Floodplain deposits occur at the top of this first sequence. This architectural element appears as succession of beds, up to 0.8 m thick, partially or completely cut laterally by the erosional surface at the bottom of the second sequence. These floodplain deposits are constituted of three facies, organised in a fining-upward succession. From the base to the top they are: fine-grained sandstone, muddy sandstone and mudstone (Fig. 8A). The fine-grained sandstone is constituted of sets, 0.1 to 0.2 m thick, showing lateral pinch-out and composed of small trough cross-stratifications with dip angles of 15-20°. Boundaries between sets are marked by accumulation of mudstone (Fig. 8B). This interval is *c.*0.5 m thick. Muddy sandstone overlays the previous facies through an abrupt transition forming a 0.3 m thick interval of lenticular sets of cross-laminations, 1 to 30 mm thick. Boundaries between laminations are evidenced by the accumulation of mudstone (Fig. 8C). A 0.05 m thick structureless mudstone layer constitutes the upper portion of this element (Fig. 8A). The bottom of this facies is abrupt and the mudstone shows bioturbation which consists of millimetre-scale tubes filled with muddy sandstone.

*Interpretation.* The fining-upward trend observed in these deposits evidences a constant reduction in flow energy. Taking in account the fine-grained nature of the sediments and the gradual transition from channelised deposits, this element can be interpreted as overbank deposits (Miall, 2006). Initially, small three-dimensional sinuous dunes (Sf) deposited on the flood plain under shallow-water conditions (Collinson and Thompson, 1982; Miall, 2006). The muddy laminae between sets and foresets indicate settling of muddy particles during episodes of stagnant water and/or oscillations of the flow. This suggests frequent interruptions of the dune field migration in response to falling water stages, caused by the return of flood water back to the adjacent channel (Miall, 2006). The superimposition of mutually erosive climbing type-A ripples (Sm) over the previous dune field records a channel shift away from its previous site (Jopling and Walker, 1968). The texture variations represent subaqueous flows dominated by low energy alternations of episodic floods and stagnant water (Miall, 2006). The last stage of this sequence is recorded by mudstone facies (M), indicating settling of mud under stagnant water conditions, further indicating the loss of channel influence as a response of the progressive shifting.

## 4.2. SECOND SEQUENCE

The second sequence is composed of tabular deposits, laterally extensive for more than 110 m and 1.6 to 2.0 m thick. This sequence comprises channel-fill at the base and floodplain deposits at the top. It is limited at the base by an undulated erosive surface, locally marked by large-scale (6 m wide), symmetrical, concave-up scours, 0.5 m deep (Fig. 9).

### 4.2.1. Channel-fill deposits

*Description.* Channel-fill deposits are constituted of laterally extensive tabular layer, bounded at the base by an undulated erosive surface that overlies channel-fill and locally floodplain deposits of the first sequence. Two interbedded lithofacies form these channel-fill deposits: sandy conglomerate and large-scale cross-bedded sandstone (Fig. 3; 5; 6).

The base of the channel-fill is constituted of structureless, matrix-supported sandy conglomerate, which forms a laterally extensive tabular layer, *c.*0.5 m thick, bounded by horizontal erosive surfaces at the base and the top (Fig. 10A). Gravels include intraformational and extraformational clasts. Extraformational clasts range from granules to pebbles, are rounded to well-rounded and composed of quartzite, chalcedony and gneiss, whereas intraformational clasts are constituted of angular to sub-angular pebbles and cobbles of mudstone and pedogenic calcareous nodules. The matrix is composed of very coarse- to coarse-grained, arkosic sandstone with carbonate cement. A crude normal grading is observed (Fig. 10B). Large-scale cross-bedded sandstone is the prevalent facies of channel-fill deposits. This overlies the sandy conglomerate and forms laterally extensive tabular layers. The facies is constituted of poorly to moderately sorted, medium- to coarse-grained sandstone organised in tabular sets of large-scale cross stratifications, up to 1.4 m thick and more than 10 m laterally extended, with slightly concave-up, low-angle foresets (varying from 10º to 15º) (Fig. 9). The base of sets is frequently outlined by symmetrical, concave-up erosive scours, varying from 4 to 20 m in width and 1 to 1.5 m in depth. Mudstone intraclasts, pebble or cobble in grain size, are common at the base of scours. The matrix is composed of fine- to very fine-grained sandstone with carbonate cement. Muddy intraclasts are commonly aligned along the foresets (Fig. 9). Palaeocurrents indicate northwestern trend (Fig. 3).

*Interpretation.* The erosive surface at the bottom of the channel-fill deposits corresponds to an environmental change from low energy or calm water depositional processes in flood plain to a renewed erosion and deposition in a channel system, probably provoked by avulsion (Allen, 1965). The lithofacies that constitute this architectural element indicate the restoration of subaqueous high-energetic environmental conditions, characterised by a channel with flow operating near supercritical conditions. The sandy conglomerate (Cs) indicate episodes of rapid deposition of bedload and suspended load reoccupying a previously active site of the channel belt. The slightly erosive base, along with the crude normal grading, indicate transient turbulence associated to these flows. Turbulence causes coarser and denser clasts to settle from suspension directly to the erosive bottom, creating a normally graded deposit (Nemec and Steel, 1984). The absence of stratification and abundant sandy matrix indicate rapid deposition of hyperconcentrated flow that inhibited any internal organisation (Costa, 1988). The relative roundness of gravels also suggests effective reworking during the transport in a continuous channelised flow (Nemec and Steel, 1984). Large-scale cross-stratified sandy bedforms (Sl) are interpreted as transitional dunes produced close to the upper-stage plane bed conditions. These structures are constructed by three main depositional processes: avalanching, suspension fall-out and countercurrent action (Røe, 1987); the relative effect of each mechanism determines the shape and inclination of dunes foresets (Reineck and Singh, 1975). When dunes are submitted to higher velocities, the dip angle of foresets decreases and the shape of stratifications progressively changes from angular to concave-up. Such geometrical changes are associated to the increasing action of suspension and countercurrent influence at the lee of the bedforms during deposition (Jopling, 1968). Notwithstanding, the presence of scattered intraclasts along foresets (similarly observed by Røe (1987) at the Fugleberget Formation) further indicates suspension fall-out as the main process during the construction of foresets. The characteristics described in the large-scale cross stratifications suggest transitional dunes developed by high velocity flows, close to the upper-plane bed conditions, marked by high suspended load to bedload ratio (Saunderson and Lockett, 1983). Scour marks present at the bottom of large-scale sandy bedforms sets represent erosive features developed at the channel floor prior to the deposition. They indicate pulses of extreme high-flow power responsible for eroding previous deposits and establishment of a network of chutes (incised scour marks) and pools (remaining channel-fill deposits) at the channel floor (Lang and Winsemann, 2013). As a result, they represent cyclic variations in water discharge operating at upper-stage plane bed conditions, varying from the transitional dunes to the chutes and pools stability fields (Parkash, 1983; Fielding, 2006). Furthermore, the presence of frequent intraclasts at the base of scours demonstrates the waning character of such seasonal floods with high erosive power (Miall, 2006).

### 4.2.2. Floodplain deposits

*Description.* Floodplain deposits occur as thin and laterally discontinuous beds of structureless mudstone. These beds are tabular, up to 0.4 m thick, and no more than 3 m laterally extended (Fig. 10C); they display local bioturbation, which consists of millimetre-scale tubes filled by fine-grained sandy silt.

*Interpretation.* Mudstone abruptly overlaying channel-fill deposits suggests a sudden environmental change due to abandonment of the channel, where sedimentation switched from bedload to exclusively overbank suspended load with deposition of mud under stagnant water conditions. Furthermore, the intense bioturbation indicates decrease of the environmental energy (Hubert and Hyde, 1982; Tunbridge, 1984; Miall, 2006).

## 4.3. THIRD SEQUENCE

The third sequence is formed by channel-fill deposits, 2.35 m thick, whose upper portion is palaeopedogenised for 0.3 m. At the bottom, the sequence is limited by an erosive surface; at the top another erosional surface is overlaid by poorly exposed coarse-grained channelised deposits.

### 4.3.1. Channel-fill deposits

*Description.* The channel-fill deposits of the third sequence are represented by a tabular layer, 110 m laterally extensive, which is bounded at the bottom by an undulated erosive surface that overlies channel-fill and locally floodplain deposits of the second sequence. The surface shows small-scale asymmetrical erosive marks, 0.1 to 0.3 m deep and 0.5 to 1 m wide (Fig. 11A). The channel deposits are characterised by a fining-upward vertical organisation, from pebbly sandstone at the base to medium-grained sandstone at the top. The sorting of sandstone also increases, from poorly sorted towards moderately sorted. This element can be divided in a lower and an upper portion. The lower portion is composed by pebbly sandstone beds with through cross stratifications, varying from 0.3 to 4 m wide and 0.2 to 0.6 m thick (Fig. 11A). Foreset dips show unidirectional trend towards northwest (Fig. 3). The boundaries of the sets and foresets are marked by the accumulation of granules and pebbles of mudstone intraclasts (Fig. 11A). The uppermost portion consists of medium-grained, apparently structureless sandstone that displays horizontal alignment of granules and cobbles of mudstone intraclasts that seem to correspond to boundary of sets (Fig. 11B). The transition between the lower and upper portion is gradual.

The top of the channel-fill deposit is overlaid by a 0.3 m thick palaeosol, more than 110 m laterally extended (Fig. 11B). The palaeosol profile shows homogeneous aspect demonstrating vertical colour variation from reddish pink (10YR 7.0/2.5) at the top (Fig. 4C) to light pink (10YR 8.0/1.5) at the bottom (Fig. 4D) and is attributed to rust coatings on quartz grains. Carbonate nodules are concentrated near the top of the profile and show subspherical, 1 to 150 mm across, less than 10% in abundance (Fig. 4D). Nodules are composed of calcite with floating coarse-grained sand clasts. Mottles are frequently disperse near the top, irregular in shape and white in colour (7.5YR 8/1) (Fig. 4C).

*Interpretation.* The erosive surface that divides this sequence from the floodplain deposits of the second sequence indicates the start of a renewed channel over a previously abandoned channel system (Miall, 2006). The channel-fill deposits share similar characteristics encountered in the first sequence. The sandstone facies (Stc) equally results from the migration and deposition of three-dimensional dunes with sinuous and linguoid crests with superimposed bedforms of different heights over the dune field. The palaeohydrological behaviour is similarly controlled by waning flow. The accumulation of intraformational mudstone granules to cobbles along horizontal surfaces corresponds to lags, resulting from the winnowing of finer sediments during episodes of higher water discharge and low sediment deposition (Miall, 2006). The higher concentration of intraclasts suggests cannibalistic behaviour of the fluvial system on flood plain deposits at this stage of deposition. The absence of sedimentary structures at the uppermost part of the sandstone partly relates to the increase in sorting and in part to the ancient pedogenesis, as suggested by carbonate nodules, mottles and bioturbation observed at the upper portion of the sequence.

