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

ANÁLISE DE FÁCIES E SEQUÊNCIAS DEPOSICIONAIS EM SISTEMAS CONTINENTAIS E ESTUARINOS DO TOPO DA FORMAÇÃO TOMBADOR, MESOPROTEROZOICO, CHAPADA DIAMANTINA, BRASIL

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ORIENTADOR – Prof. Dr. Claiton Marlon dos Santos Scherer

Volume I

Porto Alegre – 2012

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RESUMO

A Formação Tombador, Mesoproterozoico, compreende diferentes sistemas deposicionais, depositados em um bacia *sag*, que abrangem desde sistemas aluviais a estuarinos. Os depósitos bem preservados e sua ampla ocorrência em escala regional (~300 km) faz com que a Formação Tombador seja um excelente caso de estudo no Proterozoico. Foram reconhecidas três sequências deposicionais, limitadas por superfícies erosivas em escala regional no topo da Formação Tombador. A Sequência I é composta na base por canais fluviais cascalhosos entrelaçados rasos, que são sotopostos por depósitos de dunas e lençóis de areia eólicos e inundações em lençol intermediário. O limite inferior desta sequência é caracterizado por uma discordância angular intra-Tombador sobre os sistemas fluvio-estuarinos, evidenciada por uma mudança abrupta de fácies e mudança nas paleocorrentes. Os sistemas fluvio-estuarinos abaixo da discordância apresentam paleocorrentes para noroeste enquanto que os sistemas fluviais acima do limite de sequências indicam um transporte para sul. Uma nova entrada abrupta de depósitos conglomeráticos relacionados a sistemas de leques aluviais sobre a sucessão fluvio-eólica, marca o limite da Sequência II. A Sequência III é caracterizada por sistemas fluvio-estuarinos na porção superior da Formação Tombador, que são progressivamente sucedidos por sistemas marinhos rasos (Formação Caboclo), definindo uma tendência geral transgressiva. As Sequências I e II refletem um soerguimento da área-fonte em resposta a movimentações tectônicas. A mudança abrupta de paleocorrentes dos fluviais basais da Sequência I indicam uma reestruturação regional das redes de drenagens, enquanto que os sistemas de leques aluviais da Sequência II sugerem sedimentos depositados por uma tectônica sin-deposicional. Os limites de sequências II e III é marcado por uma superfície erosiva regional. A discordâncias entre as sequências II e III revela um hiato significante no topo da Formação Tombador sugerindo uma origem tectônica para esta discordância.

Palavras-chave: Formação Tombador, Mesoproterozoico, sequências deposicionais, análise de fácies, sistemas continentais e estuarinos.

ABSTRACT

The Mesoproterozoic Tombador Formation encompasses different depositional systems deposited in a sag basin, ranging from estuarine to alluvial. The well preserved deposits and their wide occurrence in the regional scale (~300 km) define the Tombador Formation as an excellent case study for the depositional patterns prevailing during the Proterozoic. Three depositional sequences were recognized for the Upper Tombador Formation, bounded by three semi-regional scale unconformities. Sequence I is composed of shallow, gravel-bed braided channels at its base, which are overlain by fine- to coarse-grained sandstones related to aeolian sand sheets and dunes and intermediate sheetfloods. The lower boundary of this sequence is characterized by an angular unconformity cutting fluvio-estuarine deposits, evidenced by an abrupt change of facies and fluvial palaeocurrents. The fluvio-estuarine deposits below the sequence boundary display palaeocurrents to northwest, whereas the fluvial strata above the unconformity show southeastward palaeocurrents. A new abrupt entrance of conglomeratic deposits related to alluvial fans systems overlying the fluvio-aeolian successions marks the lower boundary of Sequence II. The Sequence III is characterized by fluvio-estuarine systems in the top of the Upper Tombador Formation, that are progressively covered by shallow marine systems (Caboclo Formation), defining a general transgressive trend. The pattern of sequences I and II probably reflects the uplift of source areas in response to tectonic movements. The palaeocurrent change in Sequence I indicates a regional rearrangement of the drainage networks, while the alluvial fan systems of sequence II suggest sin-depositional tectonic pulses. The regional erosive surface between sequences II and III reveals a significant hiatus close to the Tombador Formation top, what suggests a tectonic origin for this unconformity.

Keywords: Tombador Formation, Mesoproterozoic, depositional sequences, facies analysis, continental and estuarine systems

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ESTRUTURA DA DISSERTAÇÃO

Sobre a Estrutura desta Dissertação:

Esta dissertação de mestrado está estruturada em torno do artigo científico intitulado: **Depositional Sequences and Facies Analysis in Continental and Estuarine Systems of the Upper Tombador Formation, Mesoproterozoic, Chapada Diamantina, Brazil**, submetido à revista *Sedimentary Geology* em dezembro de 2012. Consequentemente, a organização da dissertação esta disposta nos seguintes capítulos:

Capítulo 1: Apresenta a introdução sobre o tema central da pesquisa de mestrado.

Capítulo 2: Aborda o contexto geológico do Cráton do São Francisco e as principais unidades que compõem o Supergrupo do Espinhaço na Chapada Diamantina.

Capítulo 3: Apresenta uma abordagem teórica sobre sistemas aluviais do Pré-Cambriano, visto que as sequências deposicionais e as superfícies limítrofes definidas neste trabalho tiveram suas gêneses vinculadas totalmente ou parcialmente a estes sistemas. Foi discutido principalmente neste capítulo a dinâmica desses sistemas no Pré-Cambriano e a difícil caracterização de sistemas fluviais e leques aluviais dominados por rios no registro geológico.

Capítulo 4: Aborda as principais técnicas e métodos utilizados para a aquisição de dados e confecção dos mesmos.

Capítulo 5: Expõe as referências bibliográficas utilizadas nos capítulos anteriores.

Capítulo 6: Contém o artigo científico gerado ao término da pesquisa, apresentando uma estrutura interna similar a estrutura da dissertação.

1. INTRODUÇÃO

Sistemas de sedimentação antigos, em especial depósitos do Pré-Cambriano, são de grande interesse para a comunidade científica, visto que a natureza dos ambientes geológicos deste período – tectônica de placas, clima, atmosfera, vida – foram responsáveis pelas grandes diferenças em relação aos depósitos equivalentes no Fanerozoico. Em especial, os sistemas aluviais do Pré-Cambriano apresentam diferenças significativas quando comparados com os equivalentes do Fanerozoico (Eriksson *et al.*, 1998).

A sedimentologia dos sistemas aluviais – leques aluviais e canais fluviais entrelaçados – vem sendo amplamente descrita e discutida (Miall, 1970; Bull, 1972; Larsen & Steel, 1978; Rust, 1978; Cant & Walker, 1978; Nemec *et al.*, 1980; Allen, 1983; Nemec & Postma, 1993; Blair & McPherson, 1994a,b). O reconhecimento e a distinção de depósitos de planície fluvial entrelaçada e de leques aluviais no registro geológico muitas vezes são difíceis, especialmente no que se referem à similaridade das fácies e ausência muitas vezes de fácies gravitacionais, em decorrência da baixa preservação destes depósitos pela sua proximidade com a área fonte. Com base nisso, diversos autores (Miall, 1978, 1985; Collinson, 1978; Nemec & Postma, 1993; Postma, 1990; Reading & Orton, 1991) argumentam que não existe uma real distinção no registro entre depósitos de leques aluviais e canais fluviais entrelaçados.

A Formação Tombador compreende diferentes sistemas deposicionais, que vão desde sistemas costeiros-estuarinos a sistemas aluviais. Em conjunto com as formações Caboclo e Morro do Chapéu, compõem o Grupo Chapada Diamantina do Supergrupo Espinhaço, e consiste em depósitos sedimentares de idade Mesoproterozoica depositados numa bacia *sag*. O entendimento dos sistemas aluviais bem como os padrões deposicionais da Formação Tombador, enriquece a base científica dos depósitos sedimentares do Pré-Cambriano existentes no Brasil e no mundo, visto que reconstruções paleoambientais e análise de fácies em sistemas tão antigos são geralmente limitados devido à escassa preservação, resultantes de processos metamórficos e tectônicos ocorridos ao longo dos tempos.

Diversos trabalhos (Pedreira, 1994; Schobbenhaus, 1996; Dussin & Dussin, 1995; Guimarães *et al.*, 2008; Pedreira & Waele, 2008) realizados no Supergrupo Espinhaço abordam a evolução estratigráfica de toda a sequência sedimentar que compõe o supergrupo, em que os estudos são baseados principalmente em dados geocronológicos e litoestratigráficos. Poucos estudos (Alkmim & Martins-Neto, 2011; Magalhães *et al.*, 2012) são realizados acerca da evolução cronoestratigráfica com base principalmente no reconhecimento de sequências deposicionais limitadas por discordâncias. O estabelecimento de sequências deposicionais vinculadas geneticamente a sistemas aluviais podem refletir uma ampla interação entre tectônica, clima e eustasia, em que sistemas de leques aluviais ocorrem preferencialmente em ambientes tectonicamente ativos, estando sujeitos a alternâncias de períodos de quiescência e tectônica.

Definir discordâncias e caracterizar sequências deposicionais no Pré-Cambriano muitas vezes é difícil, devido à baixa preservação das bacias sedimentares, em que a sucessão vertical de fácies é limitada e também, pela carência de controle do tempo geológico, devido à escassez e complexidade do conteúdo fossilífero (Catuneanu, 2005). O intervalo estudado foi analisado baseado unicamente no reconhecimento de discordâncias, segundo a abordagem da estratigrafia de sequências, em que Mitchum *et al.* (1977) definem sequências deposicionais como unidades estratigráficas geneticamente relacionadas limitadas por discordâncias ou suas concordâncias correlatas. Para isso os critérios utilizados na identificação de discordâncias incluem: (1) mudança abrupta de fácies; (2) mudança na granulometria entre uma sequência e outra; e (3) mudança no padrão de paleocorrentes.

Com base nisso, os objetivos principais desse trabalho são: (1) caracterização e interpretação das principais associações de fácies; (2) elaboração de um arcabouço estratigráfico baseado na identificação de discordâncias; (3) propor um modelo paleogeográfico para os sistemas aluviais – leques aluviais e fluviais entrelaçados; e (4) estabelecer um modelo de evolução estratigráfica para as sequências aluviais e flúvio-estuarinas do topo da Formação Tombador.

Área de Localização

A Chapada Diamantina, situada na porção central do estado da Bahia, além de reunir uma ampla biodiversidade, expõem ao longo das suas serras, sucessões sedimentares proterozoicas. Este trabalho foi realizado a partir de observações de afloramentos da Formação Tombador, na Serra do Sincorá, próximos ao município de Lençóis, no Parque Nacional da Chapada Diamantina.

Foram levantados 6 perfis estratigráficos na escala de 1:100 alinhados de norte a sul em um transecto de 40 km (Fig. 1). As camadas sedimentares mergulham para leste, e os perfis verticais foram levantados ao longo dos rios com direção E-W. O mergulho das camadas é bastante variado ao longo das seções, e de uma seção à outra, devido a suaves estruturas de dobramentos existentes na região.

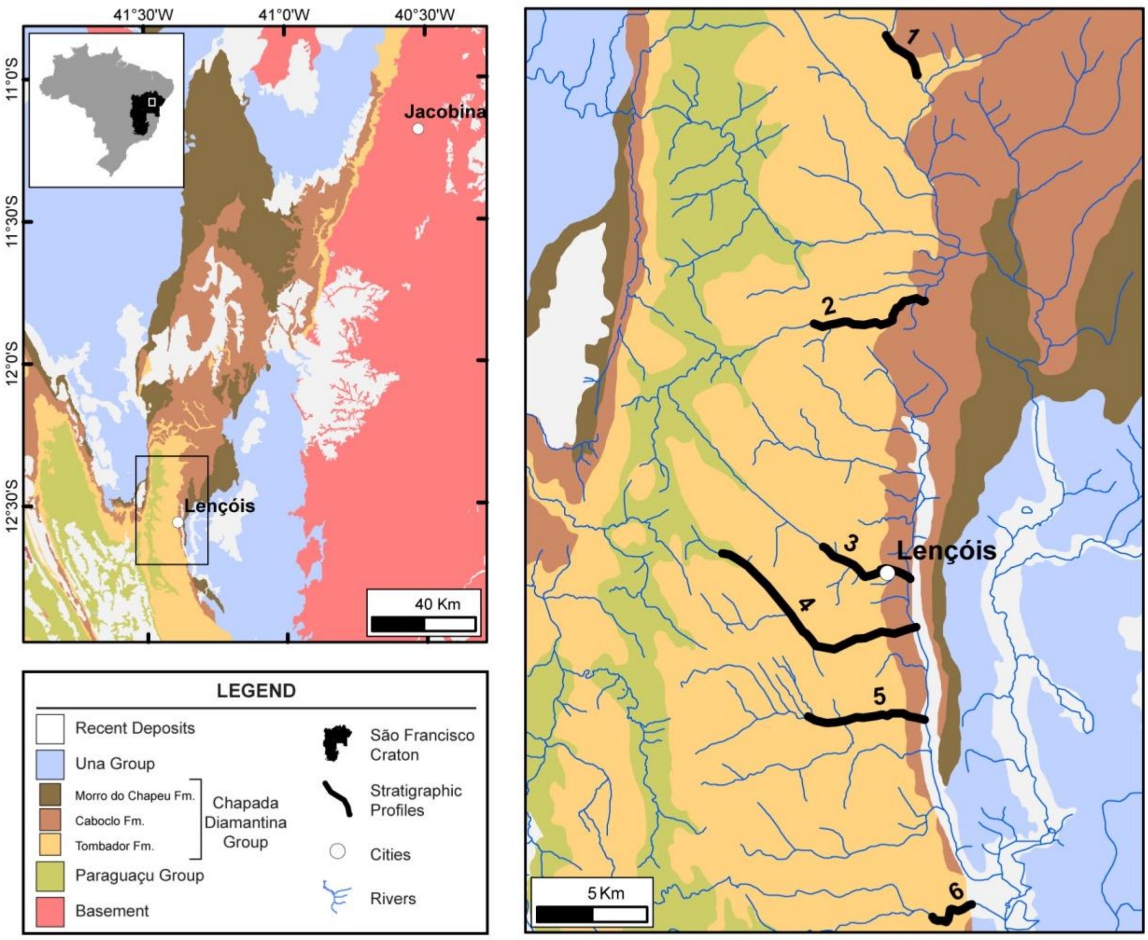

Figura 1. Mapa de localização apresentando mapa geológico simplificado da área de estudo mostrando os perfis estratigráficos levantados ao longo dos rios.

2. GEOLOGIA REGIONAL

A unidade sedimentar no qual foi desenvolvido este trabalho pertence a uma das principais unidades geotectônicas do Brasil, o Cráton do São Francisco. Em conjunto com o cráton africano do Congo, eles formaram em tempos do pré-Cambriano, a paleoplaca Congo-São Francisco, reconhecida por muitos como membro do supercontinente Rodínia (Weil *et al.*, 1998; Brito-Neves *et al*., 1999; Campos Neto, 2000). A longa ligação da paleoplaca Congo-São Francisco, que se estende talvez até 3,0 Ga (Weil *et al.*, 1998) envolve um extenso período de construções de bacias sedimentares interiores aos crátons. Entender os estilos de bacias sedimentares pré-cambrianas que se instalaram no interior dos crátons e os fatores formadores, como o magmatismo, a tectônica, a eustasia e o paleoclima é importante para compreender os processos sedimentares atuantes e os sistemas de sedimentação em tempos do pré-Cambriano.

2.1. O Cráton do São Francisco

O Cráton do São Francisco localizado no centro-leste do Brasil faz parte do Escudo Atlântico da Plataforma Sul-Americana, sendo individualizado como uma unidade geotectônica por Almeida (1977). É composto por um núcleo Arqueano e por dois segmentos de orógenos colisionais Paleoproterozoicos (Alkmim & Marshak, 1998; Alkmim & Martins-Neto, 2011), durante o evento geológico Transamazônico. Alkmim *et al.* (1993) redefiniu os limites do Cráton, anteriormente definidos por Almeida (1977). Circundado por faixas móveis de dobramentos é limitado a sul e oeste pela faixa Brasília, a noroeste limita-se com a faixa Rio Preto, a norte com as faixas Sergipana e Riacho do Pontal e a sudeste com a faixa Araçuaí. A leste o limite do Cráton é com as bacias sedimentares de Jequitinhonha, Almada, Camamu e Jacuípe.

Dois grandes domínios morfotectônicos (Cruz & Alkmim, 2006) foram individualizados no Cráton do São Francisco: a Bacia do São Francisco e o

Aulacógeno do Paramirim (Fig. 2). A Bacia do São Francisco ocupa todo o segmento alongado do cráton, enquanto que e o Aulacógeno do Paramirim é a grande feição morfoestrutural localizada a norte. Estes domínios são separados pelo Corredor do Paramirim e registram sucessões sedimentares semelhantes, com coberturas metassedimentares pré-cambrianas e fanerozoicas. O Aulacógeno do Paramirim representa uma grande feição morfoestrutural da porção norte do Cráton do São Francisco e corresponde a duas bacias riftes intracratônicas superpostas e parcialmente invertidas, preenchidos principalmente por metassedimentos Proterozoicos (Schobbenhaus, 1996; Cruz & Alkmim, 2006).