The palaeosol profile at the top of the third sequence marks a relatively long period of inactivity of the channel system in this area (Retallack, 1988). The vertical colour intensification toward the top of the profile indicates rubification (Fenwick, 1985), as similarly observed in the palaeosol from the first sequence. Mottles and incipient carbonate nodules near the top indicate exposure to the atmosphere. The absence of horizons and the reduced thickness of the profile suggest incipient palaeopedogenesis.

## 5. FLUVIAL PALAEOHYDROLOGY AND DEPOSITIONAL HISTORY

The studied succession, located at the margin of the Bauru Basin (Fig. 1), exhibits three superimposed sequences of fluvial deposits characterised by different depositional features that points out to variations on the palaeohydraulic conditions. These main peculiar aspects are shown by stratigraphic organisation of the deposits: (i) the deposits are constituted of immature, poorly-sorted, coarse-grained clastic sediments organised in sedimentary facies mostly related to high-energy flows (Tab. 1), (ii) floodplain deposits are scarce (Fig. 3) and as a result the channel deposits are commonly amalgamated, (iii) the bottom and the top of the three sequences are marked by palaeosol profiles (Fig. 5; 6). The palaeogeographic position of these deposits and their stratigraphic organisation most likely relate to the proximal portion of the fluvial system. The sequential analysis of the interval displays important palaeohydraulic oscillations of the channels through time. Each sequence relates to episodes of channelisation characterised by waning flows of varied conditions in hydraulic power, stability, sediment saturation and erosive potential. The abrupt superposition of floodplain deposits over channel-fills, and the absence of any indicators of lateral migration, suggest that transitions between channelisation episodes occurred through sudden avulsion of the channels. The palaeosol profiles, which bound the study succession at the base and the top, indicate pauses on fluvial sedimentation during periods of stable surface conditions (Fig. 3).

**5.1 First channel**

The first sequence started with the incision of a river channel over a stable and pedogenised flood plain surface. This is evidenced by the erosion of the top of a palaeosol profile, which suggests stable conditions of the topography at least for several hundreds of years (Fig. 12A). In-channel deposition began with a large three-dimensional dune field (Stc), characterised by sinuous and linguoid crests, and superimposed migrating bedforms (Fig. 12B). Subsequently, flow energy and depth decreased progressively, forming smaller three-dimensional dunes (S), until the channel was completely filled. Considering the semi-arid climate observed for the Bauru Basin during the Upper Cretaceous (Basilici et al., 2009; Dal Bó et al., 2010; Basilici and Dal Bó, 2010a), the steadier behaviour of the waning flow observed in the first channel can be linked to periods of seasonal rainfall and/or groundwater contribution (Tooth, 2000). During recurrent episodes of seasonal rainfall, semi-arid rivers are periodically submitted to floods, during which overbank infiltration acts as the main controlling factor for groundwater rise. Consequently this maintains the channels with a steadier behaviour in water discharge during more humid periods (Graf, 1988; Cooke et al., 1993; Meredith et al., 2015). The progressive sediment filling determined the abandonment of the channel. The overlaying floodplain deposit testifies the gradual abandonment of the channel. When the channel was still closed, overbank flows deposited small three-dimensional dunes, later covered by mud laminae settled during falling water stages between floods. Several floods and falling water stages are recorded within the overbank deposit, indicating the oscillatory hydraulic character of the fluvial system controlled mainly by flood events. Due to progressive shift of the active channel, a second depositional stage is indicated by the alternated deposition of ripples and mud laminae on the previous dune field. The last stage of overbank deposition occurred in distal floodplain environment, where fine particles settled under stagnant water in temporary ponds where water was lost by infiltration into the groundwater system or by evaporation (Meredith et al., 2016). The fining- and thinning-upward trend of floodplain deposits works as indirect evidences of avulsion. It occurs along a progressive trajectory where channel diverts from its original locus to a distal area of the floodplain. During this process, several floods are registered in the sedimentary succession (Slingerland and Smith, 2004).

**5.2. Second channel**

The sedimentation of the second sequence developed over an erosional surface that suggests an abrupt environmental shift due to channel avulsion, where the active channel reoccupied a previously abandoned area (Kraus and Wells, 1999). The lack of palaeosol profiles between the first and the second sequences indicates short recurrence time between channel abandonment and reoccupation, marking the high frequency avulsion behaviour of the fluvial system. Fluvial deposition into the second channel started with episodes of rapid deposition by supersaturated flows (Cs) over the previously abandoned channel. The well-developed roundness of gravels probably indicates cannibalism of older loose sediments from the first sequence during channel reoccupation (Nemec and Steel, 1984). As a result of great sediment availability, flow at the second channel assumed higher capacity and erosive power (Slatyer and Mabbutt, 1964). After the first stage of rapid deposition, subsequent filling was established by the migration of large dunes (Sl) during intense floods operating under a transitional regime near upper-flow stage (Miall, 2006). As a consequence of the higher hydraulic conditions installed by large floods, channel morphology adapted, establishing a network of chutes (transitional dunes) and pools (scours) (Fig. 12C) (Lang and Winsemann, 2013). In addition, the high frequency of mudstone intraclasts suggests the increase in cannibalistic behaviour of the second channel system over the flood plain area during flood episodes. Scours indicate deepening of channel floor whereas the high frequency of intraclasts suggests channel widening (Schumm and Lichty, 1963). Such morphological adaptations in response to large floods testify high sensitivity of the fluvial system (Downs and Gregory, 1993), a common behaviour associated to semi-arid fluvial systems (Tooth, 2000).

The superposition of mudstone over the coarse-grained channel deposits provides indirect evidence of sudden abandonment of the active channel by avulsion (Slingerland and Smith, 2004). After channel avulsion, sedimentation took place by settling of mudstone under stagnant water conditions in distal floodplain area with scarce or no influence from the active channel. When compared to the first channel, this avulsion episode records faster and farther shift of the active channel from its previous site. The second channel sequence reveals a depositional history that is constituted of strong episodic floods in which only transitional dunes are preserved. This characterises rapidly changing flows in which disequilibrium between flow and bed conditions occur, thus permitting the preservation of sole high-velocity current bedforms (Fielding, 2006). Supersaturated flows, scour-fills and large-scale sandy bedforms together testify that the palaeohydrological behaviour of the second channel was associated to sparse and isolated episodes of intense rainfall during dry periods (Tooth, 2000).

**5.3. Third channel**

Another sudden river avulsion underlined the transition to the third sequence. The absence of palaeosol profiles at the top of the second sequence testifies high recurrence time of the river avulsion. The third channel exhibits a depositional history analogous to the first. This channel relates to a waning flow with steady decrease in water discharge marked by deposition of a field of three-dimensional dunes (Fig. 12D) that reflects gradual decline in flow depth and energy. Likewise the first channel, the third channel is associated to more humid period when seasonal rainfall establishes a higher groundwater table that contributes to channel recharge, providing the steadier behaviour of the flow (Tooth, 2000; Meredith et al., 2015). Although this sequence is similar to the first, higher proportion of intraclasts suggests more cannibalistic behaviour of the system (Miall, 2006). The absence of floodplain deposits on the top of the sequence is related to channel avulsion that shifted at greater distance on the flood plain area, thus generating no depositional influence from the active channel floods on the abandoned flood plain site (Slingerland and Smith, 2004). Thereby, the presence of a palaeosol profile at the top of the channel-fill deposit (S) indicates low recurrence time of the avulsion prior to subsequence reoccupation. Coarse-grained channelised deposits above the third sequence indicates channel reoccupation (Fig. 11B). However, they are not considered in this study due to poor exposition.

## 6. CLIMATE-INDUCED CYCLES ON FLUVIAL PALAEOHYDROLOGY

The facies analysis of the three fluvial sequences allowed reconstructing the palaeohydraulic and the depositional history of three superimposed channels. Fining- and thinning-upward sets of three-dimensional dunes of the first and third channels (Fig. 12) suggest more stable and perennial river flows. Whereas large and flattened dunes of the second channel, which were generated in supercritical conditions, indicate irregular and ephemeral river flows. Thereby, the three sequences of channels suggest a temporal variability of the river flow regime. Similar palaeohydraulic variability has been described on modern rivers from Australia (Tooth, 1999), Israel (Schick, 1993) and South Africa (Tooth and Nanson, 1995) and mark a common behaviour associated to dryland (arid and semi-arid) fluvial environments (Tooth, 2000). The main cause that acts on the steadiness of river flow relates to the spatio-temporal distribution of rainfall (Graf, 1988). Drier climate periods are normally associated to isolated peaks of precipitation, which force the rivers to assume an ephemeral nature (Tooth, 2000). In more humid periods, drylands are characterised by multiple peaks of high rainfall that force the rivers to experience repeated floods. As consequence of persistent overbank infiltration after each flood, groundwater table rises up and establishes a hydraulic connection to rivers that are now recharged by the dryland aquifer system (Meredith et al., 2015). The influx from the groundwater to the channels provides the steadier flow conditions observed during more humid periods. Alternatively, drier periods are marked by scarce episodes of intense and isolated rainfall, whose contribution is insufficient to groundwater table rise; therefore, no hydraulic connection is established between the channels and the dryland aquifer (Meredith et al., 2015). In drier climate conditions, the land surface shows an uneven vegetation cover and rainfalls perform with high erosional effectiveness (Thornes, 1994). Overland flows, which act as main sources for rivers recharge, provide a great amount of sediment and in particular mudstone intraclasts and pedorelicts are torn from the flood plain deposits. Large amount of mudstone intraclasts characterises the cannibalistic behaviour of the second channel. This feature, likewise the presence of transitional dunes and scoured channel base, strongly suggest that the deposition on the second channel took place when drier climate period controlled the fluvial environment. Consequently, the studied fluvial succession demonstrates the influence of more humid and drier climate cycles, which controlled the fluvial activity during the Upper Cretaceous at the northeastern part of the Bauru Basin.

Climate oscillations from more humid to drier conditions have been inferred by interbeddings of palaeosols and deposits in stratigraphically related successions of the southeastern and northwestern parts of the Bauru Basin (Fig. 13). At the northwestern part, detailed study on cyclic interbedding of aeolian sediments and palaeosols attributed these alternations to short-time fluctuations from drier and more humid climate (Basilici et al., 2009; Dal’ Bó et al., 2010 Basilci and Dal' Bó, 2010). Drier periods were characterised by aeolian sand sheet deposition, whereas more humid periods resulted in topographic stability with growth of vegetation and pedogenesis. Palaeoprecipitation estimates, using CIA-K proxy indicated up to 1078 mm/y for more humid periods (Dal’ Bó et al., 2010). In the southeastern part of the Bauru Basin more humid periods were associated to sheet floods activity on distal portion of a fluvial distributary system, whereas dry periods were related to absence of fluvial sedimentation and development of pedogenesis (Basilici et al., 2016a). In this area, mean annual precipitation rates inferred from the depth of nodular Bk horizon in palaeosols range from 200 to 300 mm (Dal' Bó et al., 2009), pointing out arid to semi-arid conditions characterised by isolated and scarce episodes of rainfall.

During the more humid periods of the Upper Cretaceous of the Bauru Basin, ephemeral fluvial deposits were described in northwestern portion (Basilici et al., 2009) and sheet flood deposits in the southeastern portion (Basilici et al, 2016a). The studied fluvial succession, when compared with the fluvial systems described in adjacent areas of the Bauru Basin, unfolds fairly perennial to intermittent systems of channels. Indeed, during more humid periods, the northeastern margin of the basin was dominated by fluvial channels with a stable, more constant hydraulic regime. Concomitantly, due to the abundance of water and probable recharged groundwater system, the northwestern part of the basin was dominated by pedogenesis and ephemeral streams, and the southeastern portion of the basin by episodes of sheet flood deposition. Alternatively, in drier periods the northeastern portion of the Bauru Basin showed channels dominated by more ephemeral, erosive and energetic flows, whereas the northwestern portion of the basin was dominated by aeolian sand sheet deposits and the southeastern portion by pedogenesis in semi-arid environment. As a result, the fluvial cycles and the alternations between pedogenesis and sedimentation of adjacent areas enlightens how climate controlled the surface processes of the Bauru Basin during the Upper Cretaceous, determining the rates of sedimentation, surface stability and facies assemblages in varied depositional systems.

## 7. GEOMORPHOLOGIC CYCLE ON FLUVIAL DYNAMICS

The presence of amalgamated sandy channels of varied hydraulic characteristics demonstrates a fluvial system in which climate operates as the main controlling factor for channel hydraulic, hence determining the resultant fluvial facies association according to each climatic period. Alternatively, palaeosol profiles bounding the fluvial succession at the base and the top indicate relatively long periods of stability of the topographic surface characterised by absence of sedimentation (Kraus, 1999). The two palaeosol profiles suggest a long-term shift of the channel-belt to relatively distant positions on the alluvial surface. The sudden migration of a channel-belt to a new position on the alluvial surface (avulsion *sensu* Allen, 1965) is a pivotal mechanism on the construction of the alluvial architecture. Avulsion processes have been widely described in the geological record and are interpreted as the sudden or gradual relocation of rivers to the lowest point on the flood plain (e.g., Allen, 1965, 1978; Bridge and Leeder, 1979; Leeder, 1978). Trigger mechanisms of avulsion include autogenic and allogenic processes. Autogenic (intrabasin) processes include rapid channel aggradation, substrate composition and decrease in channel capacity (Makaske, 2001; Aslan et al., 2005), whereas allogenic (extrabasinal) triggers are associated to tectonics, eustasy and climate change mechanisms (Beerbower, 1964; Holbrook et al., 2003). The studied fluvial succession shows a sequence of three amalgamated sandy channels, indicating systematic reoccupation of the same area for the channel belt. This pattern of stacked sandy channel bodies have been identified in ancient and modern fluvial deposits and are associated to erodible sandy substrates as the controlling factor in avulsion (Maizels 1990; Kraus 1996; Kraus and Gwinn 1997; Makaske et al. 2002). Because channels aggrade, channel-belts become elevated and gravitationally unstable ridges (Tornqvist and Bridge, 2002). This geomorphologic condition forces the fluvial system to avulse to a new position on a laterally lower portion of the flood plain (Fig. 14) (Jones and Schumm, 1999; Slingerland and Smith, 2004). The configuration of the studied fluvial succession along stacked channels suggests autogenic mechanisms forcing the channel-belt to avulse. In the studied fluvial succession, the palaeosols, localised at the bottom and top of the succession of the three channels, indicate relatively long interavulsion periods (time period between subsequent avulsions, *sensu* Stouthamer and Berendsen, 2007). As a result, the studied succession displays the superimposition of two different sedimentary cycles. A high-frequency cycle controlled by allogenic climate factors which yielded different types of fluvial deposits, and a low-frequency cycle controlled by autogenic morphological factor, which allowed pedogenesis to occur on the flood plain.

## 8. CONCLUSIONS

The studied fluvial succession records the sedimentation of the proximal portion of a dryland fluvial distributary system wherein climate and geomorphology influenced its depositional architecture. Two architectural elements have been recognised: channel-fill and floodplain deposits. These elements are organised in three vertical sedimentary sequences; each one of them shows fining- and thinning-upward trend and is constituted of channel and floodplain deposits. The entire fluvial succession is bounded at the bottom and the top by palaeosol profiles and each sequence is separated by erosive surfaces. Channel deposits are characterised by two types of deposits that suggest flood episodes with different hydraulic behaviours: (i) the first and the third channels were formed by three-dimensional dunes deposits, which suggest floods with perennial and steady falling flow conditions; (ii) the second channel was characterised by large and flattened dunes, testifying exceptionally large and energetic floods with highly erosive, supersaturated flows operating near supercritical conditions. The first type has been associated to more humid climate, brought about by abundant and steady rainfall with probable groundwater contribution to the fluvial regime; the second type has been interpreted as related to drier periods with intense and transient episodes of exceptional rainfall. Thereby, it is possible to recognise a high-frequency climate control trough the internal organisation of the fluvial deposits, which testify alternating variations from more humid to drier conditions. Similar high-frequency more humid-drier climate oscillations are known in the Bauru Basin. They were described in adjacent portions of the study area, wherein they controlled alternating processes of pedogenesis and sedimentation of varied depositional systems. The succession of the three channel deposits is confined at the bottom and top by two palaeosol profiles. These palaeosols testify an interruption of the depositional processes and the dominance of pedogenesis on the flood plain, due to shift of the channel-belt to a distant position on the alluvial surface. Thereby, the sequence delimited by the two palaeosol profiles indicates a superimposed longer-term geomorphologic-depositional cycle controlled by the autogenic lateral dynamics of the fluvial system. In conclusion, the studied succession is characterised by allogenic high-frequency climate-induced cycles that are superimposed to autogenic low-frequency geomorphologic-induced cycles.

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**Figure 1.** (A) Location map and lithostratigraphic map of the Bauru Basin with detail to the Alto Paranaíba Uplift at the northeastern margin. (B) Lithostratigraphic map of the northeastern sector of the Bauru Basin (Minas Gerais State) with detail to the study area near the city of Uberaba; (C) Panoramic view of the study site showing sections that are perpendicular (panel 1) and parallel (panel 2) to main palaeoflow. The lithostratigraphic map was modified from the Geological Survey of Brazil (CPRM, 2004).

**Figure 2.** Lithostratigraphy of the Bauru Basin (modified from Soares et al.,1980).

**Figure 3.** General stratigraphic section of the studied succession. Three sequences of channel-fill deposits overlain by floodplain deposits are indicated with numbers 1 to 3. Palaeosol profiles bounding the fluvial sequences are localised at the base and top.

**Figure 4.** Palaeosol profiles bounding the fluvial succession at the base (A, B) and top (C, D). (A) Asymmetrical, concave-up shape scour marks occur between the lower palaeosol and the first sequence. (B) From the top to the bottom of this palaeosol profile a gradual colour variation from reddish pink (10YR 7.0/2.5) to light pink (10YR 8.0/1.5) is observed. (C) Irregular mottles are concentrated at the top of the upper palaeosol. (D) Subspherical carbonate nodules (arrows) are concentrated in B horizon of this palaeosol profile.

**Figure 5.** Architectural mosaic of the panel 1 (see Fig. 1). This architectural sketch is perpendicular to palaeoflow directions and displays three channelised sequences bounded at the base and top by palaeosol profiles.

**Figure 6.** Architectural mosaic of the panel 2 (see Fig. 1). This architectural sketch is almost parallel to the palaeoflow directions.

**Figure 7.** Channel-fill deposits of the first sequence. (A) The top of the lower palaeosol profile is overlaid by trough cross-stratifications organised in amalgamated lenticular bodies composed of trough cross-bedded conglomeratic sandstone (Stc). The dashed lines on the middle-upper part of the sequence indicate accumulation of gravels (gravel alignments) in massive sandstone (S). (B) These cross stratifications show bimodal distribution of grain size: gravel (g) and sandy gravel (sg) cross strata. Jacob stick is with scale marked by intervals of 10 cm.

**Figure 8.** Floodplain architectural element of the first sequence. (A) This element is composed of a fining-upward small sequence, which is cosstituted, from the base to the top by fine sandstone (Sf), muddy sandstone (Sm) and mudstone (M). (B) Close-up of trough cross-bedded fine-grained sandstone (Sf), interpreted as three-dimensional small dunes. (C) Close-up of muddy sandstone showing interdigitated sets of light brown, cross laminations (Sm). The brown lines between sets and foresets underline mud drapes (see arrow).

**Figure 9.** Detailed architectural sketch of the second sequence. Scour marks are filled by large-scale cross-bedded sandstone (Sl), locally showing mudstone intraclasts concentrated at the base. The bottom of the large-scale cross-bedded stes is underlined by scour marks (orange dashed line) overlaid by thin bed of floodplain deposit (mudstone). The second sequence is bounded at the base and the top by erosive surfaces (red line).

**Figure 10.** Channel-fill and floodplain deposits of the second sequence. (A) Tabular layer of structureless, matrix-supported sandy conglomerate which is constituted of extraformational and intraformational clasts. (B) Crude normal grading is locally observed in sandy conglomerate facies. (C) Thin bed of structureless mudstone which overlays the channel-fill deposit of this second sequence.

**Figure 11.** Channel-fill deposits from the third sequence. (A) Lowermost part of the sequence showing an erosive bottom, which is overlaid by trough cross-bedded conglomeratic sandstone showing a high

concentration of intraclasts. (B) Close-up of the structureless sandstone (S) marked by the accumulation of intraclasts along horizontal lines (gravel lags - Gl). A palaeosol (P) marks the top of the third sequence. Coarse-grained channelised deposits overlie the third sequence.

**Figure 12.** (A) Stratigraphic section showing three fluvial sedimentary sequences bounded by palaeosols at the base and the top. (B) This cartoon reconstructs the first channel system, which was active during the more humid period. The picture shows three-dimensional dunes with sinuous and linguoid crests (Stc). Floodplain environment is indicated by small three-dimensional dunes (Sf - proximal flood plain), ripples (Sm - intermediate flood plain) and stagnant water bodies (M - distal flood plain). (C) Reconstruction of the second channel system, active during drier periods, characterised by high-energy and erosive floods, which formed large and flattened dunes near supercritical conditions (Sl). (D) Reconstruction of the third channel, which represents the return of a more humid climate period similar to the first sequence.

**Figure 13.** Climate-induced sedimentary cycles observed in northwestern (NW), northeastern (NE) and southeastern (SE) portions of the Bauru Group. The northwest portion (NW) shows alternation between palaeosols (P) and aeolian sand sheet (Ss) alternatively deposited to more humid and dry periods, respectively (see Basilici et al., 2009). Deposits at the northeast area (NE - this study) expose channel deposits testifying steady river flow during the more humid periods (Ch) and channel deposits yielded by ephemeral and energetic flows during the drier periods (Cd). The southeast portion (SE) of the basin reveals alternation between palaeosols (P) formed in drier period interbedded with sheet flood deposits (Sh) developed during more humid conditions (see Basilici et al., 2016a).