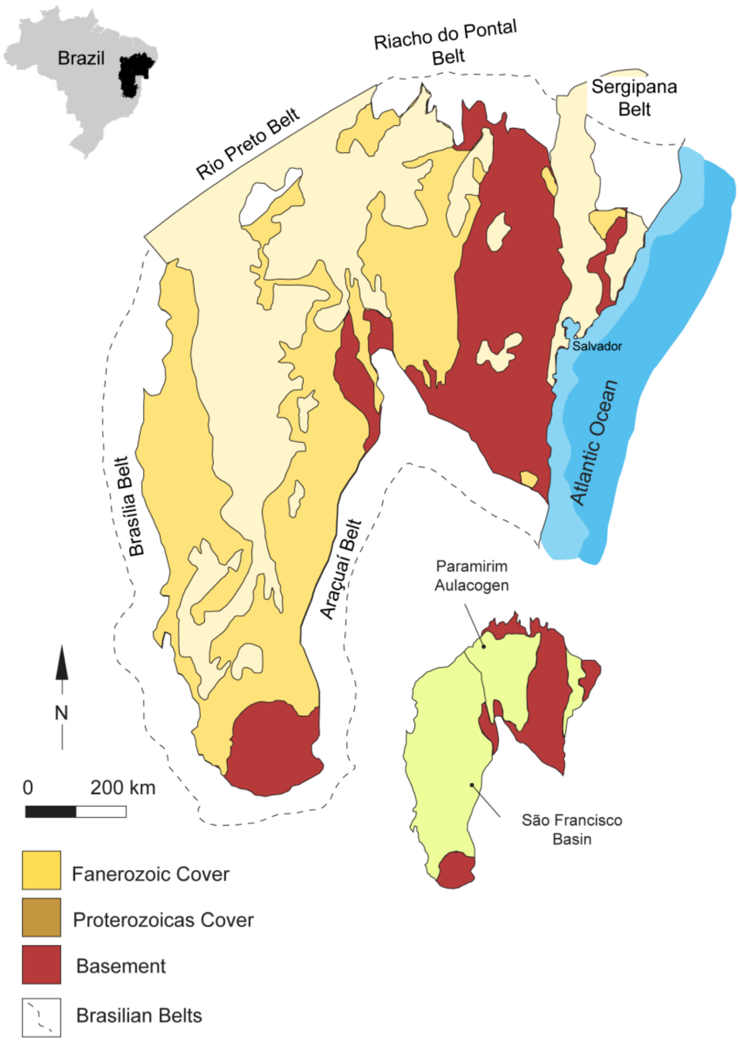

Figura 2. Mapa Geológico simplificado do Cráton do São Francisco e os domínios morfotectônicos: Bacia do São Francisco e Aulacógeno do Paramirim (Modificado de Alkmim *et al.*, 2003).

2.2. O Supergrupo Espinhaço

O Supergrupo Espinhaço é divido em três domínios: Serra do Espinhaço Meridional, Serra do Espinhaço Setentrional e Chapada Diamantina. O primeiro e o segundo domínio localizam-se a oeste do Corredor de Deformação do Paramirim, e o terceiro domínio localiza-se a leste. Para cada domínio foram adotadas nomenclaturas diferentes para as unidades deposicionais. O Supergrupo Espinhaço no domínio Chapada Diamantina, sendo um subobjetivo desta pesquisa será aqui caracterizado com uma breve revisão da estratigrafia. No domínio Chapada Diamantina, ele é dividido em três grupos (Figs. 3 e 4): Grupo Rio dos Remédios, Grupo Paraguaçu e Grupo Chapada Diamantina. Os dois primeiros grupos compõem uma sequência deposicional de 1ª ordem, com idade de 1,75 Ga (Schobbenhaus, 1996) e o Grupo Chapada Diamantina compõem uma segunda sequência deposicional de 1ª ordem, com idade de 1,5 Ga (Alkmim & Martins-Neto, 2011).

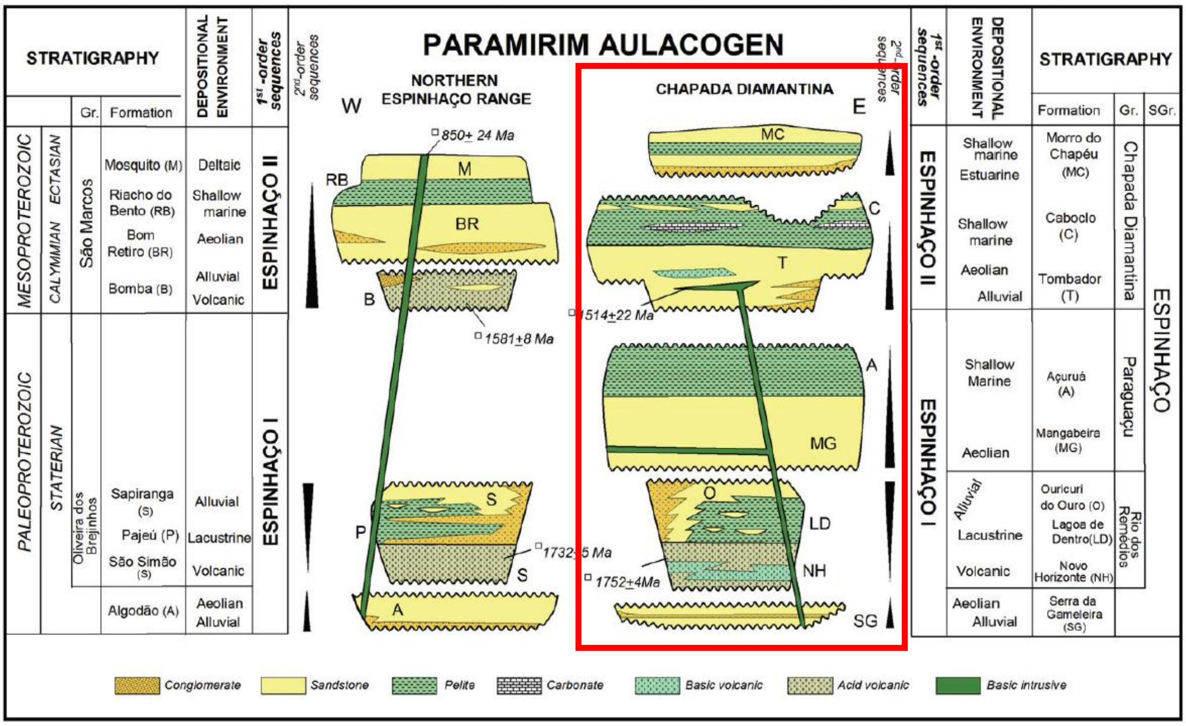

Figura 3. Coluna estratigráfica do Aulacógeno do Paramirim. O quadro vermelho coloca em destaca o domínio Chapada Diamantina (Extraída de Alkmim & Martins-Neto, 2011).

Grupos Rio dos Remédios/Paraguaçu

Os Grupos Rio dos Remédios e Paraguaçu foram depositados em uma bacia do tipo *rift-sag*, que em conjunto formam uma sequência deposicional de 1ª ordem (Alkmim & Martins-Neto, 2011), em que a evolução dessa bacia iniciou há *ca.* 1,75 Ga (Schobbenhaus, 1996). O Grupo Rio dos Remédios corresponde ao estágio *rift* (fase tectônica sinrifte), e o Grupo Paraguaçu representa o estágio *sag* (fase tectônica pós-rifte).

O Grupo Rio dos Remédios representa uma sequência deposicional de 2ª ordem (Alkmim & Martins-Neto, 2011), sendo dividido em três formações (Figs. 3 e 4): Novo Horizonte, Lagoa de Dentro e Ouricuri do Ouro. A primeira representa depósitos vulcânicos ácidos, relacionados a um magmatismo alcalino continental do início do rifte, enquanto que as duas últimas unidades representam depósitos sedimentares relacionados a sistemas lacustres (Formação Lagoa de Dentro) e aluviais (Formação Ouricuri do Ouro).

O Grupo Paraguaçu representa uma nova sequência deposicional de 2º ordem em que as unidades que compõem esse grupo foram depositadas sob um regime de subsidência termo-flexural, sem grandes atividades tectônicas relacionadas à fase *sag*. Separados da sequência anterior por uma discordância erosiva, a deposição desta unidade registra uma expansão da área deposicional da bacia (Alkmim & Martins-Neto, 2011), que é marcada pelo surgimento de sistemas costeiro-marinhos. É dividida em duas unidades deposicionais (Figs. 3 e 4): Formação Mangabeira e Formação Açuruá. A Formação Mangabeira compreende depósitos dominantemente eólicos, com alguma incursão fluvial, depositados em um sistema de *erg* costeiro, enquanto que a Formação Açuruá é representada por depósitos deltaicos e marinhos.

Grupo Chapada Diamantina

Durante o Caliminiano (1,5 Ga) um novo evento cratogênio na bacia do Espinhaço se estabelece, sendo depositado o Grupo Chapada Diamantina. Esta nova bacia *sag* foi implantada sobre o sítio deposicional anterior ultrapassando os limites da bacia (Guimarães *et al.*, 2008). A área deposicional destas unidades se estendeu por uma área aproximada de 68.000 km^2, apresentando uma ampla variação de fácies e de espessura. O Grupo Chapada Diamantina é divido em três formações (Figs. 3 e 4): Tombador, Caboclo e Morro do Chapéu.

A Formação Tombador, objeto de estudo neste trabalho, em conjunto com a Formação Caboclo representam um sequência deposicional transgressiva de 2ª ordem (Alkmim & Martins-Neto, 2011). Na borda oriental da bacia, entre os municípios de Jacobina e Morro do Chapéu, a Formação Tombador apresenta espessuras de até 160 metros (Silva Born, 2011), consistindo dominantemente de depósitos eólicos e fluviais efêmeros assentados diretamente sobre o embasamento cristalino. Já na região do município de Lençóis o limite basal da Formação Tombador é sobre a Formação Açuruá e é marcado por uma discordância angular (Derby, 1906; Pedreira, 1994). Nesta região a Formação Tombador apresenta espessuras de até 800 metros, consistindo em unidades basais flúvio-estuarinas que passam para depósitos essencialmente continentais, com sedimentação aluvial e eólica. O limite superior da Formação Tombador é definido por depósitos flúvio-estuarinos que passam gradativamente para depósitos marinhos rasos da Formação Caboclo.

Uma segunda sequência deposicional de 2ª ordem se estabelece, sendo depositados os sedimentos da Formação Morro do Chapéu. Essa unidade compreende sedimentos basais depositados por sistemas fluviais entrelaçados que preenchem vales incisos escavados nos sedimentos plataformais da Formação Caboclo, sendo sucedidos por depósitos estuarinos e deltaicos (Barbosa & Dominguez, 1996).

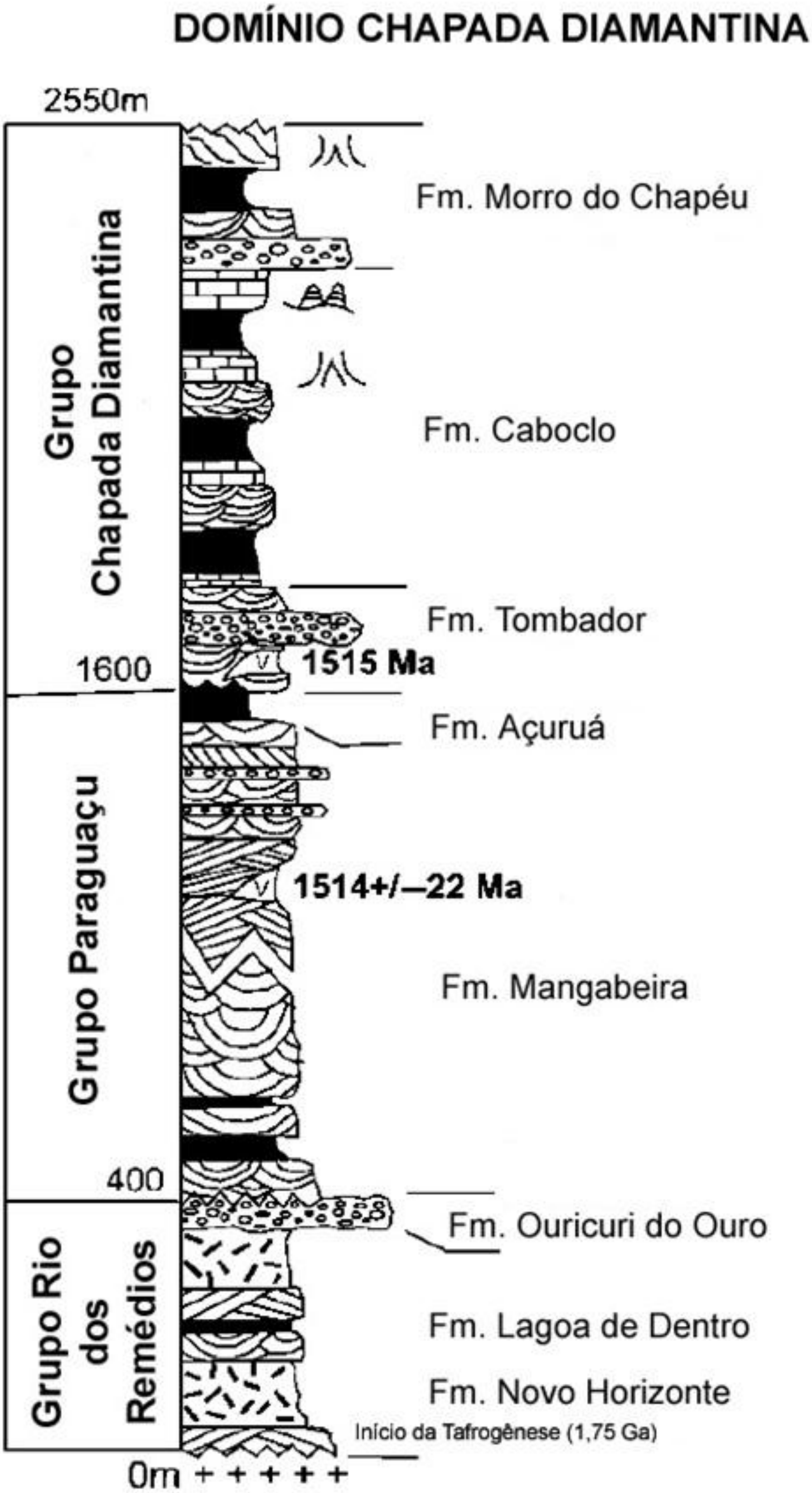

Figura 4. Coluna estratigráfica do Supergrupo Espinhaço, no domínio Chapada Diamantina, apresentando as grandes unidades deposicionais (Modificado de Pedreira & De Waele, 2008).

3. SISTEMAS ALUVIAIS NO PRÉ-CAMBRIANO: REVISÃO TEÓRICA

Durante o Pré-Cambriano, devido à ausência da vegetação, existiam amplos sistemas de canais fluviais com abundante carga de fundo, e altas descargas, formando extensas planícies fluviais entrelaçadas. Os depósitos de leques aluviais, no entanto, não foram muito comuns neste período. Isso porque a proximidade destes sistemas com as áreas fontes, tectonicamente instáveis, tornou difícil a preservação. A diferenciação entre sistemas fluviais e leques aluviais é bastante problemática em sucessões fanerozoicas, e ainda mais em depósitos do Pré-Cambriano, em que os sistemas de leques aluviais em suas porções distais são caracterizados por planícies fluviais entrelaçadas. A seguir será levantada uma discussão sobre a diferenciação entre esses depósitos e as principais características dos sistemas aluviais descritas no Pré-Cambriano (Eriksson *et al.*, 2006, 2008; Van der Neut & Eriksson, 2009; Davidson & Hartley, 2010; Köykkä, 2011).

3.1. SISTEMAS ALUVIAIS PROTEROZOICOS

Sistemas aluviais do Pré-Cambriano apresentam diferenças significativas quando comparados com os equivalentes do Fanerozoico (Eriksson *et al.*, 1998). A ausência da vegetação afeta as assinaturas sedimentológicas e geomorfológicas de uma bacia hidrográfica, alterando os processos hidráulicos e de deposição (Davies & Glibing, 2010). A ausência de raízes diminui a infiltração de água no substrato aumentando as taxas de escoamento superficial (Knighton, 1998) da mesma forma que os processos químicos de desagregação das rochas foi acelerado (Corcoran *et al.*, 1998), produzindo mais sedimentos para serem erodidos e transportados.

Schumm (1968) foi o primeiro autor que sugeriu que a falta de vegetação nos tempos do Pré-Cambriano implicou na alteração dos estilos fluviais. Sem a influência de proteção das plantas terrestres, o transporte eólico de sedimentos finos foi significativo (Dalrymple *et al.*, 1985), onde a remoção de sedimentos finos pelo sistema eólico teriam influenciado no predomínio de sistemas fluviais dominados por cargas de fundo (*bedload dominated rivers*).

A ausência da vegetação também permitiu com que os rios fluviais fossem instáveis e mais suscetíveis às variações climáticas, gerando uma instabilidade dos bancos arenosos e por consequência disso, frequente avulsão do sistema. Estes rios arenosos experimentaram uma rápida comutação e migração lateral dos canais por dezenas de quilômetros (MacNaughton *et al.*, 1997), consequência também da resposta efetiva dos canais às descargas instantâneas.

A geometria em lençol dos canais fluviais, formando corpos com razão de largura e espessura variando de 200:1 a 1000:1 (Fuller, 1985; Els, 1990; MacNaughton *et al.*, 1997), sugerem que houve um predomínio de canais fluviais entrelaçados durante o pré-cambriano (Schumm, 1968; Cotter, 1978; Long, 1978; Sønderholm & Tirsgaard, 1998). Alem disso, alguns autores chegam a sugerir que sem a vegetação para agir como um defletor entre deflúvio e evaporação, a maioria dos sistemas fluviais entrelaçados do pré-cambriano foram efetivamente efêmeros (Trewin, 1993b; Eriksson *et al.*, 1998; Long, 2004).