**Figure 14.** Cartoon of the depositional area. The channel belt containing laterally shifting channel is abandoned to a new distally lower position on the alluvial surface. Detail to the stratigraphic product of climate-driven fluvial cycle superimposed by the longer-term geomorphologic fluvial cycle where fluvial sequences are bounded at the base and the top by palaeosols.

**Table 1.** Synthetic table with description and interpretation of the lithofacies.

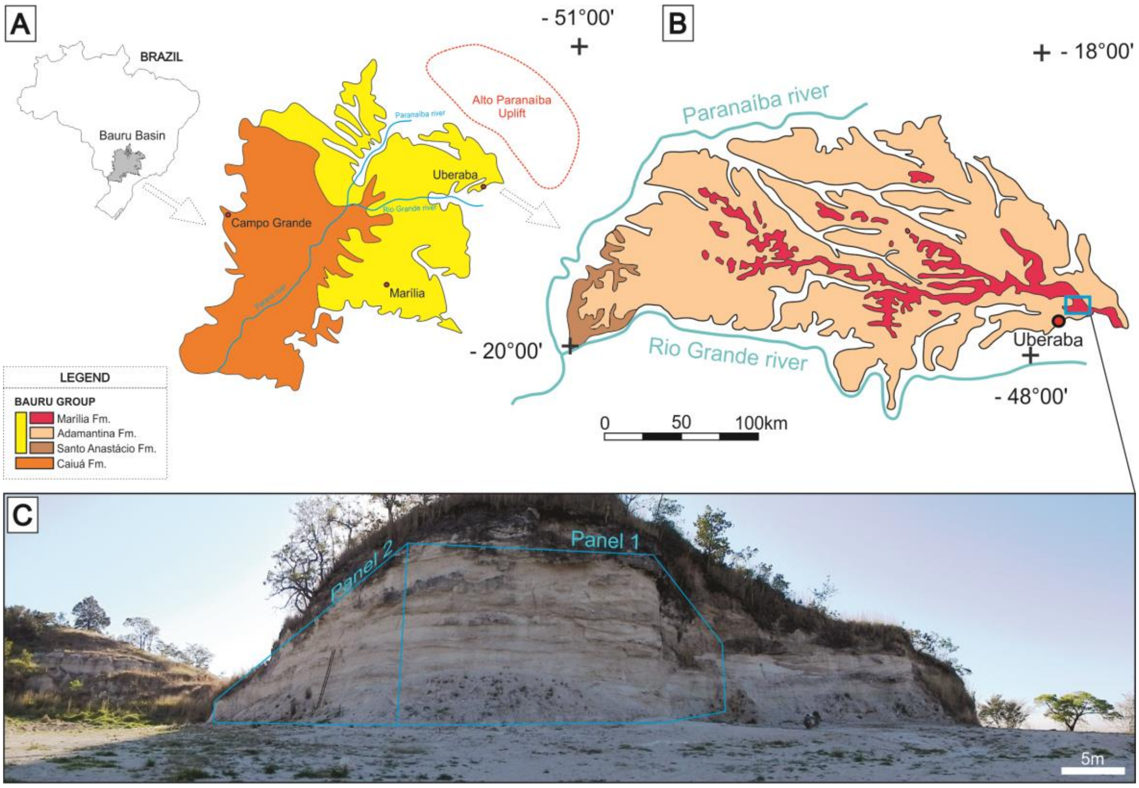

A
BRAZIL
Bauru Basin
Campo Grande
Uberaba
Marília
Paranaíba river
Rio Grande river
Alto Paranaíba Uplift
- 51°00'
B
+ - 18°00'
Paranaíba river
- 20°00'
Rio Grande river
Uberaba
- 48°00'
0
50
100km
LEGEND
BAURU GROUP
Marília Fm.
Adamantina Fm.
Santo Anastácio Fm.
Caiuá Fm.
C
Panel 1
Panel 2
5m

FIGURE 1

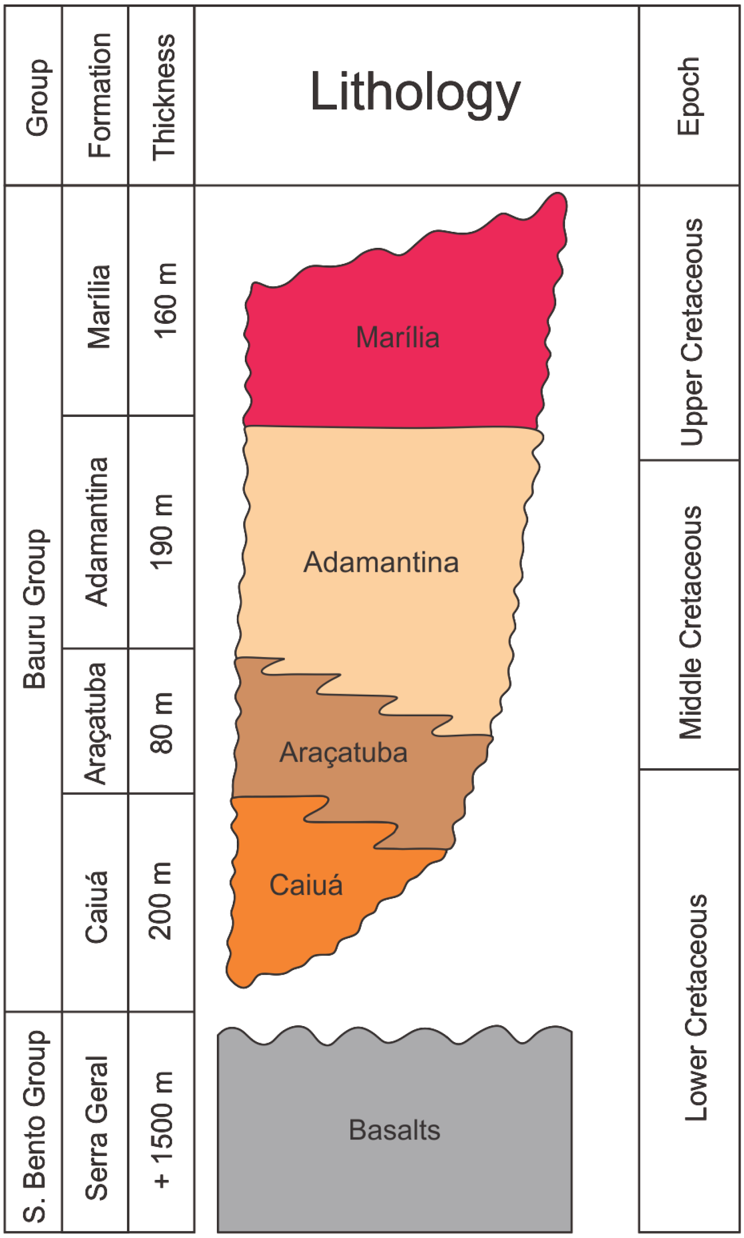
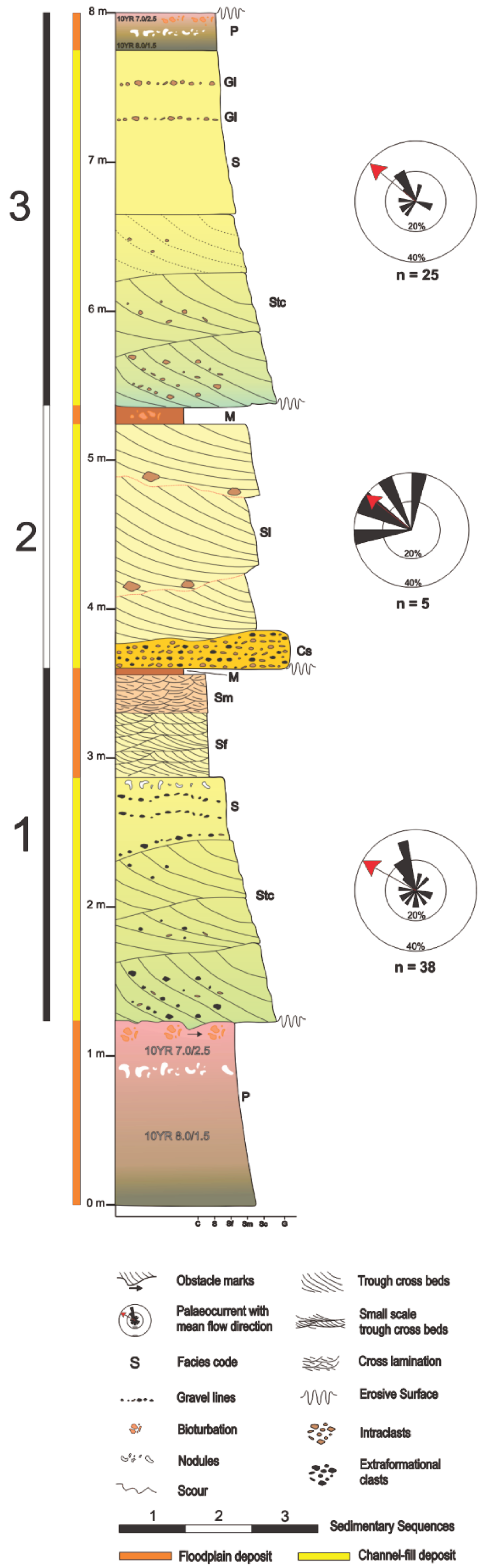

Group
Formation
Thickness
Lithology
Epoch
Bauru Group
Marília
Adamantina
Araçatuba
Caiuá
160 m
190 m
80 m
200 m
Upper Cretaceous
Middle Cretaceous
Lower Cretaceous
S. Bento Group
Serra Geral
+ 1500 m
Basalts

FIGURE 2



8 m
7 m
6 m
5 m
4 m
3 m
2 m
1 m
0 m
3
2
1
10YR 7.0/2.5
10YR 8.0/1.5
P
Gl
Gl
S
Stc
M
Sl
Cs
M
Sm
Sf
S
Stc
10YR 7.0/2.5
P
10YR 8.0/1.5
20%
40%
n = 25
20%
40%
n = 5
20%
40%
n = 38
Obstacle marks
Palaeocurrent with mean flow direction
Facies code
Gravel lines
Bioturbation
Nodules
Scour
Trough cross beds
Small scale trough cross beds
Cross lamination
Erosive Surface
Intraclasts
Extraformational clasts
Sedimentary Sequences
Floodplain deposit
Channel-fill deposit