A sedimentação nos sistemas de leques aluviais em tempos de pré-vegetação também foi diferente, embora as diferenças possam ter sido mais sutis, em virtude do fato dos leques aluviais atuais se desenvolverem em contextos desérticos, onde a vegetação ocorra de maneira escassa (Went, 2005). Este autor observou que a falta de vegetação afetou significantemente os processos de sedimentação nos sistemas de leques aluviais em ambientes úmidos e áridos, sobretudo acelerando a erosão na superfície de declive desses sistemas e nas áreas de captação.

Os sistemas de leques aluviais ocorrem preferencialmente em ambientes tectonicamente ativos, nas regiões de borda de bacia, o que muitas vezes dificulta a sua preservação no registro geológico (Bose *et al.*, 2008). Estes sistemas estão sujeitos a alternâncias de períodos de intensa atividade tectônica, com períodos de quiescência. Durante os períodos de quiescência dominam os processos fluviais, predominando inundações em lençol que apresentam sedimentação cascalhosa na sua porção mais proximal, que passam para depósitos arenosos nas suas porções distais (Eriksson, 1978).

Durante os períodos ativos, a ausência de vegetação na superfície dos leques gera uma maior concentração de depósitos, facilitando à ruptura do talude, e consequentemente originando mais depósitos de fluxos de detritos e deslizamentos de rocha (Bose *et al.*, 2008). As condições paleoclimáticas do Pré-Cambriano, especialmente sobre o efeito estufa dominante na atmosfera daquela época, também foi um acionador para a grande quantidade de detritos produzidos (Donaldson & De Kemp, 1998).

Leques Aluviais Versus Canais Fluviais: Problemas na Diferenciação

A sedimentologia dos sistemas aluviais – leques aluviais e rios fluviais entrelaçados – há muito tempo vem sendo descrita e discutida (Miall, 1970; Bull, 1972; Larsen & Steel, 1978; Rust, 1978; Cant & Walker, 1978; Nemec *et al.*, 1980; Allen, 1983; Nemec & Postma, 1993; Blair & McPherson, 1994a,b). O reconhecimento e a distinção de depósitos de planície fluvial entrelaçada e de leques aluviais no registro geológico muitas vezes são extremamente difíceis, ainda mais quando se trata de sistemas aluviais Pré-Cambrianos.

Diversos autores (Miall, 1978, 1985; Collinson, 1978; Postma, 1990; Reading & Orton, 1991; Nemec & Postma, 1993) argumentam que não existe uma real distinção no registro, entre depósitos de leques aluviais e canais fluviais entrelaçados. Fundamentados em seus trabalhos, eles afirmam que os depósitos fluviais entrelaçados “*braided-stream*” ocorrem em ambos os sistemas, e alegam que a distinção só ocorre se associados a estes coexistirem depósitos de fluxos de detritos.

Miall (1990) sugere que o termo "leque aluvial" possa ser usado para qualquer sistema fluvial que não seja inteiramente marinho e/ou lacustre, contanto que a rede de canais seja distributária. Como observado por Miall (1992), existem diferentes tipos de leques aluviais, classificados por critérios faciológicos e geomorfológicos. Segundo ele, existem leques menores, dominados por processos gravitacionais, e leques aluviais "gigantes", como o moderno *Kosi*, localizado na Índia, que predominam processos fluviais. Existem também leques aluviais arenosos onde predominam os sistemas fluviais entrelaçados e os leques terminais, característicos de ambientes áridos, caracterizados por fluxos efêmeros. A partir disso, Stanistreet & McCarthy (1993) propuseram uma classificação para os diferentes estilos de leques aluviais, onde os processos fluviais podem ocorrer em diferentes proporções, dependendo de variáveis como o clima, a natureza da área-fonte, entre outros. A primeira classe de leques aluviais definida por eles foram os leques aluviais dominados por fluxos de detritos (Fig. 5), consistindo em sistemas menores com comprimento radial de no máximo 10 km. São leques aluviais que ocorrem particularmente em regiões áridas, em que os processos gravitacionais de sedimentos predominam. O segundo e terceiro estilo de leques aluviais são aqueles dominados por rios, entrelaçados e meandrantes (Fig. 5), denominados também como leques fluviais. Estes apresentam extensão radial maior que 50 km predominando processos fluviais. O reconhecimento desses sistemas no registro geológico muitas vezes é problemático, principalmente em dados de subsuperfície, em que os dados de paleocorrentes são ausentes, tornando-se impossível o reconhecimento do padrão semi-radial comum nesses sistemas.

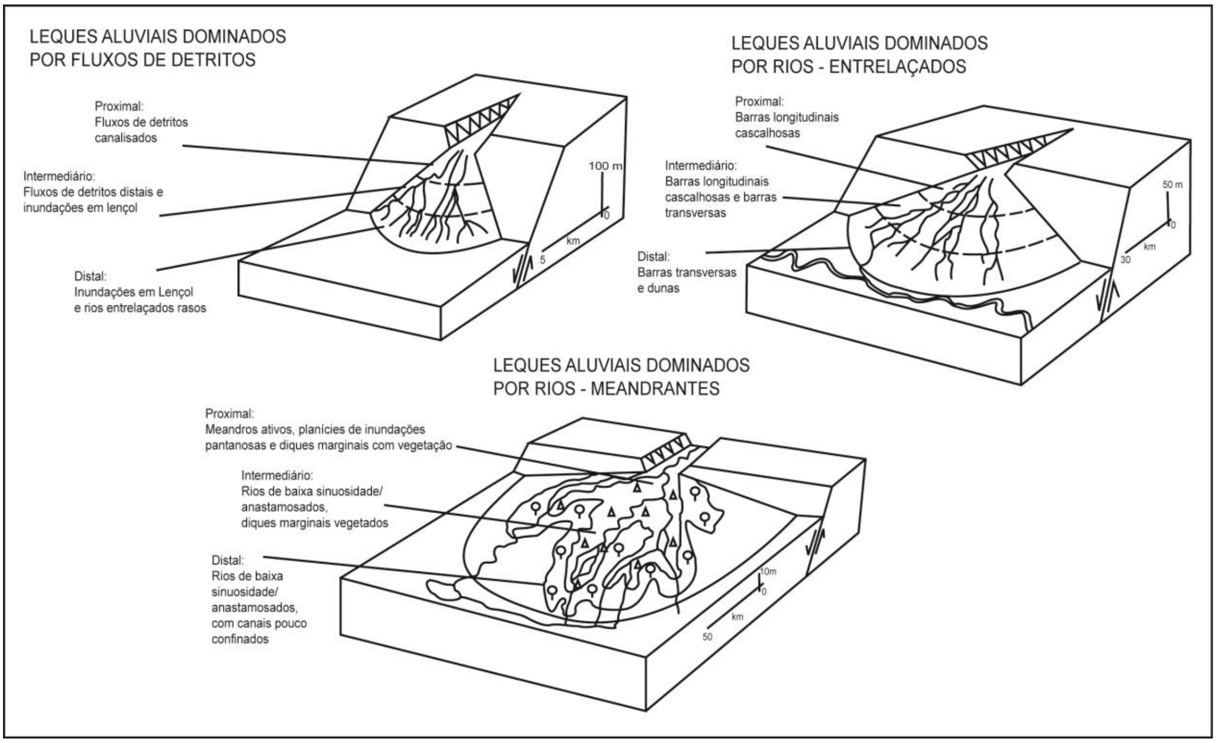

Figura 5. Modelos de leques aluviais de Stanistreet & McCarthy (1993): Leques Aluviais dominados por fluxos de detritos; Leques Aluviais dominados por Rios Entrelaçados e Leques Aluviais dominados por Rios Meandrantes.

Contrastando com esta abordagem Blair & McPherson (1994a, b) afirmam que existe distinção entre leques aluviais e sistemas fluviais, onde essa diferença é determinada pela morfologia, processos sedimentares e hidráulicos, e assembleia faciológica. Estes autores reconhecem os componentes geomórficos dos leques aluviais, que incluem a forma cônica radial, aclive íngreme deposicional e sua associação com áreas-fontes elevadas, sendo reconhecidos por eles dois estilos de leques aluviais (Fig. 6): leques aluviais dominados por fluxos de detritos e dominados por inundações em lençol. Blair & McPherson (1994a, b) afirmam que a singularidade da assembleia faciológica facilita a diferenciação no registro em ambientes onde o contexto geomórfico não se reconhece mais. Segundo eles, estes sistemas de leques aluviais são caracterizados por depósitos sedimentares de fluxo gravitacional, no qual dominam os processos de fluxos de detritos, fluxos hiperconcentrados e inundações em lençol, enquanto que processos de fluxos trativos são raros e/ou ausentes.

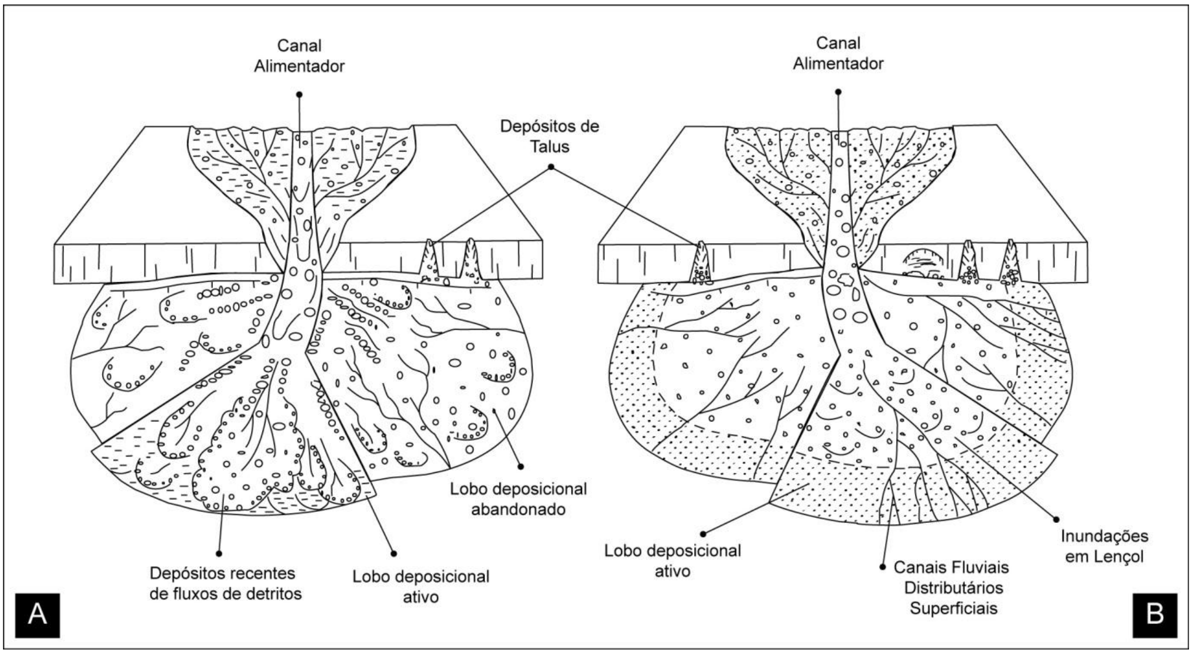

Figura 6. Modelos de leques aluviais de Blair & McPherson (1994a, b): a) Leques Aluviais dominados por fluxos de detritos e b) Leques Aluviais dominados por inundações em lençol.

Blair & McPherson (1994a, b) argumentam que talvez o maior equívoco a respeito dos leques aluviais é a crença de que eles são construídos a partir de sistemas de canais fluviais entrelaçados distributários. A ideia foi popularizada por Bull (1972) que escreveu:

> *[...] A maioria dos sedimentos dos leques aluviais consistem de depósitos em lençol siltico-areno-cascalhoso depositados por uma rede de canais fluviais entrelaçados distributários. . .. Os canais distributários rasos rapidamente são preenchidos por sedimentos e em seguida, deslocam-se a uma curta distância para outro local. Os depósitos resultantes comumente são depósitos fluviais arenosos e cascalhosos com geometria em lençol que*

> *são atravessados por canais rasos que repetidas vezes se dividem e se unem. . [...]*

No entanto a análise feita por Blair & McPherson (1994b) nos diferentes sistemas de leques aluviais que mostram canais fluviais distributários entrelaçados revelaram que estas características são superficiais. Elas são formadas tanto pelos processos primários de sedimentação, como a incisão de pequenos canais durante as inundações, e/ou tanto pelos processos secundários, que remoldam os depósitos primários, incluindo os fluxos de detritos e inundações em lençol. A identificação equivocada acerca da construção dos leques aluviais por processos secundários tem sido a causa das interpretações erradas de muitos sistemas fluviais entrelaçados, analisados como sistemas de leques aluviais. Estes autores apontam uma diferença contrastante entre os sistemas de leques aluviais e canais fluviais, em que este último apresenta superfícies côncavas para cima em cortes transversais enquanto que os leques aluviais apresentam superfícies convexas para cima.

A Questão da Caracterização dos Leques Aluviais no Pré-Cambriano

Conforme discutido anteriormente, a caracterização dos sistemas fluviais e leques aluviais geram discussões e controvérsias. Blair & McPherson (1994b) propuseram a diferenciação entre leques aluviais e canais fluviais entrelaçados com base nos parâmetros hidráulicos dos fluxos. Tanto nos canais fluviais quanto nos leques aluviais os três parâmetros - velocidade, regime do fluxo e tensão cisalhante - são fortemente influenciados pelas diferentes declividades. Eles argumentam também que existe uma quebra distinta nos valores dos gradientes longitudinais para os vários tipos de sistemas aluviais. Eles recomendam limitar o termo "leque aluvial" para sistemas com alto aclive, que apresentam valores de 1.5º e 25º (0.026 - 0.466) para as declividades. Já os sistemas fluviais entrelaçados, meandrantes e distributários exibem declividades menores do que 0.4º (declividade: 0.007). De acordo com estes autores, sistemas fluviais que apresentam valores entre 0.4º-1.5º (0.007 - 0.026) são raros (Fig. 7).

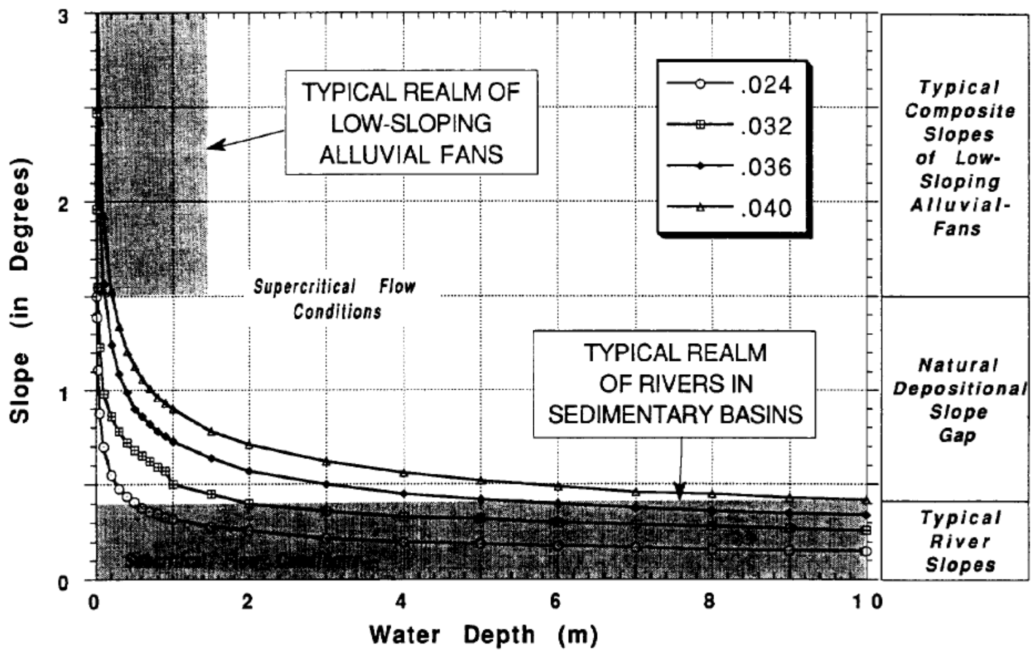

Figura 7. Diagrama de profundidade da lâmina da água *versus* declividade, proposto por Blair & McPherson (1994b). Valores de declividade de 0,024 – 0,040 indicam sistemas fluviais e valores superiores a 1,5 indicam leques aluviais. *Gap* deposicional natural apresenta valores de 0,04 – 1,5.

A questão é: Os parâmetros hidráulicos propostos pelos autores supracitados podem ser aplicados para as sucessões sedimentares do Pré-Cambriano? Para responder a esta pergunta, diversos autores (Eriksson *et al.*, 2006, 2008; Van der Neut & Eriksson, 2009; Davidson & Hartley, 2010; Köykkä, 2011) realizaram estudos paleohidrológicos em sucessões Pré-Cambrianas, a fim de estabelecer critérios acerca desta questão.

Eriksson *et al.* (2006) estimaram os parâmetros paleohidrológicos da Formação *Blouberg* (Grupo *Waterberg*, 2.06 - 1.88 Ga, África do Sul), a fim de explorar as possíveis características dos sistemas fluviais do Pré-Cambriano. Eles concluíram que não houve diferença nos valores dos hiatos (*gap*) das paleodeclividades para o Grupo *Waterberg*, e que o "hiato de deposição natural" (*gap depositional*) proposto por Blair & McPherson (1994b) apresentava valores menores no Pré-Cambriano. Eriksson *et al.* (2006) concluíram também que o cálculo da paleodeclividade a partir da carga variável de sedimentos usando a porcentagem de 5% de argila e silte é mais confiável do que utilizar os parâmetros de profundidade e largura dos canais, e que os valores que eles encontraram apresentam um comportamento similar aos rios fluviais, não existindo, portanto um estilo fluvial único para o Pré-Cambriano.

Eriksson *et al.* (2008) discutem um estilo fluvial único para o Paleoproterozoico baseado em dados paleohidrológicos. Ele contra argumenta o trabalho realizado por Blair & McPherson (1994b) onde não tem como aplicar os mesmos parâmetros hidrológicos para esta época. Esses autores realizaram um estudo no Grupo *Waterberg* (2.06 - 1.88 Ga, África do Sul), para estimar os valores paleohidrológicos da Formação *Mogalakwena*, pertencente a Bacia Principal (*Main Basin*) e também para comparar os resultados das paleodeclividades desta formação com as formações *Wilgerivier* (Bacia de *Middleburg*) e *Blouberg* (Bacia Principal). Estas unidades foram caracterizadas como sistemas fluviais entrelaçados, sendo que as duas últimas são correlatas entre si. Eles observaram que as paleodeclividades apresentaram valores entre 0.007 (máximo de rios fluviais) e 0.026 (mínimo de leques aluviais), valores que correspondem ao intervalo do *gap* deposicional definido por Blair & McPherson (1994b). Eles viram que é necessário postular algum mecanismo para o Paleoproterozoico, onde existiram de maneira localizada e de curta duração, aclives elevados, que aparentemente apresentavam configurações de sistemas fluviais entrelaçados.

Ao trabalhar com depósitos do Pré-Cambriano, é importante salientar que as taxas e intensidades dos processos foram diferentes, mas não os processos em si (Donaldson *et al.*, 2002; Eriksson *et al.*, 2004). Van der Neut & Eriksson (2009) sugeriram uma combinação única de intemperismo, ausência da vegetação e bacias com margens escarpadas (paleodeclividades íngremes) para os depósitos destas formações. Condições paleoclimáticas quentes e úmidas são inferidas em grande parte no Paleoproterozoico, produzindo maior quantidade de sedimentos finos. Com isso, é postulado que fluxos de detritos e fluxos hiperconcentrados tenham ocorrido nos sistemas fluviais cascalhosos, sendo trazidos por sistemas de leques aluviais e posteriormente incorporados aos sistemas de rios fluviais.

Köykkä (2011) realizou um estudo numa bacia rifte, de idade Mesoproterozoica (*Rjukan Rift,* Noruega), a fim de caracterizar os padrões de sedimentação de planícies fluviais entrelaçadas e leques aluviais. Os valores apresentados por ele sugerem interpretar os sistemas como leques aluviais do que rios fluviais, embora muito dos valores encontram-se plotados no intervalo do gap deposicional proposto por Blair & McPherson (1994b). Ele considera que os canais fluviais das margens escarpadas não foram muito bem preservados, devido à tectônica e a evolução da bacia. Köykkä (2011) relaciona que os poucos valores plotados que apresentaram valores de 0.026 m/m indicam resquícios destes canais íngremes, relacionados à borda escarpada e que o gap deposicional indica uma intercalação dos sistemas de leques aluviais distais e sistemas de planícies fluviais entrelaçadas. Como apontado por Eriksson *et al.* (2006) é possível que este "hiato" tenha sido muito menor durante o Pré-cambriano.

4. TÉCNICAS E MÉTODOS

As técnicas e métodos utilizados envolvem trabalhos de laboratório e de campo. O levantamento bibliográfico em conjunto com análise de mapas e fotografias aéreas permitiu um reconhecimento preliminar da Formação Tombador, onde os melhores afloramentos consistem em exposições naturais ao longo dos rios e serras existentes no Parque Nacional da Chapada Diamantina. O levantamento dos perfis estratigráficos e as paleocorrentes foram adquiridos em várias idas ao campo, no período de janeiro a novembro de 2011, totalizando 53 dias de campo. A seguir, uma breve descrição das técnicas e métodos.

4.1. Levantamento Bibliográfico

O levantamento bibliográfico persistiu durante todo o trabalho e consistiu na aquisição e leitura de artigos científicos, teses de doutorado e trabalhos de conclusões acerca do contexto geológico, abordando a Formação Tombador e a Bacia do Espinhaço. Somado a isto, também foi feita uma revisão bibliográfica sobre sistemas deposicionais do Pré-Cambriano, principalmente sistemas aluviais Proterozoicos. Entender os processos geológicos que atuaram no Pré-Cambriano foi importante para caracterizar as associações de fácies e o modelo deposicional da Formação Tombador.

4.2. Imagens, Fotografias Aéreas e Mapas

Foram utilizadas imagens de Radar SRTM (*Shuttle Radar Topography Mission*) obtidas gratuitamente através do site da USGS (http//:seamless.usgs.gov). O uso dessas imagens serviu como base altimétrica para a construção das seções geológicas. As fotografias áreas tiveram importância no estudo preliminar da área.

Foram obtidas através do site da CBPM (Companhia Baiana de Pesquisa Mineral), apresentando escala 1:108.000. O mapeamento pelas fotografias aéreas foi importante para definir áreas com prováveis afloramentos, em que os critérios principais utilizados para identificar essas áreas foram as diferenças de tonalidades e o relevo. A integração dos dados gerou como produto final mapas geológicos, topográficos e de detalhes. Foi utilizado o *software ESRI® ArcMap*^{TM} *10.0*, em que todos as imagens e fotografias áreas, bem como os dados dos alforamentos, como as coordenadas foram inseridos neste programa (Fig. 8). O sistema de coordenada utilizado foi a projeção UTM e datum horizontal SAD69, zona 24S. A base geológica do mapa foi extraída da CPRM (Companhia de Produção e Recursos Minerais) e a base topográfica, contendo dados de hipsografia, hidrografia, estradas, pontos de referência foi obtida através da SEI (Superintendência de Estudos Sociais e Econômicos da Bahia).

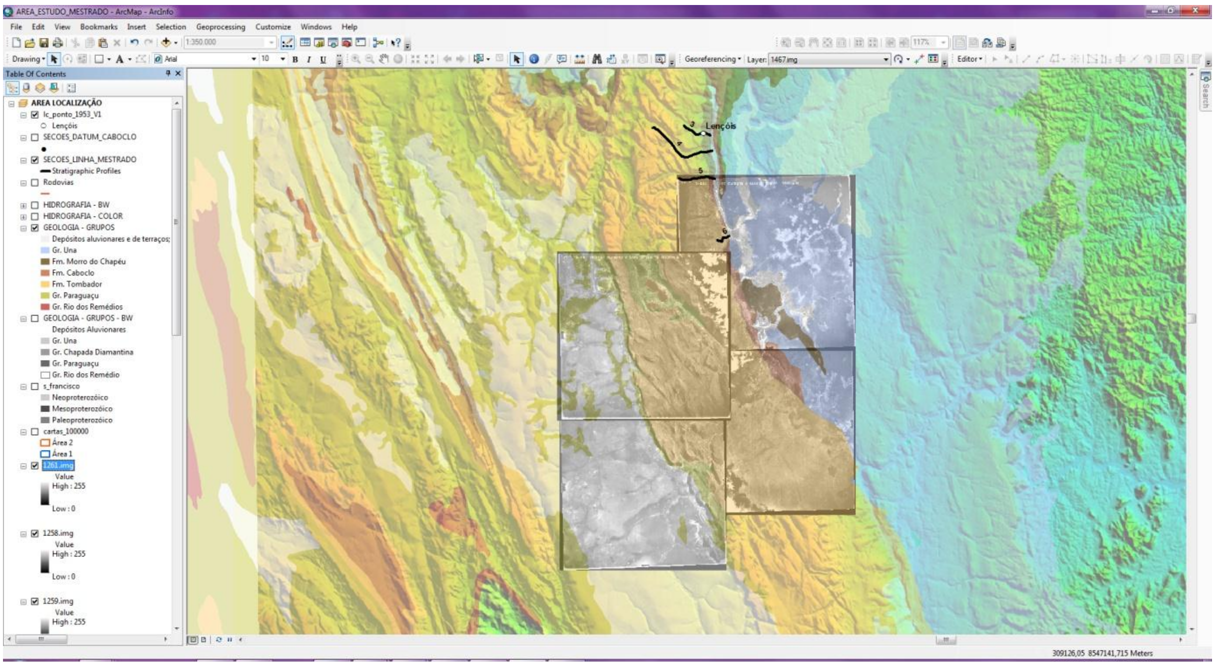

Figura 8. Mapa geológico confeccionado no *ESRI® ArcMap*^{TM} *10.0*, com todos os elementos utilizados: imagem SRTM, fotografia aérea e base geológica.

4.3. Levantamento Estratigráfico

O levantamento estratigráfico representa a principal etapa para a realização do estudo. Como em muitos casos, a área a ser estudada localiza-se em lugares distantes da localidade em que se reside, exigindo um deslocamento, é importante que a aquisição dos dados seja feita de maneira correta. Para isso, o estabelecimento de coletas sistemáticas é indispensável para obter um resultado final satisfatório.

O levantamento estratigráfico consiste na confecção de seções colunares, descrição sedimentológica, aquisição de dados de paleocorrentes, aquisição de fotografias e coleta de coordenadas geográficas para cálculos de encobertos, quando existir. As seções colunares foram construídos seguindo uma planilha já preparada no laboratório (Fig. 9). São representações gráficas das rochas em forma de coluna, em que o eixo horizontal representa a granulometria e o eixo vertical representa a espessura das camadas. Neste trabalho foi utilizada a escala 1:100 e o preenchimento das lacunas é feito através das fácies observadas.

Os atributos que definem a fácies são: cor, geometria, composição, textura, estruturas sedimentares e conteúdo fossilífero. Para determinação da textura, foi utilizada uma tabela textural de campo, elaborada pela Petrobras. Através dela, pode-se determinar com precisão a granulometria e com o auxílio de uma lupa, estima-se o grau de arredondamento do grão e a seleção dos sedimentos. Neste trabalho foram utilizados os conceitos de litofácies de Reading (1996). Este autor sugere que se o conteúdo fossilífero for ausente ou de pouca importância e a ênfase for sobre as características físicas e químicas da rocha, o termo mais indicado é litofácies. As diferentes litofácies podem ser agrupadas em associações de litofácies, caracterizando subambientes deposicionais implicando em um significado genético dentro de sistemas deposicionais definidos (Miall, 1984).

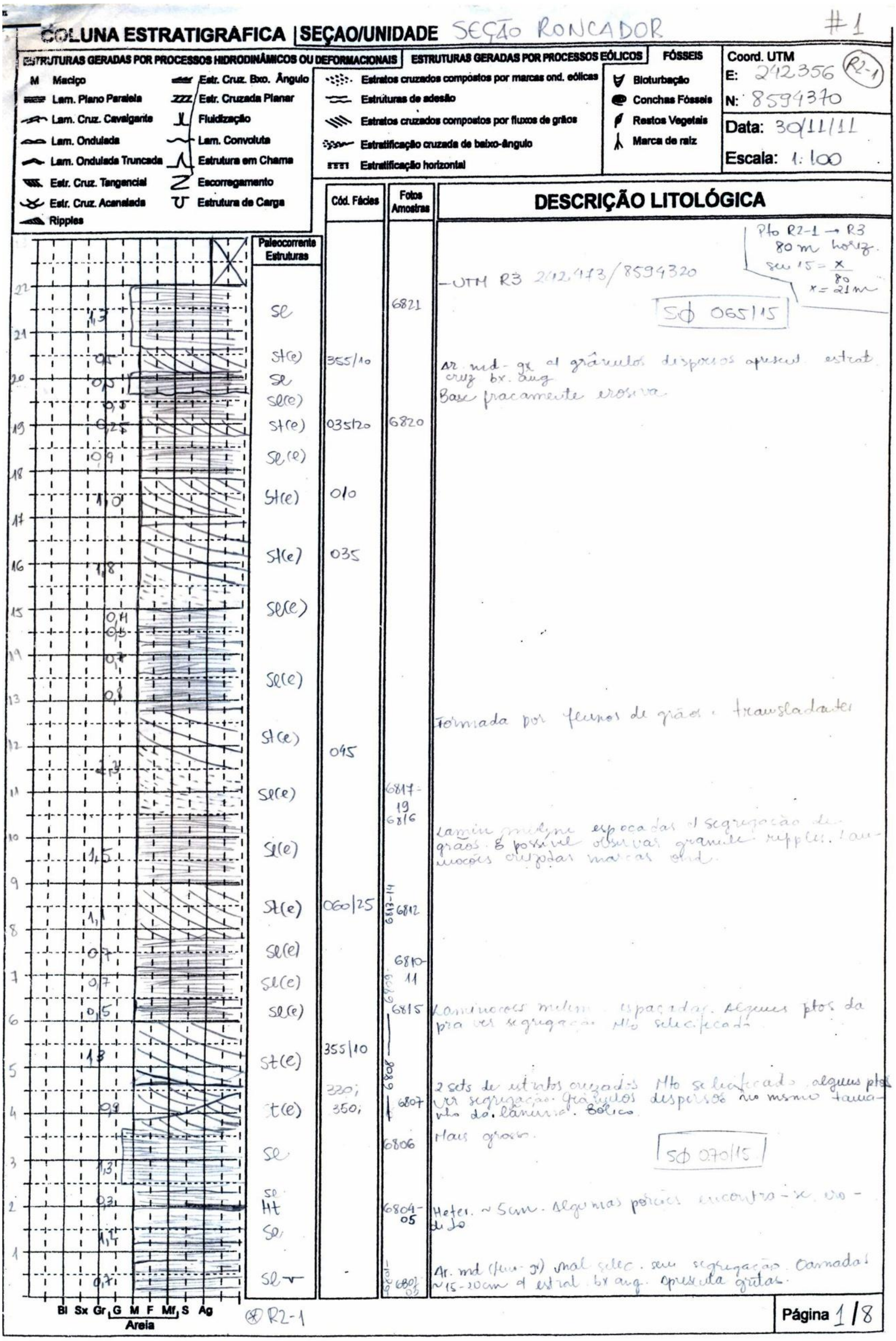

Figura 9. Parte da seção colunar levantada no Rio Roncador. Exemplo de como é adquirido o dado geológico, em que é possível observar da esquerda para a direita: desenho gráfico com as estruturas observadas, o código de litofácies, os dados de paleocorrentes, a numeração das fotografias e a descrição sucinta das litofácies.

As litofácies foram classificadas de acordo com Miall (1996), onde este propôs uma simples classificação para sistemas fluviais, usando duas letras como código (Fig. 10). A primeira letra é maiúscula e indica o tamanho de grão dominante, onde G = *gravel* (cascalho), S = *sand* (areia) e F = *fine-grained* (areia muito fina, silte e argila) e a segunda letra é minúscula e indica textura ou estrutura, como exemplo, p = estratificação cruzada planar (*planar cross-bedding*). Para classificar as litofácies do sistema eólico foi utilizada a mesma tabela, porém, foi adotado o uso da letra “e” entre parênteses depois do código, da mesma forma que as litofácies dos sistemas estuarinos também foram adaptadas.

A aquisição dos dados de paleocorrentes foi obtida utilizando uma bússola Brunton. A notação trama (*Dip Direction*) foi adotada, em que o ângulo horizontal entre a direção de mergulho do plano e o norte magnético e o ângulo vertical entre o plano da estrutura e um plano horizontal imaginário foram medidos. As principais estruturas sedimentares medidas foram as superfícies deposicionais (S_0) das camadas e estruturas e fábricas que indicam a direção do fluxo, como, marcas onduladas, estratificação cruzada, lineação de partição, seixos imbricados.

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Table 4.1. Facies classification. (Modified from Miall 1978c)

Facies code	Facies	Sedimentary structures	Interpretation
Gmm	Matrix-supported, massive gravel	Weak grading	Plastic debris flow (high-strength, viscous)
Gmg	Matrix-supported gravel	Inverse to normal grading	Pseudoplastic debris flow (low strength, viscous)
Gci	Clast-supported gravel	Inverse grading	Clast-rich debris flow (high strength), or pseudoplastic debris flow (low strength)
Gcm	Clast-supported massive gravel	–	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits
Gt	Gravel, stratified	Trough cross-beds	Minor channel fills
Gp	Gravel, stratified	Planar cross-beds	Transverse bedforms, deltaic growths from older bar remnants
St	Sand, fine to very coarse, may be pebbly	Solitary or grouped trough cross-beds	Sinuous-crested and linguoid (3-D) dunes
Sp	Sand, fine to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Transverse and linguoid bedforms (2-D dunes)
Sr	Sand, very fine to coarse	Ripple cross-lamination	Ripples (lower flow regime)
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination parting or streaming lineation	Plane-bed flow (critical flow)
Sl	Sand, very fine to coarse, may be pebbly	Low-angle (< 15°) cross-beds	Scour fills, humpback or washed-out dunes, antidunes
Ss	Sand, fine to very coarse, may be pebbly	Broad, shallow scours	Scour fill
Sm	Sand, fine to coarse	Massive, or faint lamination	Sediment-gravity flow deposits
Fl	Sand, silt, mud	Fine lamination, very small ripples	Overbank, abandoned channel, or waning flood deposits
Fsm	Silt, mud	Massive	Backswamp or abandoned channel deposits
Fm	Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
Fr	Mud, silt	Massive, roots, bioturbation	Root bed, incipient soil
C	Coal, carbonaceous mud	Plant, mud films	Vegetated swamp deposits
P	Paleosol carbonate (calcite, siderite)	Pedogenic features: nodules, filaments	Soil with chemical precipitation

Figura 10. Classificação das litofácies de Miall (1996).