FIGURE 3

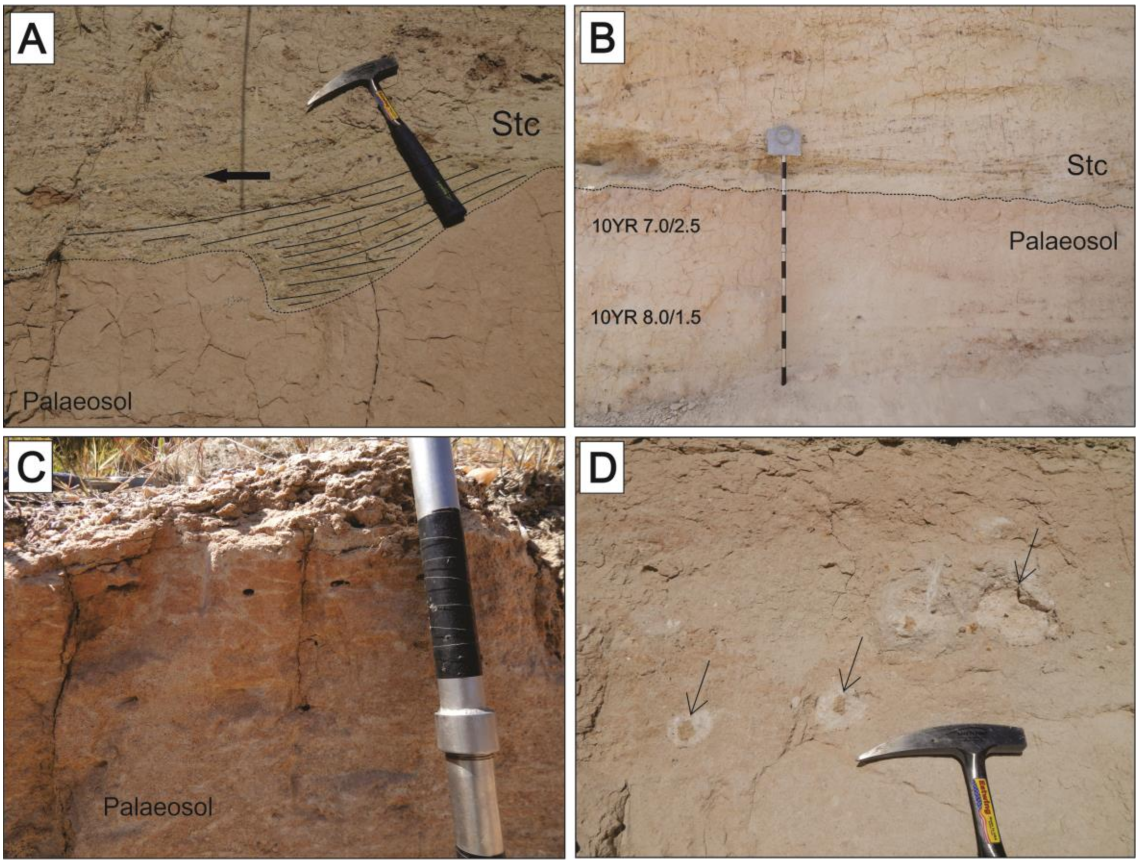

A
Stc
Palaeosol
B
Stc
10YR 7.0/2.5
Palaeosol
10YR 8.0/1.5
C
Palaeosol
D

FIGURE 4

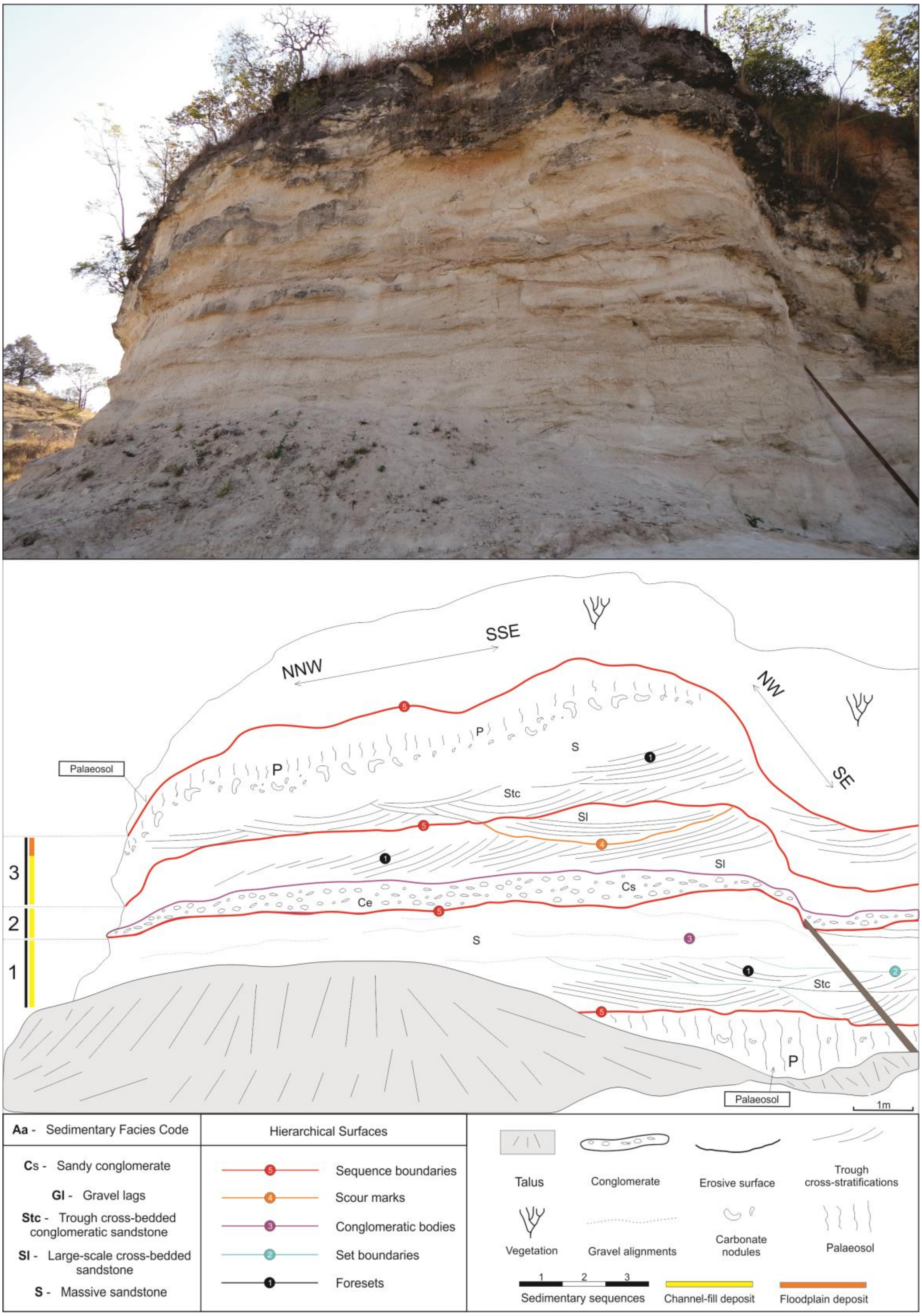
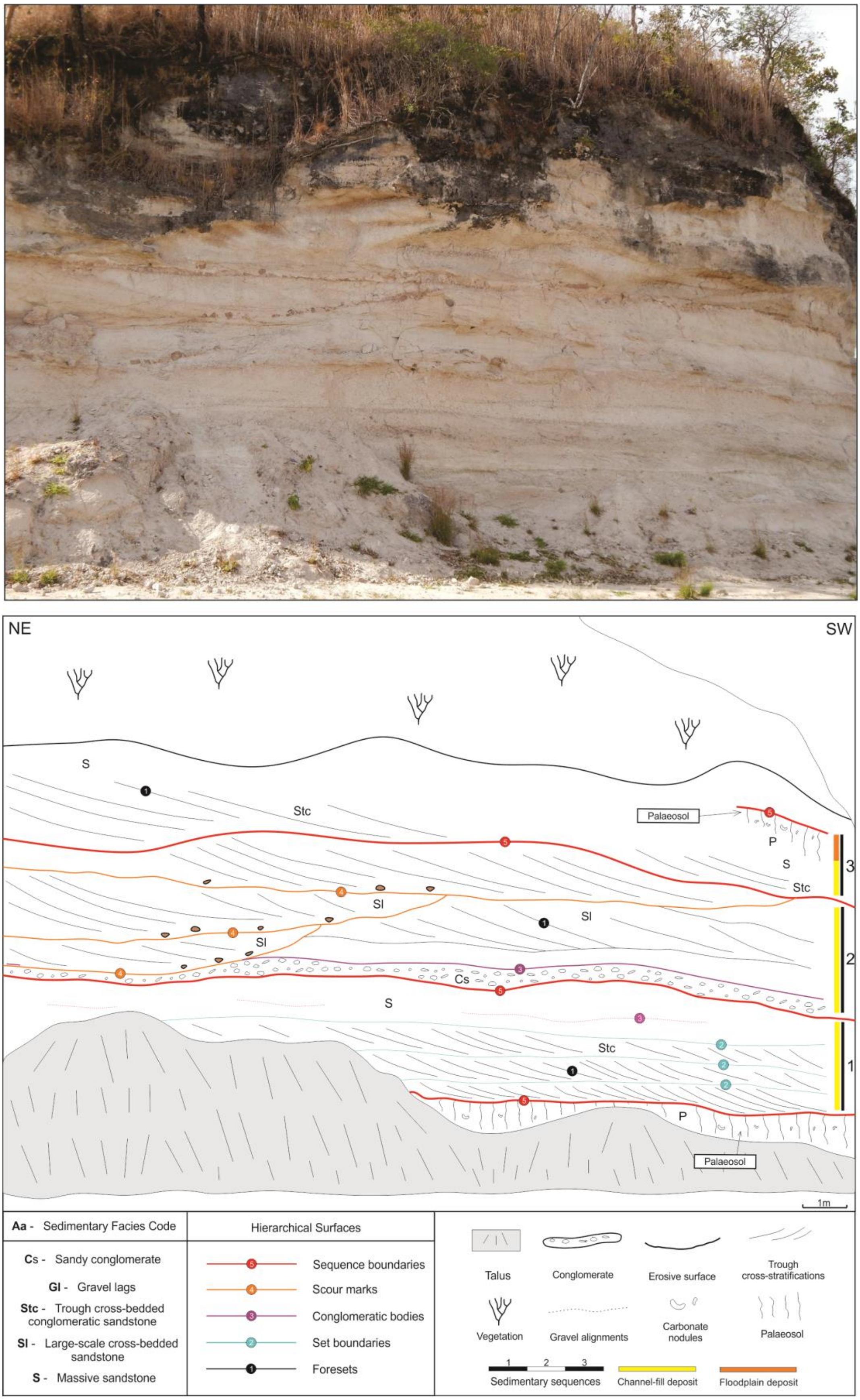

NNW
SSE
NW
SE
Palaeosol
P
S
Stc
Sl
Cs
Ce
Stc
P
Palaeosol
1m
3
2
1
Aa - Sedimentary Facies Code
Cs - Sandy conglomerate
Gl - Gravel lags
Stc - Trough cross-bedded conglomeratic sandstone
Sl - Large-scale cross-bedded sandstone
S - Massive sandstone
Hierarchical Surfaces
Sequence boundaries
Scour marks
Conglomeratic bodies
Set boundaries
Foresets
Talus
Conglomerate
Erosive surface
Trough cross-stratifications
Vegetation
Gravel alignments
Carbonate nodules
Palaeosol
Sedimentary sequences
Channel-fill deposit
Floodplain deposit