Em todos os perfis estratigráficos foram tiradas fotografias de detalhe, de intervalo e fotografias para a confecção de fotomosaicos. Os números das fotografias foram anotados na planilha da coluna estratigráfica e as descrições das fotografias foram descritas na caderneta de campo. Como os perfis estratigráficos foram levantados ao longo dos rios, e devido ao difícil acesso para levantar o perfil foi necessário calcular o encoberto. O encoberto foi calculado utilizando funções trigonométricas. Quando possível era calculado no campo e, mas muitas vezes foi calculado em laboratório, através de seções geológicas, construídas através do programa *Global Mapper 11.0* (Fig. 11).

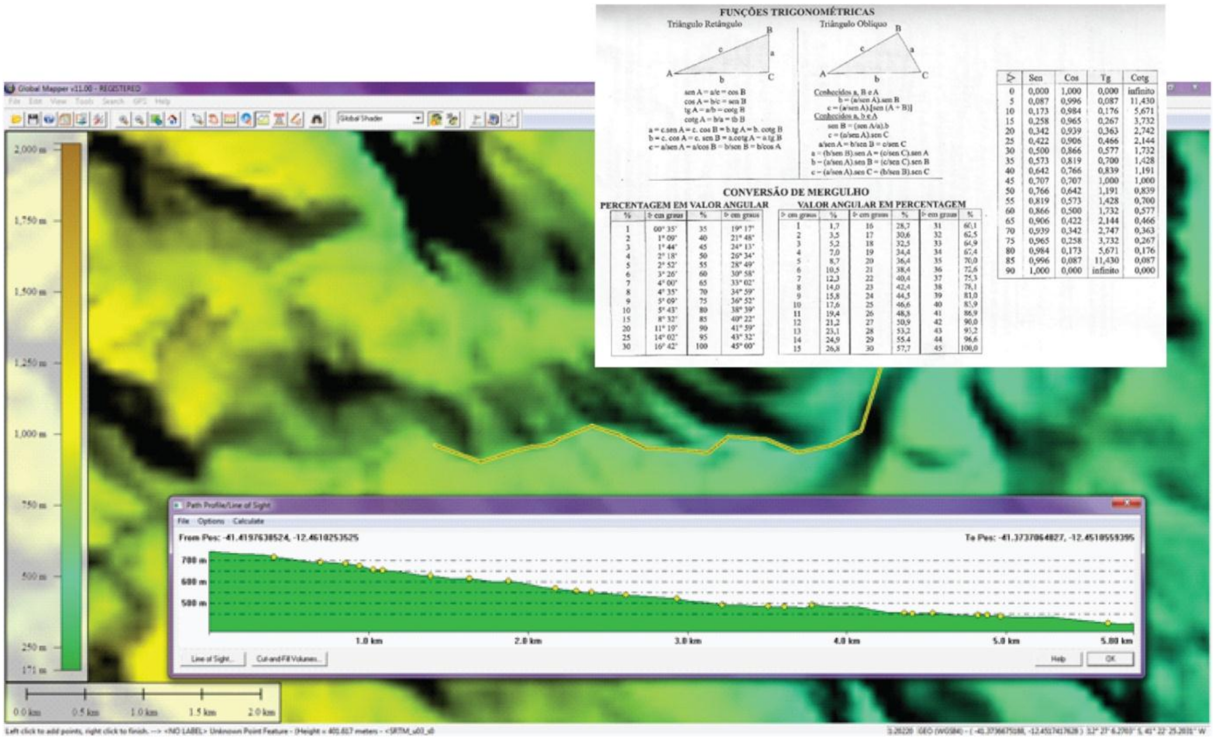

Figura 11. Seção geológica do Rio Mucugêzinho utilizando o programa *Global Mapper*, e funções trigonométricas, ambas utilizadas para o cálculo de encobertos.

4.4. Correção e Confecção dos Diagramas de Paleocorrentes

Como os afloramentos da Formação se encontram em sua maioria tectonicamente inclinados, apresentando um ângulo superior a 12º, grande partes das estruturas medidas foram corrigidas e tratadas estatisticamente (Fig. 12). Segundo Tucker (1982) quando camadas sedimentares encontram-se inclinadas é necessário restaurar as direções medidas nas estruturas sedimentares para suas orientações originais. A correção foi realizada a partir do programa *StereoWin* e os dados foram apresentados na forma de diagramas de rosetas pelo software *RockWorks 15.0*.

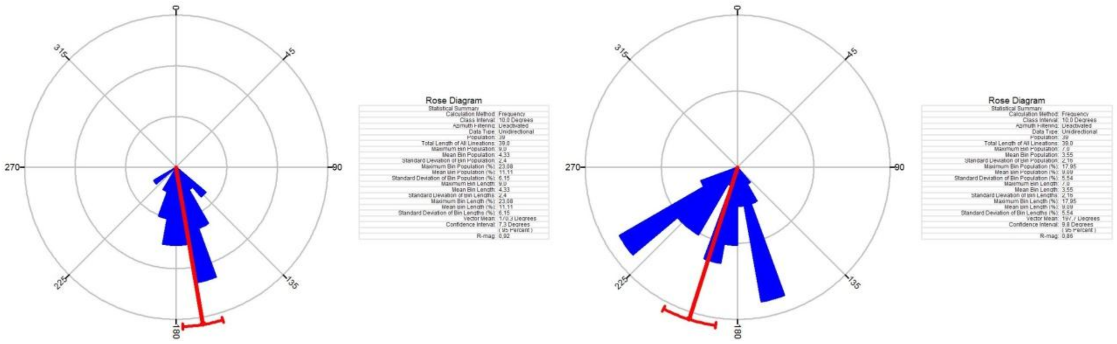

Figura 12. À esquerda: diagrama de rosetas das paleocorrentes medidas. À direita: diagrama de rosetas das paleocorrentes corrigidas.

4.5. Correlação de Seções Estratigráficas

A correlação estratigráfica consiste numa ferramenta essencial para interpretações geológicas. No entanto, os depósitos aluviais geralmente são difíceis de mapear e correlacionar devido a frequente mudança lateral das fácies e a ausência de camadas contínuas individuais (Miall, 1996).

Neste trabalho, a correlação estratigráfica teve como base a correlação de sequências deposicionais limitadas por discordâncias regionais. Os critérios adotados para a identificação de superfícies de discordâncias foram: mudança abrupta da granulometria, mudança abrupta de associações de fácies e mudança no padrão de paleocorrentes.

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Depositional Sequences and Facies Analysis in Continental and Estuarine Systems of the Upper Tombador Formation, Mesoproterozoic, Chapada Diamantina, Brazil

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Abstract

The Mesoproterozoic Tombador Formation encompasses different depositional systems deposited in a sag basin, ranging from estuarine to alluvial. The well preserved deposits and their wide occurrence in the regional scale (~300 km) define the Tombador Formation as an excellent case study for the depositional patterns prevailing during the Proterozoic. Three depositional sequences were recognized for the Upper Tombador Formation, bounded by three semi-regional scale unconformities. Sequence I is composed of shallow, gravel-bed braided channels at its base, which are overlain by fine- to coarse-grained sandstones related to aeolian sand sheets and dunes and intermediate sheetfloods. The lower boundary of this sequence is characterized by an angular unconformity cutting fluvio-estuarine deposits, evidenced by an abrupt change of facies and fluvial palaeocurrents. The fluvio-estuarine deposits below the sequence boundary display palaeocurrents to northwest, whereas the fluvial strata above the unconformity show southeastward palaeocurrents. A new abrupt entrance of conglomeratic deposits related to alluvial fans systems overlying the fluvio-aeolian successions marks the lower boundary of Sequence II. The Sequence

III is characterized by fluvio-estuarine systems in the top of the Upper Tombador Formation, that are progressively covered by shallow marine systems (Caboclo Formation), defining a general transgressive trend. The pattern of sequences I and II probably reflects the uplift of source areas in response to tectonic movements. The palaeocurrent change in Sequence I indicates a regional rearrangement of the drainage networks, while the alluvial fan systems of sequence II suggest sin-depositional tectonic pulses. The regional erosive surface between sequences II and III reveals a significant hiatus close to the Tombador Formation top, what suggests a tectonic origin for this unconformity.

Keywords

Tombador formation, Mesoproterozoic, depositional sequences, facies analysis, continental and estuarine systems

1. Introduction

The study of the Proterozoic continental succession is very difficult, both in a sedimentological and a stratigraphic point of view. Precambrian alluvial systems exhibit significant differences when compared with their Phanerozoic equivalents (Eriksson et al., 1998). The sedimentology of alluvial systems – including alluvial fans and braided channels – has been widely reported and discussed (Miall, 1970; Bull, 1972; Cant and Walker, 1978; Allen, 1983; Nemec and Postma, 1993; Blair and McPherson, 1994a, b). The recognition and distinction between these systems in the geological record are not easy, since the alluvial fan systems, in many cases, pass to fluvial braidplain towards in their more distal portions. The similarity of facies, poor preservation of debris flow deposits and the need to identify the palaeocurrent patterns at semi-regional scale, causes the frequent misinterpretation of Precambrian alluvial fan systems as braided channels. Furthermore, few papers in the literature develop a sequence stratigraphic approach in Proterozoic continental successions. The recognition of unconformities and the definition of depositional sequences are limited, due to poor preservation of sedimentary basins, combined with the absence of fossil content, which renders difficult the establishment of a cronostratigraphic framework (Catuneanu et al., 2005).

The Mesoproterozoic Tombador Formation, Espinhaço Supergroup of the Chapada Diamantina domain, eastern Brazil, comprises different depositional systems deposited in a sag basin, ranging from estuarine-coastal to alluvial systems. The Upper Tombador Formation, object of this work, comprises mostly alluvial fan and fluvial systems. Several studies, based mostly on lithostratigraphic and geochronological data (Pedreira, 1994; Schobbenhaus, 1996; Dussin and Dussin, 1995; Guimarães *et al.*, 2008; Pedreira and Waele, 2008), address the stratigraphic evolution of the entire Espinhaço Supergroup sedimentary succession. Considering this, the aim of this works are to: (1) characterize and interpret the main facies associations; (2) develop of a stratigraphic framework based on the identification of unconformities; (3) propose a palaeogeographic and depositional model for the alluvial systems; and (4) establish an evolutive stratigraphic model for the alluvial and fluvio-estuarine sequences on the Upper Tombador Formation.

2. Geological Setting

The Palaeo-Mesoproterozoic Espinhaço Supergroup comprises a succession of metasedimentary and subordinate volcanic rocks and is one of the main sedimentary successions of the São Francisco Craton. Along with the São Francisco Supergroup (Alkmim, 2004), these units comprise the Proterozoic sedimentary cover on the morphotectonic features of the Paramirim aulacogen in the northern portion of the craton (Fig. 1). The Espinhaço Supergroup was subdivided into three main domains: the southern Espinhaço, located on the Araçuaí Belt (Minas Gerais state), the northern Espinhaço, and the Chapada Diamantina, located on the Paramirim Aulacogen (Bahia state; Almeida, 1977; Alkmim, 2004).

The Espinhaço basin records a series of depositional events, alternating different sedimentation and tectonic episodes over time (Danderfer and Dardene, 2002; Danderfer et al., 2009). Recent studies on the Espinhaço Supergroup in the Paramirim aulacogen defined two depositional sequences bounded by first order surfaces (Guimarães et al., 2008; Danderfer et al., 2009; Alkmim and Martins-Neto, 2011), reflecting the evolution of two superimposed rift-sag basins. In the Chapada Diamantina domain, the first rift-sag basin (1.75 – 1.57 Ga) is represented by the Rio dos Remédios and Paraguaçu groups, while the other sag basin (1.57 – 0.9 Ga) is represented by the Chapada Diamantina Group.

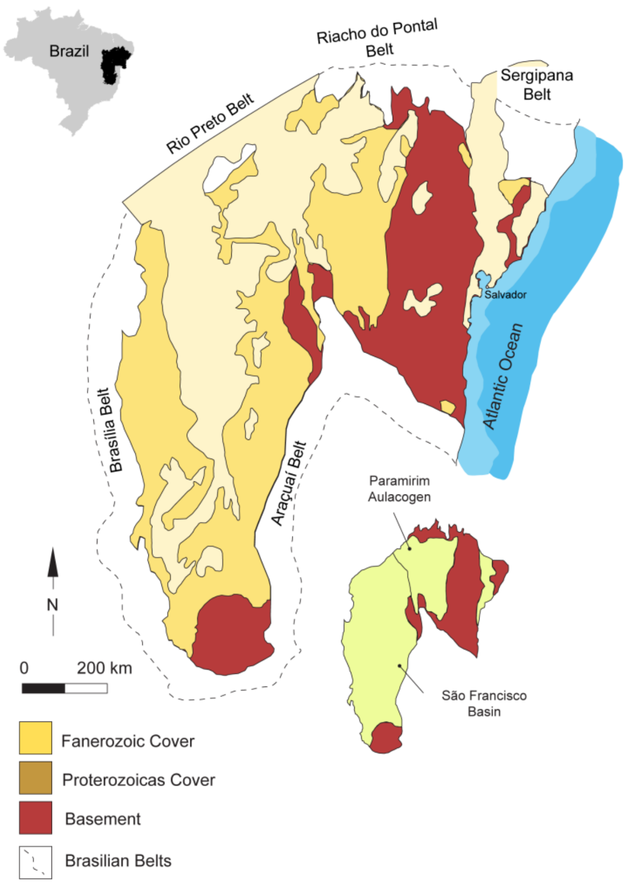


Fig. 1. Simplified map of the São Francisco Craton and its sedimentary cover (Modified from Alkmim et al., 1993).

The beginning of the Espinhaço Supergroup sedimentation in the Chapada Diamantina domain occurred at approximately 1.75 Ga. Related to an extensional intracratonic event with associated anorogenic magmatism, it generated a series of intracontinental rifts. The rifting stage is represented by the Rio dos Remédios Group, and the Paraguaçu Group represents the sag basin stage. The Rio dos Remédios Group comprises continental siliciclastic depositional systems (alluvial fans, aeolian, and fluvio-deltaic-lacustrine systems) and associated volcanic units deposited under conditions in which tectonics primarily controlled sedimentation. These deposits are covered by the sedimentary succession of the Paraguaçu Group, representing a phase of thermal subsidence in which the paleoclimate and eustasy began controlling the sedimentation (Guimarães et al., 2008; Loureiro et al., 2009). A new event occurred during the Calymmian (1.4 – 1.2 Ga), and a second episode of basic magmatism (1.57 Ga, Babinski et al., 1999; Battilani et al., 2007; Loureiro et al., 2009; Danderfer et al., 2009) marks a new tectonic extension in the Paramirim aulacogen. This new extensional and expansion phase in the basin is controlled by flexural crust subsidence (Guimarães et al., 2008), which created a second boundary of first-order sequences (Guimarães et al., 2008; Danderfer et al., 2009; Alkmim and Martins-Neto, 2011; Guadagnin *et al.*, in prep.). The Chapada Diamantina Group represents this new sag basin, which is placed on the rift-sag sedimentary sequences of the Rio dos Remédios and Paraguaçu groups. This sequence comprises alluvial, estuarine, and fluvio-aeolian deposits (Tombador Formation) succeeded by shallow marine systems (Caboclo Formation). A new sequence boundary occurs at the top of the marine sequence (Dominguez, 1993; Alkmim and Martins-Neto, 2011), representing a fluvial incision combined with a lowering of the base level and depositing tidal estuarine sediments (Morro do Chapéu Formation, Dominguez, 1992; Pedreira, 1994).

The Tombador Formation, together with the Caboclo and Morro do Chapéu formations, comprises the Chapada Diamantina Group (Fig. 2a). In the present study, the maximum described thickness Tombador Formation was of 600 meters, overlying with an angular unconformity the deltaic deposits of the Açuruá Formation (Derby, 1906; Pedreira, 1994), and being composed of alluvial, estuarine, and aeolian deposits. The upper limit to the Caboclo Formation is gradational, characterising the Tombador and Caboclo formations as a transgressive sequence.

3. Methods and Study Area

The study was carried out along six vertical sections at 1:100 scale from outcrops of the Tombador Formation in the Sincorá Range, near the Lençóis city, and outcrops near the Jacobina city in the central portion of the state of Bahia (Fig. 2a). The sedimentary layers dip to the east, and vertical sections were collected along the EW direction on river valleys (Fig. 2b). Generally, the rivers cliffs offer excellent exposures with good lateral continuity. However, it was necessary to calculate the stratigraphic thickness covered by vegetation using trigonometric functions. The dip of the layers varies throughout the sections and from one section to another, because of soft folding structures. The dip angle of the layers ranged from 5° to 25°, and corrections in paleocurrent data were performed for structural dips exceeding 12°. Data collected included grain size, mineralogy, sedimentary structures, geometry and surface boundaries. Paleocurrent data were recorded mostly from cross-stratified beds, ripple cross-laminations and, less frequently, pebble imbrication.

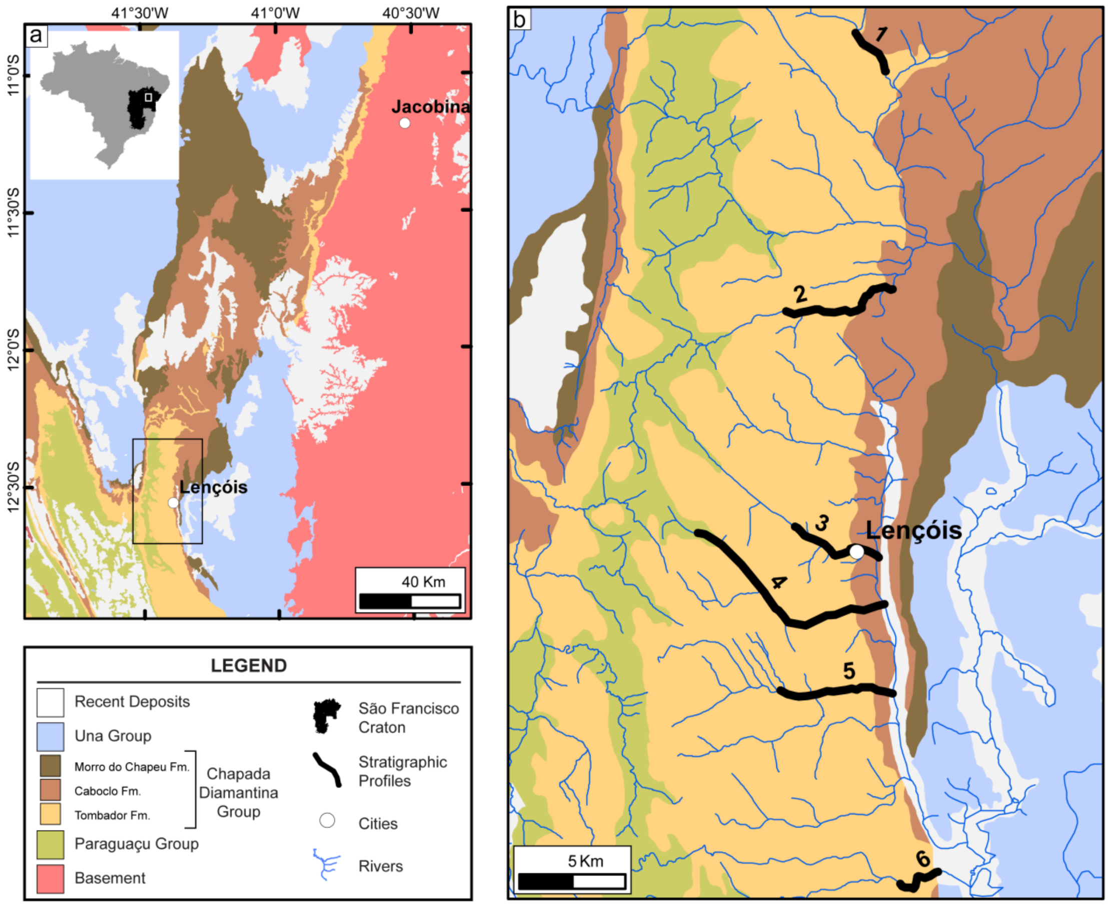


Fig. 2. In (a) simplified geologic map of the study area in the Chapada Diamantina Domain and (b) location of the vertical sections studied.

4. Sedimentary Facies and Facies Association

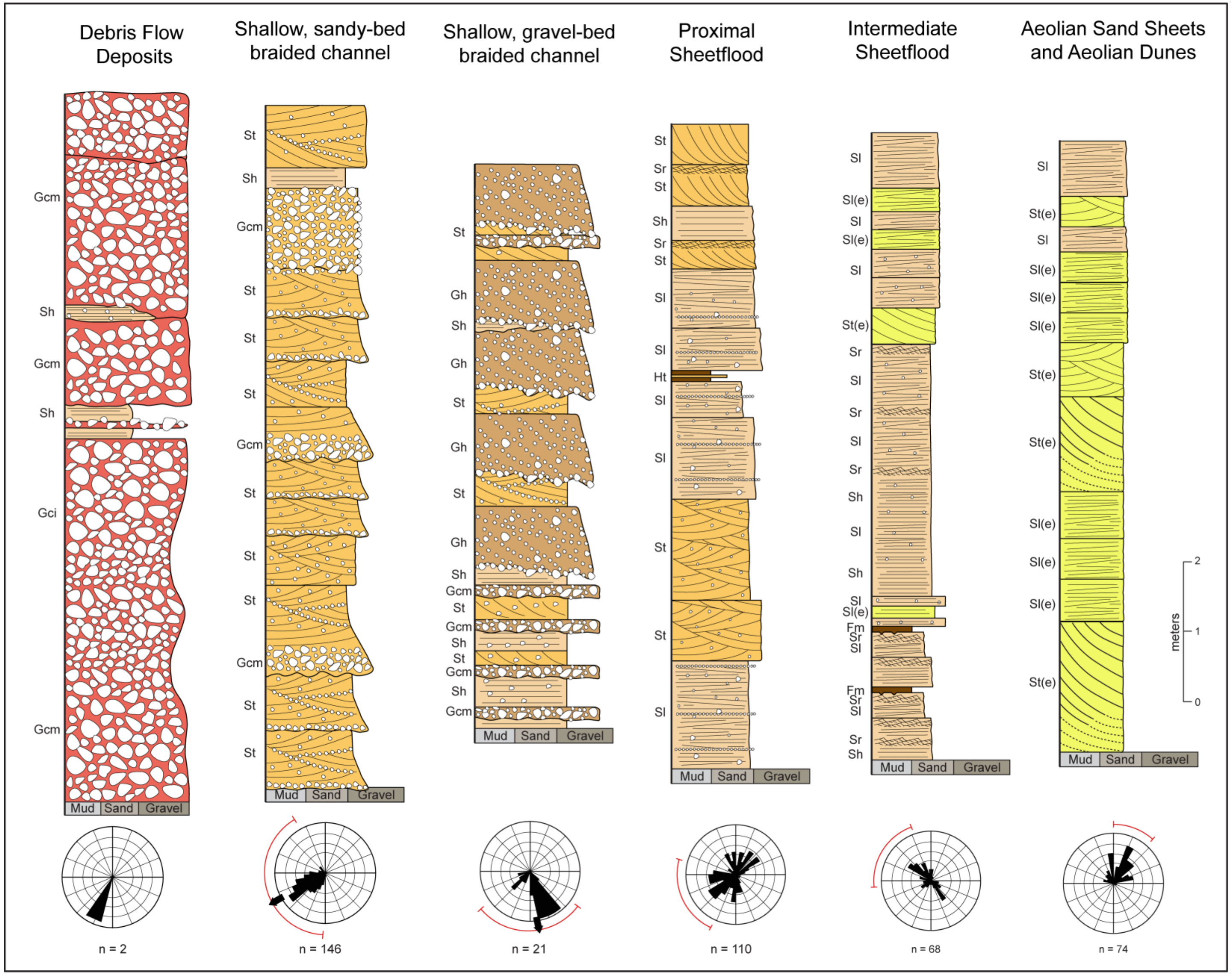
Based on the characteristic lithology, grain size, and sedimentary structures, seventeen different sedimentary facies were recognized in the Tombador Formation (Table 1). These facies were grouped into ten genetically-related facies associations (Fig. 3): (i) debris flow deposits; (ii) shallow, gravel-bed braided channel; (iii) shallow, sand-bed braided channel; (iv) proximal sheetflood; (v) intermediate sheetflood; (vi) aeolian sand sheets and aeolian dunes; (vii) floodplain deposits; (viii) tide-influenced shallow, sand-bed braided channel; (ix) upper flow regime tidal flats; and (x) shoreface.

Table 1. The main facies and their occurrence in the facies association identified in the Upper Tombador Formation (modified from Miall, 1996).

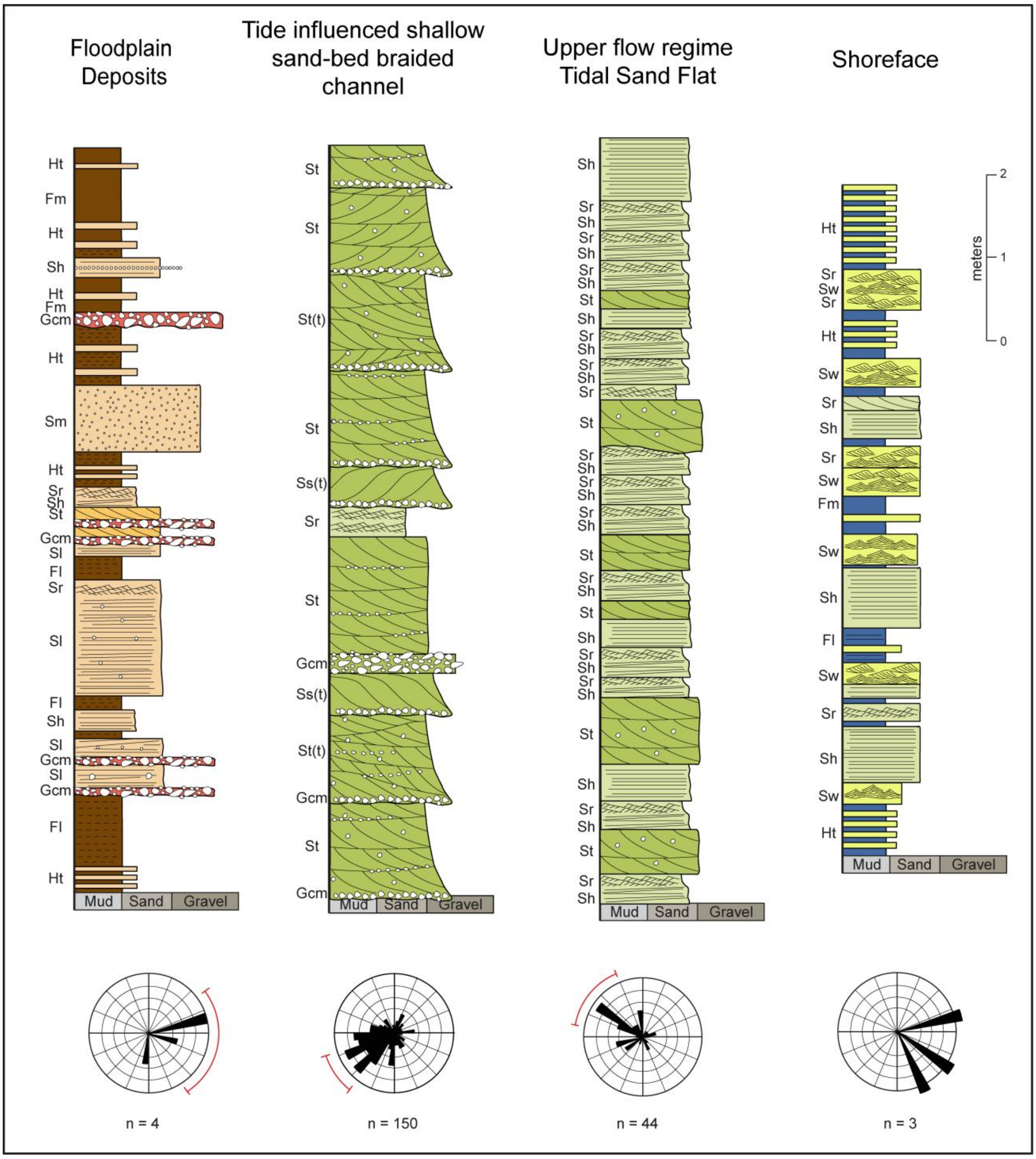
Facies Code	Textures	Structures	Interpretation	Facies Association
Gci	Pebble- to boulder-supported conglomerates	Inverse grading	Clast-rich debris flow (high strength) or pseudoplastic debris flow (low strength)	Debris flow deposits
Gcm	Pebble- to boulder-supported conglomerates	Massive	Pseudoplastic debris flow (inertial bedload, turbulent flow) or deposition by high-density hyperconcentrated flows	Debris flow deposits; Shallow, gravel-bed braided fluvial; Shallow, sand-bed braided fluvial; Floodplain deposits
Gh	Pebble- to cobble-supported conglomerates	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits	Shallow, gravel-bed braided fluvial
Sh	Very fine- to coarse-grained sandstones, may be pebble	Horizontal lamination, parting lineation	Plane-bed flow (upper flow regime)	Debris Flow Deposits; Shallow, gravel-bed braided fluvial; Shallow, sand-bed braided fluvial; Proximal Sheetfloods; Intermediate Sheetfloods; Floodplain deposits; Upper flow regime Sand Flats; Shoreface
Sl	Very fine- to coarse-grained sandstones, may be pebble	Low-angle cross-stratification (<10º)	Scour fills, washed-out dunes, attenuated dunes (transitional flow regime)	Proximal Sheetfloods; Intermediate Sheetfloods; Tide Influenced Shallow, sand-bed braided channels

St	Very fine- to coarse-grained sandstones, may be pebble	Solitary or grouped trough cross-stratification	Sinuous-crested and linguoid dunes (3D), migration of longitudinal bars in the channels (lower flow regime)	Debris Flow Deposits; Shallow, gravel-bed braided fluvial; Shallow, sand-bed braided fluvial; Proximal Sheetfloods; Intermediate Sheetfloods; Floodplain deposits; Tide Influenced Shallow, sand-bed braided channels; Upper flow regime Sand Flats
Sr	Very fine- to coarse-grained sandstones	Ripple cross-lamination	Climbing ripple migration, subcritical to supercritical, unidirectional to bidirectional. Lower flow regime subaqueous traction deposits	Proximal Sheetfloods; Intermediate Sheetfloods; Floodplain deposits; Tide-influenced braided fluvial; Tide Influenced Shallow, sand-bed braided channels; Upper flow regime Sand Flats; Shoreface
Sm	Very fine- to coarse-grained sandstones, may be pebble	Massive	Hyperconcentrated flow, intense bioturbation	Shallow, gravel-bed braided fluvial; Intermediate Sheetfloods; Floodplain deposits; Upper flow regime Sand Flats
Sw	Siltstone to very fine- to medium-grained sandstones	Climbing wavy ripple-lamination	Alternating flow energy under wave influence	Upper flow regime Sand Flats; Shoreface
St(t)	Very fine- to coarse-grained sandstones, may be pebble with mud drapes	Trough cross-stratification bounded by reactivation surfaces	Subaqueous dunes migration 2D and 3D and migration of subaqueous bars in the channels under the influence of tidal currents, bidirectional current, mud drapes from slack-water periods	Tide Influenced Shallow, sand-bed braided channels
Ss(t)	Very fine- to coarse-grained sandstones, may be pebble	Sigmoidal-cross-stratification bounded by reactivation surfaces	Acceleration changing to full vortex flow conditions, followed by deceleration within a single tide	Tide Influenced Shallow, sand-bed braided channels
Ht	Very fine- to fine-grained sandstones alternating with siltstone	Horizontal lamination and/or ripple cross-lamination	Alternating deposition from traction currents and suspension, channel abandonment or overbank	Proximal Sheetfloods; Floodplain Deposits
Fl	Very fine-grained sandstones to siltstone	Horizontal lamination	Deposition from suspension or from very low current	Floodplain deposits; Shoreface

Fm	Very fine-grained sandstones to siltstone	Massive, may be mudcracks and rain prints	Deposition from suspension and flocculation, subaerial exposure	Shoreface
Sh(e)	Fine- to coarse-grained sandstones	Horizontal and wind-ripple lamination	Migration of wind-ripple under conditions of net sedimentation	Aeolian sand sheets and Aeolian dunes
Sl(e)	Fine- to coarse-grained sandstones	Low-angle stratification and wind-ripple lamination;	Residual deposits of dunes or sandsheets with attenuated dunes	Aeolian sand sheets and Aeolian dunes
St(e)	Fine- to coarse-grained sandstones	Grainflow laminae; wind-ripple lamination; trough cross-stratification	Residual deposits of 3D crescentic bedforms. Grainflow laminae indicate dunes with well-developed slipfaces.	Aeolian sand sheets and Aeolian dunes


Debris Flow Deposits
Shallow, sandy-bed braided channel
Shallow, gravel-bed braided channel
Proximal Sheetflood
Intermediate Sheetflood
Aeolian Sand Sheets and Aeolian Dunes
Gcm
Sh
Gci
St
Gh
Sr
Sl
Ht
Sl(e)
St(e)
Fm
Mud
Sand
Gravel
meters
0
1
2
n = 2
n = 146
n = 21
n = 110
n = 68
n = 74

Part 1



Part 2

Fig. 3. Typical facies assemblages and vertical logs for facies association 10, with respective palaeocurrent values. Facies codes are informed at left.

4.1. Facies Association 1: Debris Flow Deposits

Description

This facies association consists of poorly-sorted, massive, clast-supported (**facies Gcm;** Fig. 4a) and inverse-graded (**facies Gci;** Fig. 4b) conglomerates. Modal grain size varies from granules to boulders with boulder dominant clast size. Clasts are sub-angular to sub-rounded and the matrix is constituted by coarse-grained feldspathic sand. The clasts show weak imbrication (Fig. 4c). At the Jacobina area, this facies association occurs directly on the gneissic-granitic basement, with a maximum thickness up to 40 m and individual beds 1 to 5-m-thick. Occasionally, some clast-supported conglomerate exhibits inverse, coarse-tail grading (**facies Gci**) arranged in 1-m-thick beds, and the dominant clast composition is green and white quartzite. At the Lençóis city, the thicknesses range from 2 to 18 m, and individual beds are 2 to 5 m-thick. Clasts are composed by 70% sedimentary rocks and 30% white and green quartzites (Fig. 4d). In both regions the clast-supported conglomerate beds are up to 100-m-wide with irregular sub-horizontal, weakly erosive basal surfaces. The clast-supported conglomerate beds are capped by lenticular beds up to 0.3-0.5-m-thick, horizontal-stratified (**facies Sh;** Fig. 4e) or trough cross-stratified (**facies St**), coarse-grained sandstones. Sandstone beds usually contain dispers small pebbles and clast imbrication, with unidirectional palaeocurrent to the southwest.