FIGURE 5



NE
SW
S
Stc
Palaeosol
P
S
Stc
3
SI
SI
SI
2
Cs
S
Stc
1
P
Palaeosol
1m
Aa - Sedimentary Facies Code
Cs - Sandy conglomerate
Gl - Gravel lags
Stc - Trough cross-bedded conglomeratic sandstone
Sl - Large-scale cross-bedded sandstone
S - Massive sandstone
Hierarchical Surfaces
Sequence boundaries
Scour marks
Conglomeratic bodies
Set boundaries
Foresets
Talus
Conglomerate
Erosive surface
Trough cross-stratifications
Vegetation
Gravel alignments
Carbonate nodules
Palaeosol
Sedimentary sequences
Channel-fill deposit
Floodplain deposit


FIGURE 6

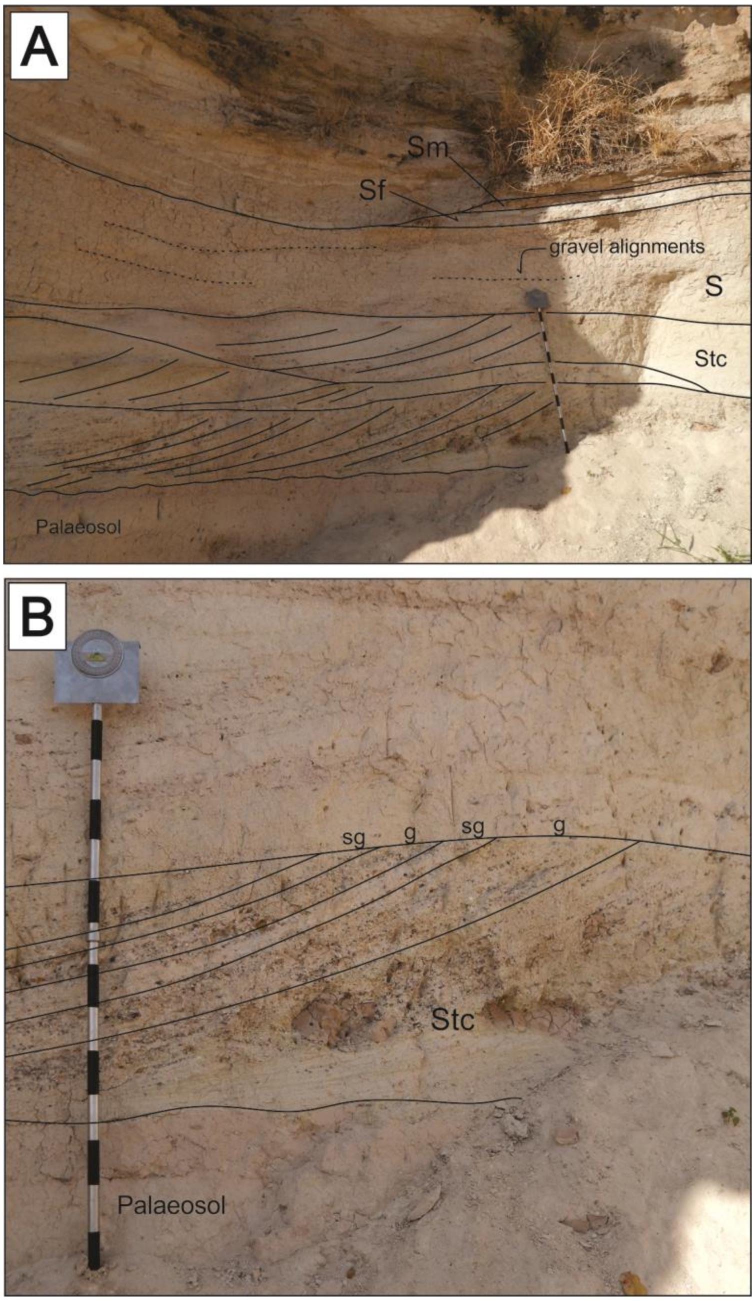

A
Sm
Sf
gravel alignments
S
Stc
Palaeosol
B
sg
g
sg
g
Stc
Palaeosol

FIGURE 7

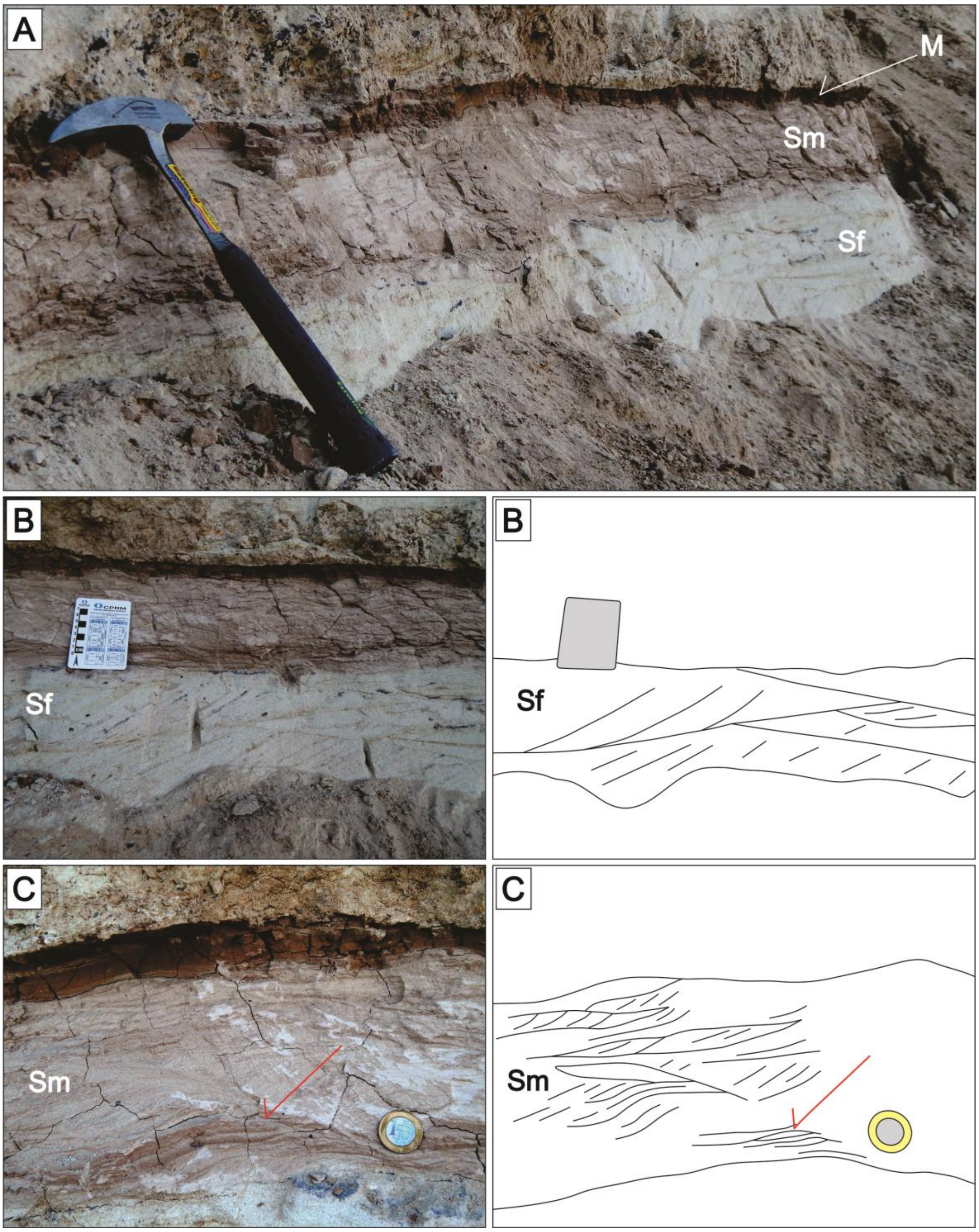



FIGURE 8

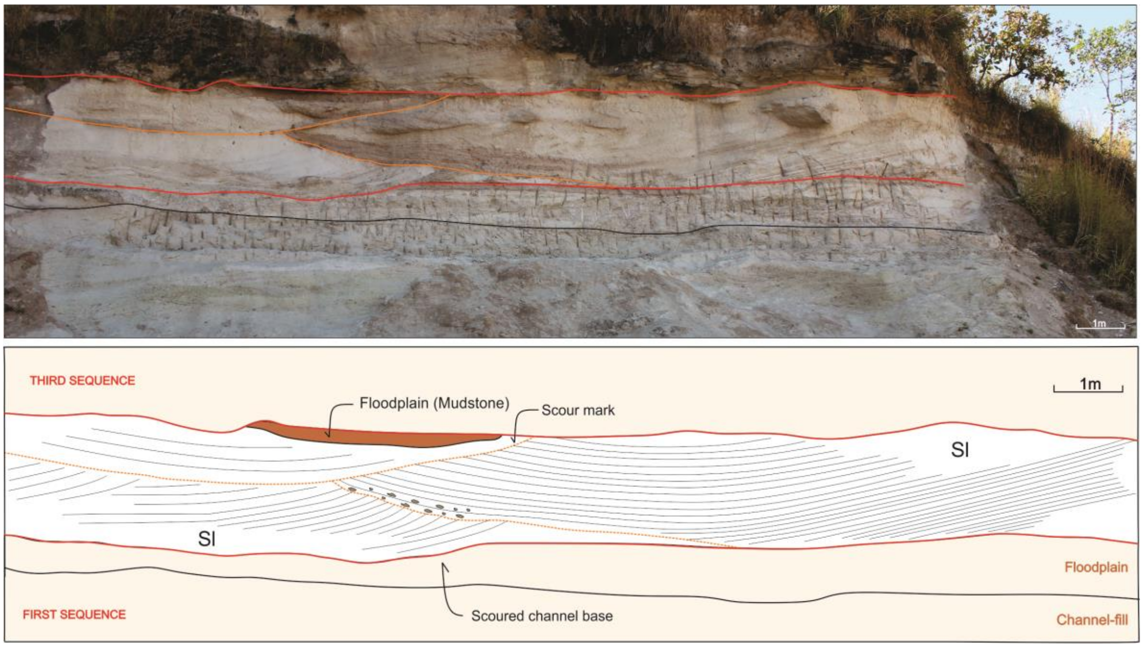

1m
THIRD SEQUENCE
Floodplain (Mudstone)
Scour mark
Sl
Sl
Floodplain
FIRST SEQUENCE
Scoured channel base
Channel-fill