Interpretation

This facies association is interpreted as sediment-gravity-flow deposits. The clast-supported nature, poor sorting, absence of internal organisation and presence of sand matrix, suggest deposition from cohesionless debris flows in which the sediments are transported by frictional grain interactions (Nemec and Steel, 1984; Blair and McPherson, 1994a, b). The absence of clay in the interparticle matrix causes the flow not to present cohesive strength, and instead, dispersive, turbulent, buoyant and structural-grain forces are the sedimentary transport mechanisms (Blair and McPherson, 1994a, b). The presence of sub-horizontal, irregular and weakly erosive basal contacts suggest the presence of a more turbulent flow in a first stage (Wells and Harvey, 1987). The deposition of clast-supported conglomerates with coarse-tail inverse grading indicates different responses to the dispersive and buoyant forces, in which larger clasts are concentrated on the top and front of the flow due to the density differences between these particles and surrounding material (Nemec and Steel, 1984). The occurrence of amalgamated beds suggests that the debris flows deposits consist of a sum of surges, wherein the deposition occurs by incremental aggradation of individual surges (Davies, 1986, 1990; Major, 1997; Sohn, 1999). The localised imbrication of some clasts in restricted intervals is common in deposits of cohesionless debris flows, in which the transfer of the solid-solid momentum is dominant, and clasts are forced to parallel the shear tension of the grain to grain collisions (Rees, 1968; Postma et al., 1988; Todd, 1989, 1996). The coarse grained plane-parallel laminated and trough cross-bedded sandstones are attributed to the aqueous flows from sheetfloods that succeeded debris flows (Ballance, 1984; Wells, 1984).

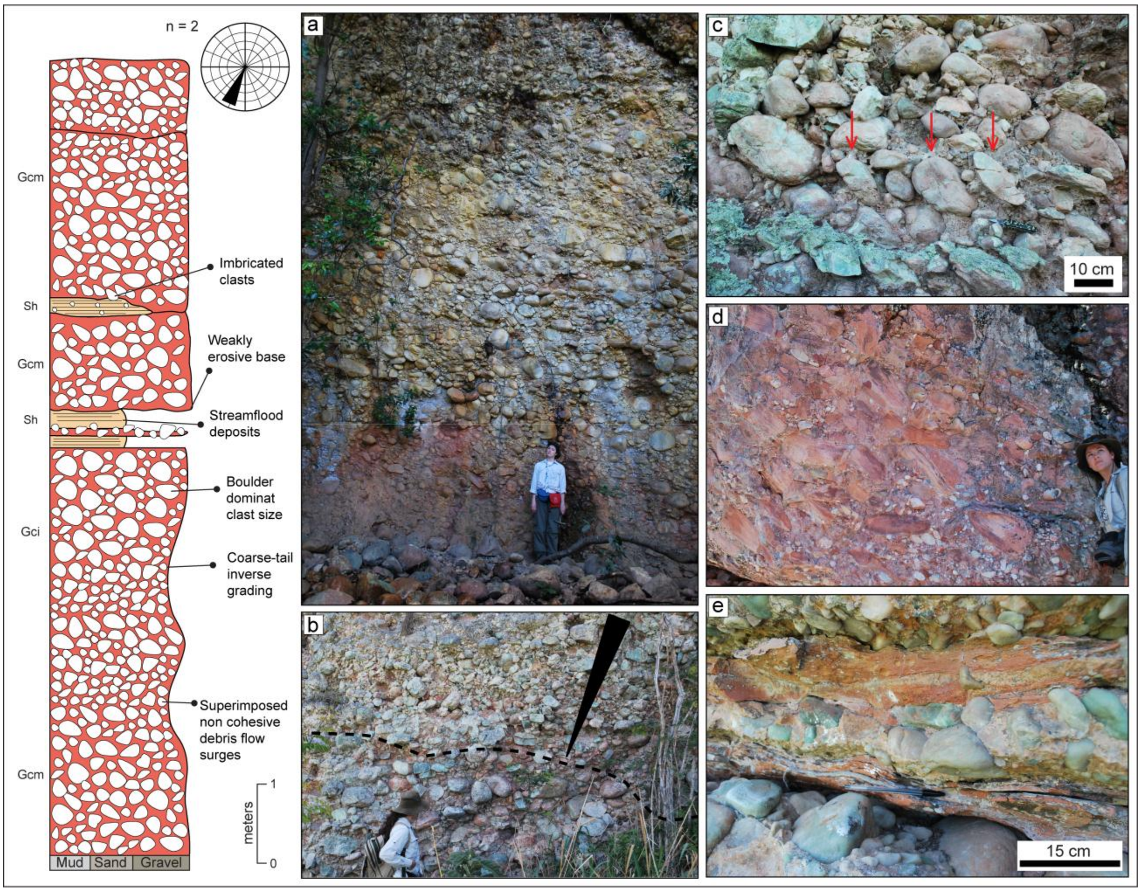


Fig. 4. Plate showing debris flow deposits facies association. In (a) massive, boulder conglomerates (facies Gcm), in (b) cobble-boulder conglomerate showing coarse-tail inverse grading (facies Gci), in (c) poorly sorted conglomerate showing cobble imbrication, in (d) composition predominantly sedimentary clasts (Lençóis region), in (e) thin bedded/stratified coarse-grained sandstones interbedded with lenses of conglomerate (facies Sh).

4.2. Facies Association 2: Shallow, gravel-bed braided channel

Description

This facies association is composed of sheet-like conglomerate bodies (Fig. 5a) ranging from 2 to 5 m in thickness that extend laterally for more than 500 m. The *w/t* ratios are greater than 100:1 for individual conglomerate bodies. These conglomerate bodies are bounded by sharp to horizontal basal contacts. Internally, these bodies show fining-upward cycles (Fig. 5b), with basal massive, clast-supported conglomerates (**facies Gcm**), or with horizontal stratification and incipient imbrications (**facies Gh**), intercalated upward with massive **(facies Sm)**, horizontally-stratified (**facies Sh**), or trough cross-stratified, medium- to coarse-grained sandstones (**facies St**). The conglomerates are poorly-sorted, ranging from granules to cobbles, predominantly in cobble size (Fig. 5c), with sandy matrix. The clasts are generally sub-rounded, predominantly composed of white and green quartzite (Fig. 5c), but occasionally including granite clasts and mud intraclasts. The conglomerate beds are disposed in 0.5 to 2.5-m-thick beds that extend laterally tens of meters and show minor internal erosion surfaces (Fig. 5d). Sandstones beds present lenticular geometry, ranging from 0.3 to 0.6 m in thickness, being eroded by the overlying conglomerates. Dispersed pebbles and cobbles occur along the sand beds. In some intervals, the alternation of sandstones and conglomerates becomes less frequent, giving way to amalgamated conglomerate beds (Fig. 5d). Palaeocurrents indicate a mean vector to South.

Interpretation

This facies association can be interpreted as fluvial channel deposits (Miall, 1978, 1985). The clast-supported conglomerate with horizontal stratification is interpreted as longitudinal gravel bar deposits (facies Gh). The stratified sandstones are interpreted as products of flat-bed upper-flow regime (facies Sh) and of migration of sinuous-crested dunes, deposited under lower-flow regime (facies St). The occurrence of massive clast-supported conglomerates (facies Gcm) with sand matrix suggests deposition by high-density, hyperconcentrated flows (Wells and Harvey, 1987). The set of the lithofacies Gcm and Sm can be interpreted as traction carpets (Todd, 1989), in which the shear tension and dispersive forces are the primary mechanism of grain collision. The deposition of the Gcm facies on the base of the conglomerate bodies presenting erosive base suggests a high-energy flow in which the transported gravels are moved by high density dispersive forces along the channels during the high magnitude flooding periods. The massive sandstones that succeeded the conglomerates represent the deceleration periods of these floods (Todd, 1989). The absence of macroforms and the dominance of horizontal lamination and isolated cross-strata suggest shallow and wide fluvial channels. The occurrence of tabular conglomerate bodies with numerous minor internal erosion surfaces, associated with gravel traction-carpets current deposits, indicate predominance of gravel bedforms, characteristic of shallow, gravel-bed braided channels (Miall, 1996).

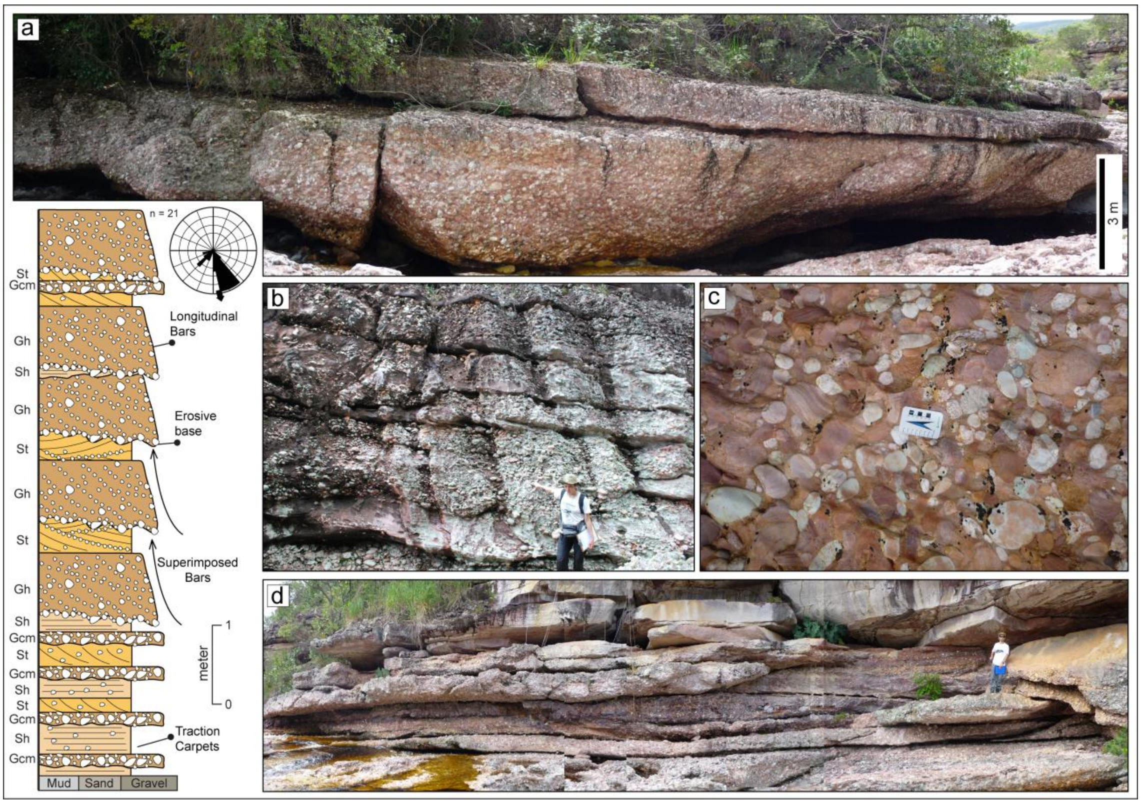


Fig. 5. Plate showing shallow, gravel-bed braided channel facies association. In (a) tabular beds with erosive base of cobble conglomerate, in (b) superimposed cycles of cobble conglomerate and coarse-grained sandstones, in (c) well-rounded boulders of predominantly white and green quartzite, in (d) amalgamated conglomerate beds with internal erosion surfaces.

4.3. Facies Association 3: Shallow, sand-bed braided channel

Description

This facies association is characterized by extensive sheets of sandstones ranging from 0.5 to 2.0 m in thickness and extending laterally for tens of meters. These tabular sandbodies are bounded at the base by erosive surfaces, with of up to 1 m of relief in outcrop scale (Fig 6a). Internally, they are composed of medium- to coarse-grained, poorly sorted sandstone and clast-supported pebble conglomerate (Fig. 6b). The clasts are rounded to sub-rounded, composed of white quartzites and less common green quartzites and sandstones (Fig. 6c). The sandstone bodies commonly show internally fining-upward trends (Figs. 6b and 6d), arranged from massive clast-supported pebble conglomerate (**Facies Gcm**) to trough cross-bedded, coarse-grained sandstones (**Facies St**) arranged in 10 to 60-cm-thick sets. Horizontally-stratified coarse-grained sandstones (**Facies Sh**) occur locally. Sometimes, superimposed trough cross-bedded sets separated by sub-horizontal surfaces can constitute the whole sandbodies. Palaeocurrents display a wide dispersion, varying throughout the sections, ranging from northwest to southeast, with a mean vector mean to southwest. Typically, these deposits occur intercalated with sediment-gravity-flow deposits.

Interpretation

Based on the presence of sandbodies bounded by erosive surfaces covered by conglomeratic deposits, the occurrence of a fining-upward succession and the prevalence of trough cross-bedding with unidirectional paleocurrent trends suggest the deposition of fluvial channels. The occurrence of superimposed sets of trough cross-bedding separated by sub-horizontal surfaces suggests that the filling of channels occurred by the migration and climbing of 3D dunes, with the development of sand bedforms (SB element), suggesting shallow, sand-bed braided channel (Miall, 1996). The sandstones with horizontal stratification that sometimes occur associated with facies Gcm and St are interpreted as products originated from shallow, fast flows deposited under upper-regime plane bed conditions (Miall, 1996). The intercalation of these deposits with debris-flow deposits and the high dispersion of their palaeocurrents suggests fluvial distributary channels, formed from the bifurcation of the main feeder channel of alluvial fans that are the proximal deposits of the distributary zone, according to Kelly and Olsen (1993).

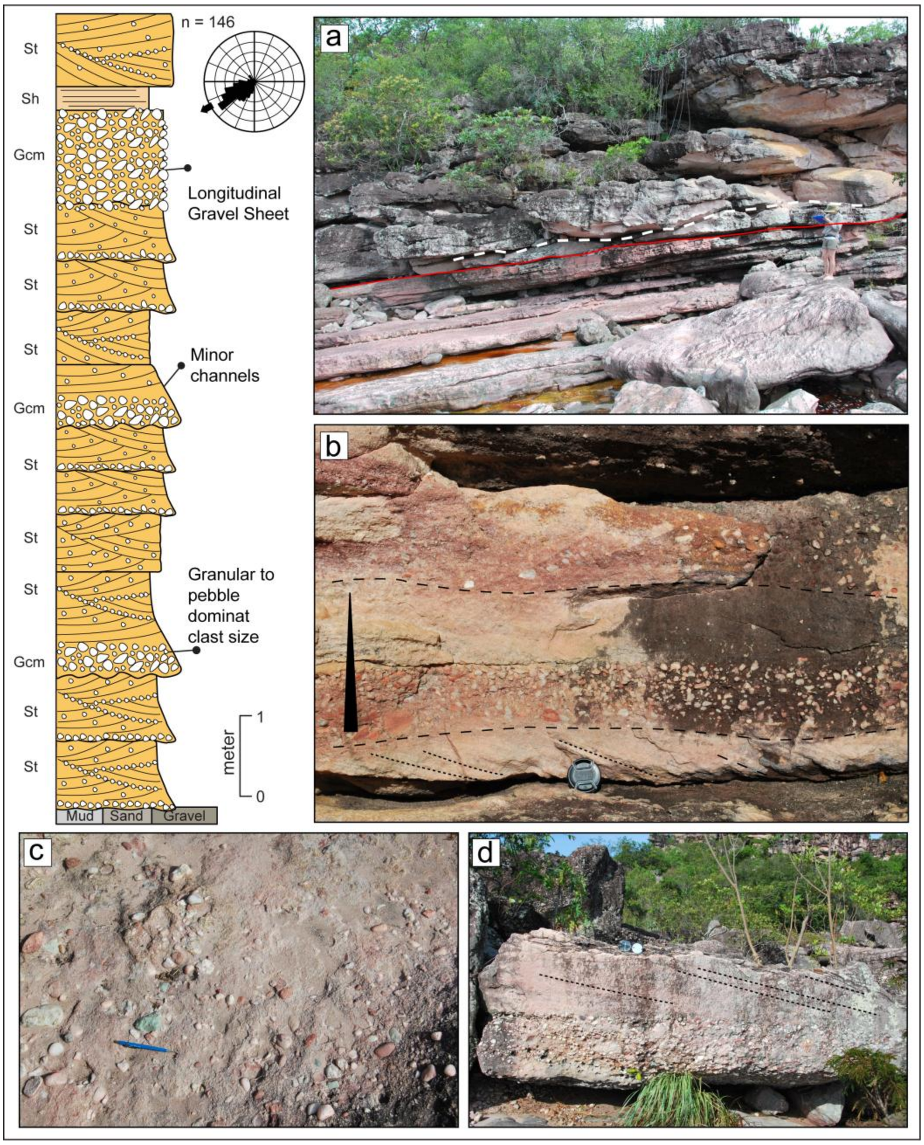


Fig. 6. Plate showing shallow, sand-bed braided channel facies association. In (a) red line indicate the contact with the intermediate sheetflood facies association and white dashed line indicate the internal weakly erosive surfaces, in (b) fining-upwards succession of pebble conglomerate (facies Gcm) and coarse-grained sandstones (facies St), in (c) plan view of a lag pavement showing the pebble composition, in (d) black dashed line indicate the trough cross-stratified sandstones (facies St) covering massive pebble conglomerate (facies Gcm).

4.4. Facies Association 4: Proximal sheetflood

Description

This facies association comprises tabular multiple stacked sandbodies, and consists of thin (<1.5-m-thick) and laterally extensive sheets, generally with sharp, slightly undulating erosive basal surfaces (Fig. 7a). These tabular bodies are composed of medium- to very coarse-grained sandstones with granules and pebbles dispersed (Fig. 7b) or concentrated at the base of the sets. Internally, they show predominantly low-angle **(facies Sl; Fig. 7c)** and trough cross-bedding **(facies St; Fig. 7d)** in sets that are 0.3 to 0.8-m-thick. Horizontally-stratified **(facies Sh; Fig. 7e)** and ripple cross-laminated sandstones **(facies Sr)**, and heterolites of siltstone and laminated sandstone (**facies Ht**), occur less frequently. Palaeocurrents show wide dispersion from south to northeast. This facies association typically occur associated with debris flow deposits.