FIGURE 9

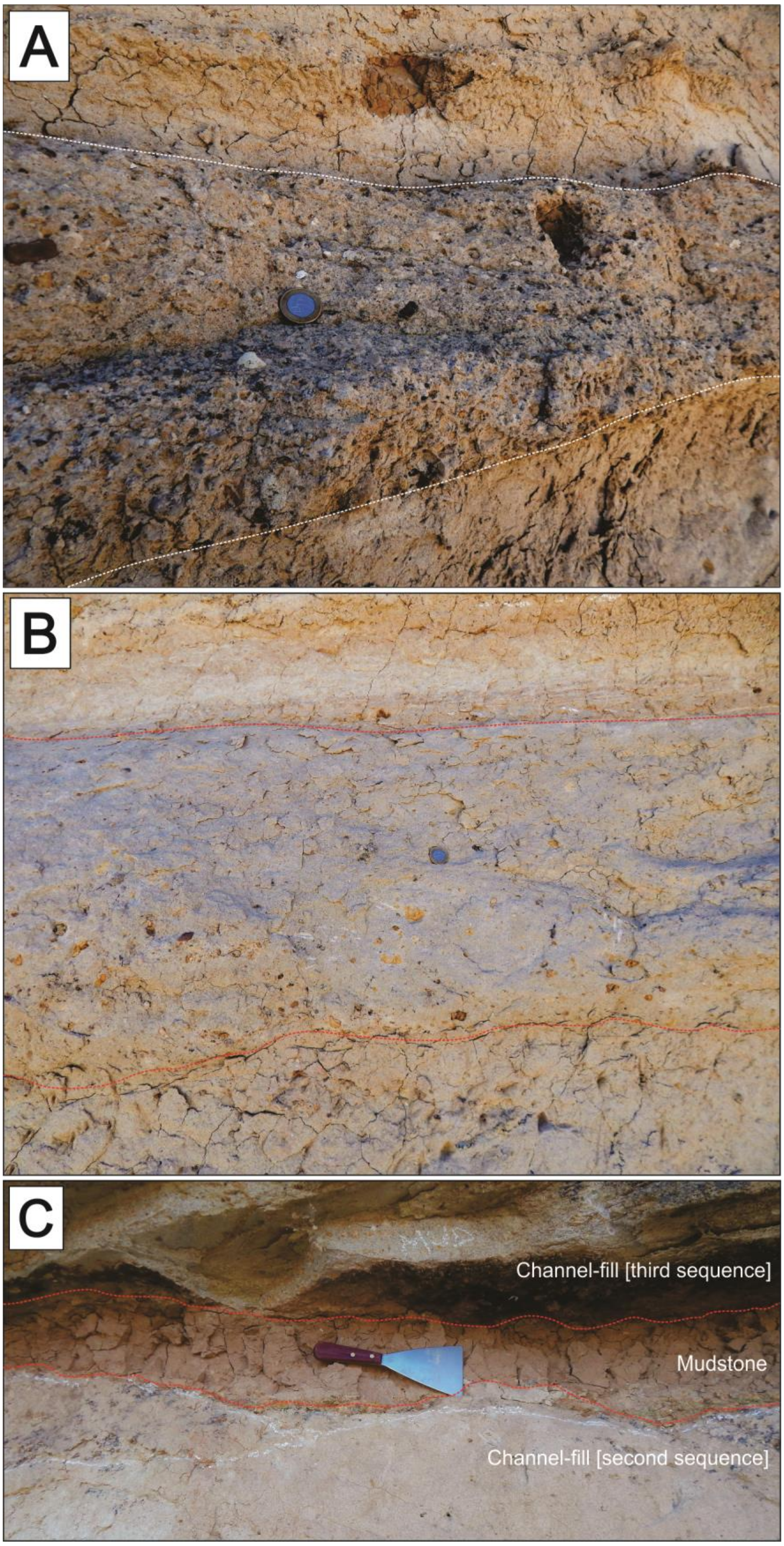

A
B
C
Channel-fill [third sequence]
Mudstone
Channel-fill [second sequence]

FIGURE 10

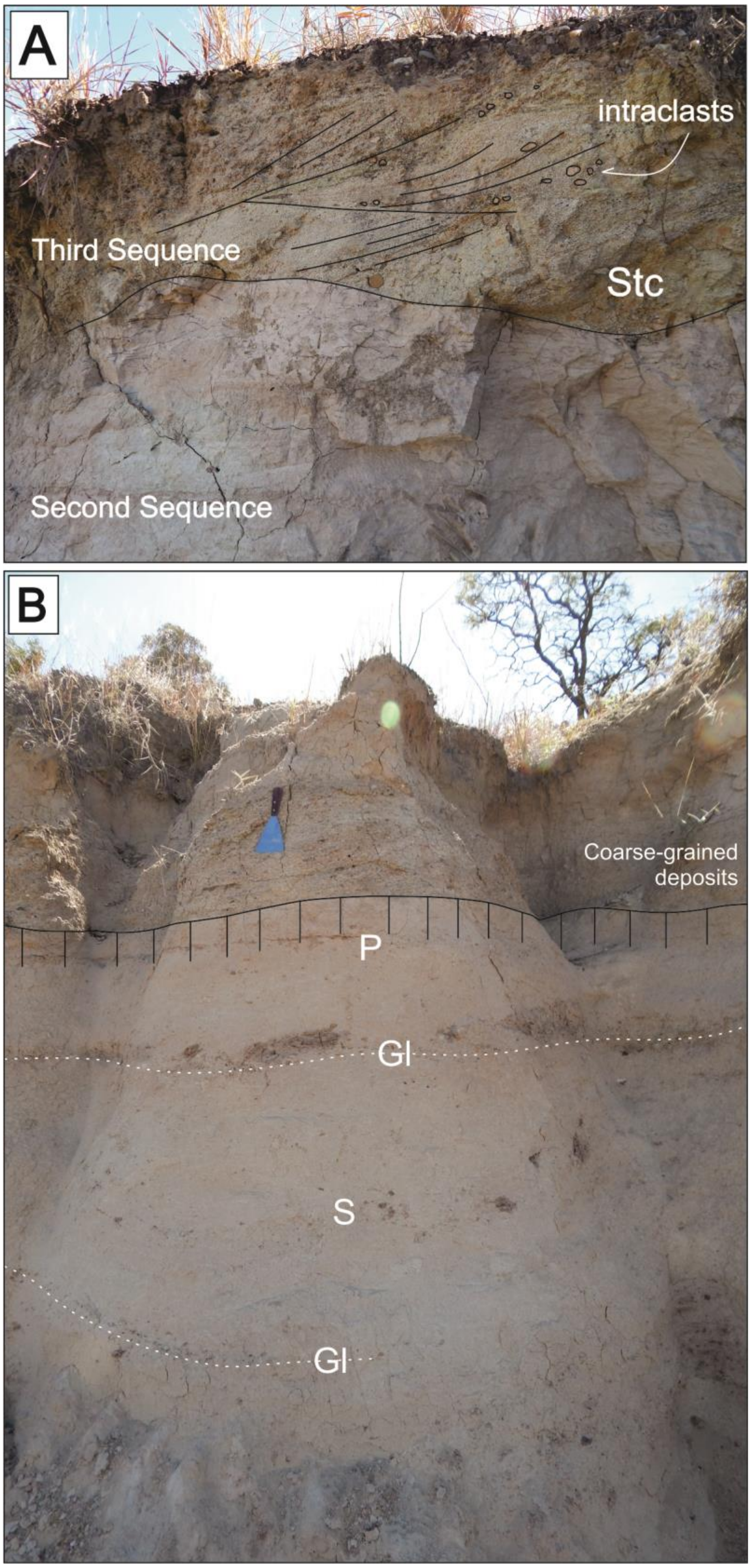
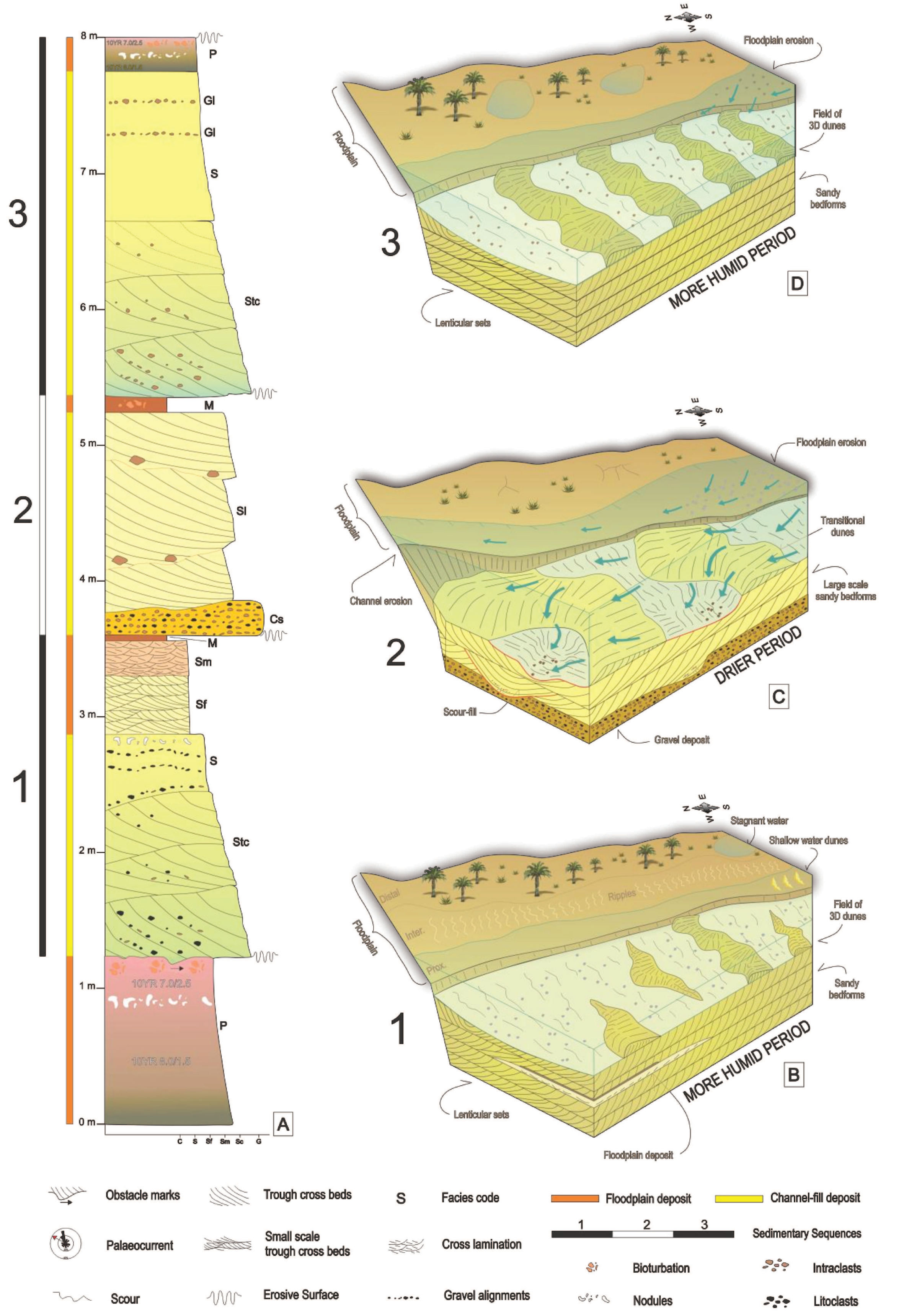

A
intraclasts
Third Sequence
Stc
Second Sequence
B
Coarse-grained
deposits
P
Gl
S
Gl

FIGURE 11



3
2
1
8 m
7 m
6 m
5 m
4 m
3 m
2 m
1 m
0 m
P
Gl
Gl
S
Stc
M
Sl
Cs
M
Sm
Sf
S
Stc
P
10YR 7.0/2.5
10YR 6.0/1.5
A
C S Sf Sm Sc G
Floodplain erosion
Floodplain
Field of 3D dunes
Sandy bedforms
3
MORE HUMID PERIOD
D
Lenticular sets
Floodplain erosion
Floodplain
Transitional dunes
Channel erosion
Large scale sandy bedforms
2
DRIER PERIOD
C
Scour-fill
Gravel deposit
Stagnant water
Shallow water dunes
Distal
Ripples
Inter.
Prox.
Floodplain
Field of 3D dunes
Sandy bedforms
1
MORE HUMID PERIOD
B
Lenticular sets
Floodplain deposit
Obstacle marks
Trough cross beds
S Facies code
Floodplain deposit
Channel-fill deposit
Palaeocurrent
Small scale trough cross beds
Cross lamination
1 2 3 Sedimentary Sequences
Bioturbation
Intraclasts
Scour
Erosive Surface
Gravel alignments
Nodules
Litoclasts


FIGURE 12

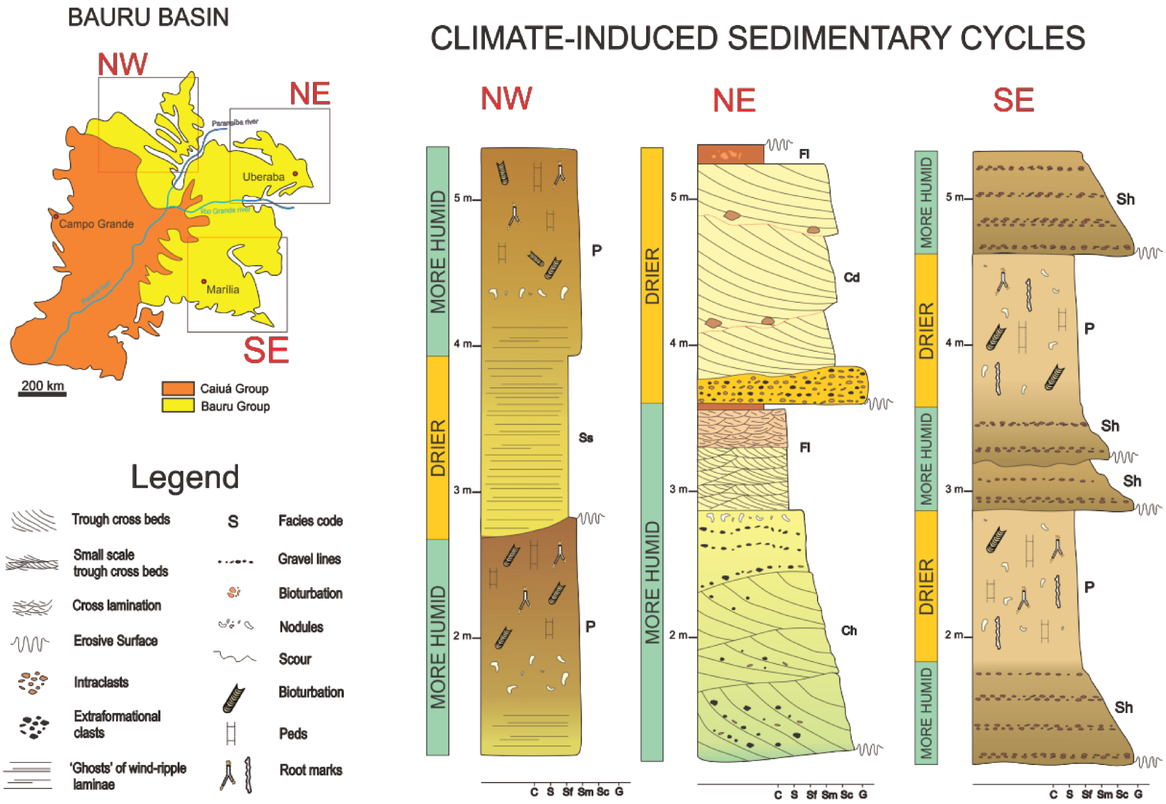
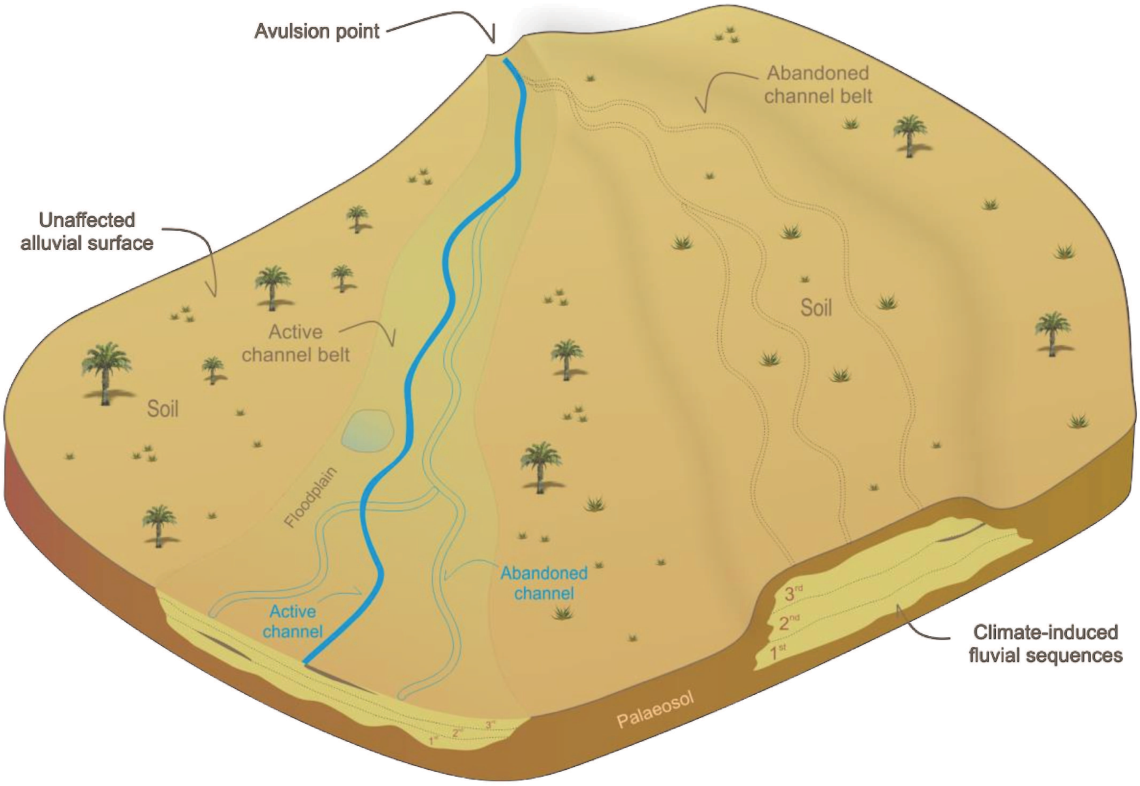

BAURU BASIN
NW
NE
SE
Paranaíba river
Uberaba
Campo Grande
Rio Grande river
Marília
200 km
Caiuá Group
Bauru Group
Legend
Trough cross beds
Small scale trough cross beds
Cross lamination
Erosive Surface
Intraclasts
Extraformational clasts
'Ghosts' of wind-ripple laminae
S
Facies code
Gravel lines
Bioturbation
Nodules
Scour
Bioturbation
Peds
Root marks
CLIMATE-INDUCED SEDIMENTARY CYCLES
NW
NE
SE
MORE HUMID
DRIER
MORE HUMID
P
Ss
P
DRIER
MORE HUMID
Fl
Cd
Fl
Ch
MORE HUMID
DRIER
MORE HUMID
DRIER
MORE HUMID
Sh
P
Sh
Sh
P
Sh
5 m
4 m
3 m
2 m
C S Sf Sm Sc G

FIGURE 13



Avulsion point
Abandoned channel belt
Unaffected alluvial surface
Soil
Active channel belt
Soil
Floodplain
Abandoned channel
Active channel
3rd
2nd
1st
Climate-induced fluvial sequences
Palaeosol


FIGURE 14

| Code | Facies | Description | Interpretation | Figures |
|---|---|---|---|---|
| Cs | Sandy conglomerate | Tabular bodies composed by sandy conglomerate with matrix-supported, massive texture, with sporadic crude normal grading | Hyperconcentrated flows developed by reworking of sediments from the alluvial surface during large floods | (Fig. 10B) |
| Gl | Gravel lags | Irregular surfaces of thin, matrix-supported layers of clasts | Gravel lags developed by kinetic sorting during pulses of higher discharge | (Fig. 11A, B) |
| Stc | Trough cross-bedded pebbly sandstone | Tabular layers of immature, pebbly sandstone composed by superimposed lenticular sets of unidirectional trough cross-stratifications showing fining-upward trend and accumulation of clasts between sets and foresets | Sinuous and linguoid crested tri-dimensional dunes | (Fig. 7A, B; 11B) |
| Sl | Large-scale cross-bedded sandstone | Tabular and scoop-shaped bodies marked by erosive bases, filled by medium- to coarse-grained, immature, poorly-sorted, carbonate cemented sandstone, with a fine- to very fine-grained sandy matrix, organised in unidirectional, low-angle (6° to 15° dip angle), large scale trough cross-stratifications, marked by normal grading and intraclasts scattered along foresets and as basal lags | Dunes developed near supercritical conditions during episodes of large floods | (Fig. 9) |
| S | Structureless sandstone | Tabular layers of medium to fine, immature sandstone marked by the accumulation of gravel lags | Well-sorted smaller dunes deposited during final stage of waning channelised flow | (Fig. 7A; 11A, B) |
| Sf | Fine sandstone | Tabular layers of laterally eroded immature, fine-grained sandstone formed by sets of trough cross-stratifications (0.1 to 0.2 m thick)with sets and foresets (up to 20º dip angles) limited by clay accumulation | Sinuous crested dunes developed under proximal floodplain environment marked by successive episodes of flooding and falling water stages | (Fig. 8A, C) |
| Sm | Muddy sandstone | Tabular layers of laterally eroded immature, muddy sandstone formed by interdigitated sets of low-angle cross-laminations with clay accumulation between sets and foresets | Type-A ripples developed under intermediate floodplain environment marked by successive episodes of flooding and falling water stages | (Fig. 8B, C) |
| M | Mudstone | Thin, tabular layers of laterally eroded mudstone showing both massive and bioturbated texture | Settling of clay and silt particles at distal floodplain environment under stagnant water, with development of temporary ponds when associated to intense bioturbation | (Fig. 10C) |
| P | Palaeosol profiles | Massive layers, bounded by at top erosive surfaces, marked by gradual colour transition from reddish pink (10YR 7.0/2.5) at the top to light pink (10YR 8.0/1.5) at the bottom, marked by horizons with bioturbation, mottles and carbonate nodules | Incipient palaeosol profiles developed under semi-arid conditions | (Fig. 4) |

TABLE 1