Interpretation

The presence of tabular sandbodies with a slightly undulating erosive base and the predominance of low-angle and trough cross-bedded, coarse-grained sandstones are interpreted to be the result of high-energy flood deposition, unconfined sheets and poorly defined fluvial channels (Nemec and Postma, 1993; Blair, 2000). The amalgamated packages of sandbodies represent a series of flooding events that frequently aggraded in wide shallow channels. The occurrence of ripple cross-laminated sandstones is a common product of waning flow velocity associated with flow termination (Miall, 1996). The laminated heterolites represent low energy flows related to the final stage of the floods (Tunbridge, 1981).

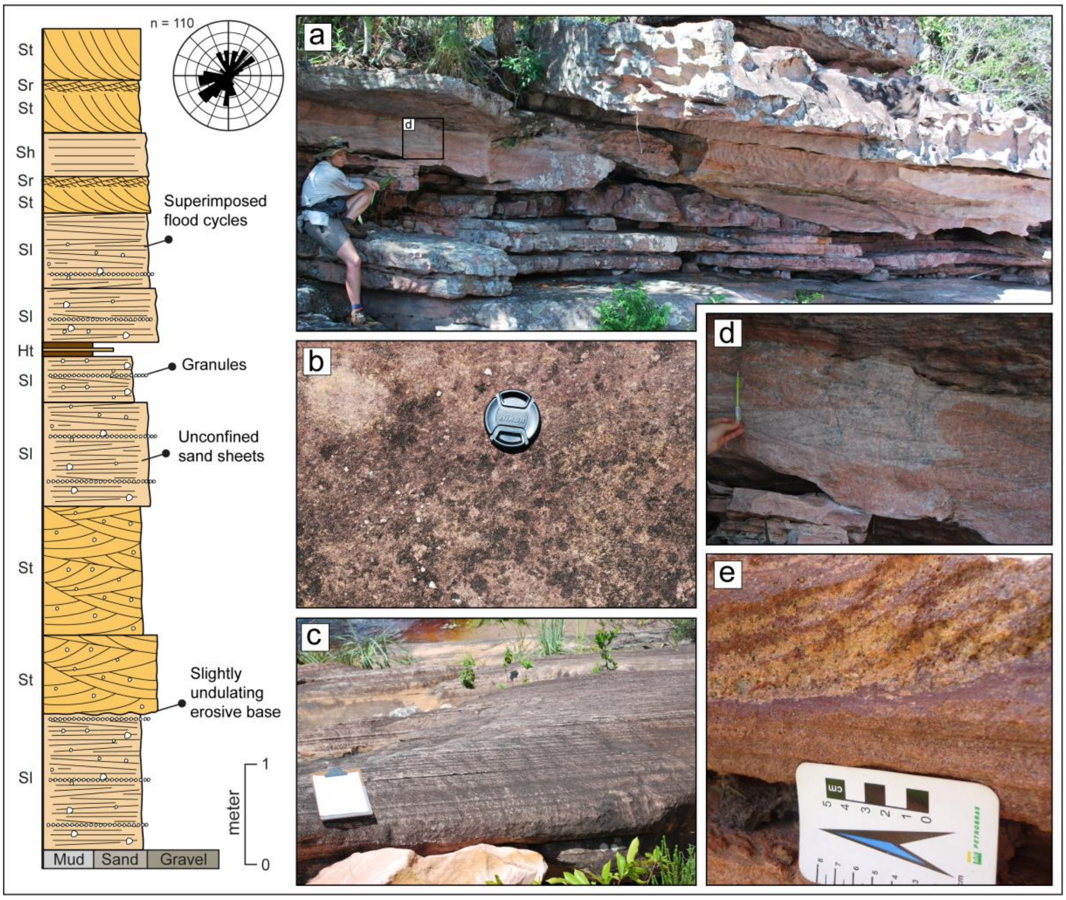


Fig. 7. Plate showing proximal sheetflood facies association. In (a) white line indicates slightly undulating erosive base. Box indicate the zoom of figure 7d, in (b) poorly sorted sandstone, in (c) low-angle cross-stratified sandstone (facies Sl), in (d) internally the trough cross-stratified sandstones (facies St) are arranged in 20-cm-thick sets, in (e) horizontally-stratified sandstones (facies Sh) underlain by trough cross-stratified sandstones (facies St).

4.5. Facies Association 5: Intermediate sheetflood

Description

This facies association consists of tabular sheets with 0.6 to 1.2-m-thick and extend laterally for >200 m, exhibiting non-erosive basal contacts (Fig. 8a). Internally, these deposits are composed by moderately-sorted, fine- to medium-grained sandstones. Horizontally-stratified **(facies Sh; Fig. 8b)**, low-angle **(facies Sl; Fig. 8c)** and ripple cross-lamination **(facies Sr; Figs. 8b and 8d)** is abundant throughout the sandbodies. Ripple cross-stratification and massive siltstones **(facies Fm)** are most common, occurring near the upper parts of sandstones sheets. Some tabular sheets are composed essentially by Sl and Sh facies. Massive **(Facies Sm)** and trough cross-stratified **(facies St)** sandstones also occur, but are not abundant. Desiccation cracks (Fig. 8e) in the siltstones are rare to absent. They exhibit palaeocurrents with wide dispersion from south to northeast. This facies association is typically intercalated with the aeolian sandsheet and dune deposits (Fig. 8a).

Interpretation

Laterally extensive tabular sandstones with horizontal and low-angle cross-stratification are interpreted as distal deposits of unconfined or poorly-confined sheetfloods (Tunbridge, 1981, 1984; Hampton and Horton, 2007). The cycles of facies Sh/Sl/Sr indicate oscillation of upper to lower flow regime during a single depositional event. The alternation of Sh/Sl facies at the base and Sr at the top reveals the cyclical nature of these deposits, in which the initial floods had a high-energy flow character that rapidly decreased its energy before finally dissipating (Williams, 1971). The presence of dissecation cracks or silt drapes bounding the sets results from a decrease of the flow related to final stages of floods with frequent subaerial exposure (Miall, 1996). The intercalation of distal ephemeral sheetfloods with aeolian sandsheets and dunes deposits suggests arid or semiarid settings (Tunbridge, 1981, 1984; Sneh, 1983; Stear, 1983, 1985).

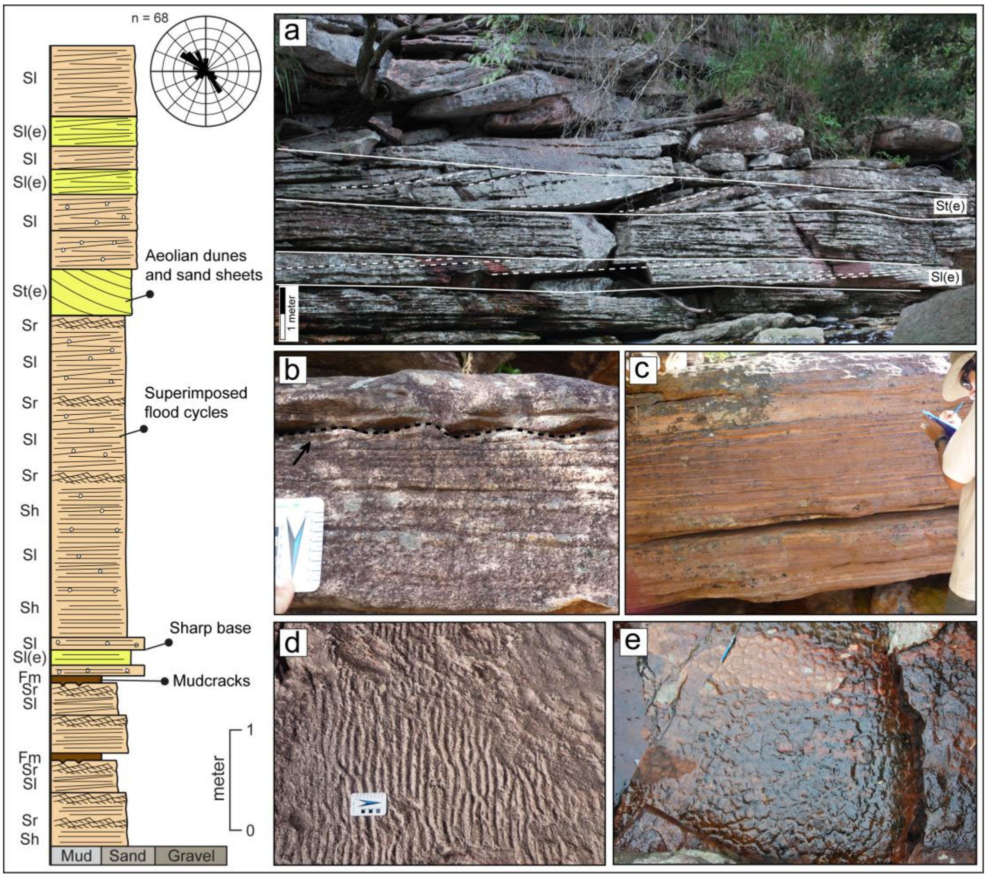


Fig. 8. Plate showing intermediate sheetflood facies association. In (a) intercalation of aeolian (facies St(e) and Sl(e)) and intermediate sheetfloods facies association (facies Sl), showing tabular beds with sharp contacts, in (b) cycles of horizontal stratification (facies Sh) and ripple cross-lamination (facies Sr) sandstones (arrow), in (c) low-angle cross-stratified sandstones (facies Sl), in (d) climbing ripples in a plan view, in € desiccation cracks in siltstones.

4.6. Facies Association 6: Aeolian sand sheets and aeolian dunes

Description

This facies association consists of bimodal, moderately to well-sorted, fine- to coarse-grained sandstones arranged in tabular bodies up to 3-m-thick and tens of meters wide (Fig 9a). Internally, these sandbodies are composed by 0.3 to 1.5-m-thick sets of horizontal **(facies Sh(e))** to low-angle cross-stratification **(facies Sl(e); Fig. 9b)** (<5°) composed by inversely graded, millimetric wind-ripple laminae (Fig. 9c). Occasionally, well-sorted, fine- to medium-grained sandstones organized into isolated sets or co-sets of trough cross-bedding **(facies St(e); Fig. 9d)** composed by wind-ripple lamination and inversely-graded grainflow strata (1 to 4 cm; Fig. 9e). From a view parallel to palaeflow, cross-strata are tangential to their basal bounding surfaces, which are planar and dip gently (<2°) in a direction opposite to cross-bedding. Cross-strata define a mean dip towards the northeast.

Interpretation

The bimodal sandstones with horizontal or low-angle cross-stratification, composed exclusively by wind-ripple lamination, are interpreted as aeolian sandsheet deposits (Scherer, 2002; Scherer et al., 2007). The interlayered well-sorted, fine- to medium-grained sandstones organized into isolated sets or co-sets of trough cross-bedding formed by wind-ripple laminae and grain flow strata suggest as residual deposits of aeolian dunes. The occurrence of grain flow strata indicates aeolian dunes with a well-developed slipfaces. The presence of isolated cross-strata interlayered with horizontal or low-angle cross-stratification indicates aeolian dunes migration on wide aeolian sand sheets areas. The presence of successive sets of cross-strata indicates climbing of the aeolian dunes formed in conditions of larger availability of sand in the system. The horizontal to upwind-dipping surfaces bounding cross strata (view parallel to paleoflow) are interpreted as first order surfaces, generated from the successive climbing of aeolian dunes (Brookfield, 1977). Unimodal distribution of dip azimuths of cross-strata indicates crescentic aeolian dunes. The presence of trough cross-strata from a view transverse to paleoflow indicate 3D crescentic dunes.

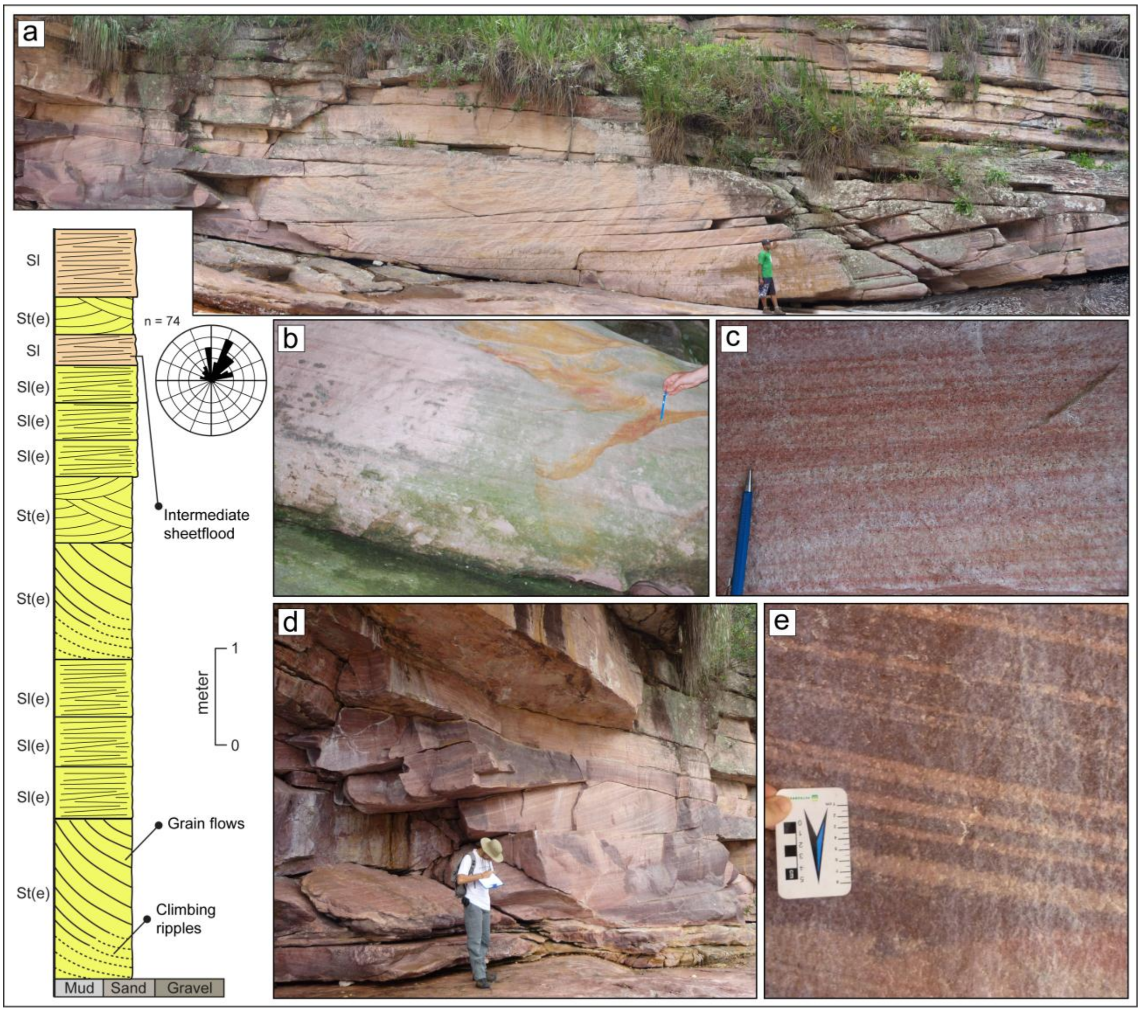


Fig. 9. Plate showing aeolian sand sheets and aeolian dunes facies association. In (a) large scale trough cross-beds of aeolian dunes (facies St(e)) overlain by aeolian sand sheet deposits (facies Sl(e)), in (b) low-angle cross-stratified aeolian sandstones (facies Sl(e)), in (c) wind-ripple strata in the aeolian sand sheet facies, in (d) trough cross-bedded aeolian sandstones formed by the climbing of 3D aeolian dunes, in (d) grain flow strata in a set of trough cross-strata sandstone.

4.7. Facies Association 7: Floodplain deposits

Description

This facies association consists of laterally extensive tabular sheets of interbedded fine-grained sandstones and siltstones, with up to 3-m-of thickness. Individual beds exhibit non-erosive basal contacts and are generally 0.05 to 0.3-m-thick. Horizontally-stratified **(facies Sh; Fig. 10a)** and ripple cross-stratified sandstone **(facies Sr; Fig. 10b)**, massive sandstone **(facies Sm)** and finely laminated **(Facies Fl)** to massive siltstones **(Facies Fm)** characterized these deposits. Commonly associated with these deposits, centimetric layers of massive clast-supported conglomerate **(facies Gcm; Fig.10c)** and medium- to coarse-grained sandstones with trough cross-stratification **(facies St; Fig.10d)** occur. Sub-angular to sub-rounded pebbles and cobbles of quartzites, sandstones and minor dark volcanic rocks (Fig.10e) occur locally dispersed along the heterolithic sets (Fig.10f). Massive, greenish, up to 0.2-cm-thick mudstone can be observed (Fig. 10g), intercalated with heterolithic siltstones and sandstones **(Facies Ht)**. Mud cracks and rain prints are present in some siltstones. Palaeocurrents show mean vector to southwest.

Interpretation

The tabular, heterolithic siltstones and sandstones are interpreted as floodplain deposits that can represent two distinct depositional settings: (a) lateral overflows of channels during fluvial floods (overflow lobes) or (b) distal portions of ephemeral, high-energy sheetfloods deposits (Spalletti and Piñol, 2005; Hampton and Horton, 2007). The unidirectional palaeocurrents approximately transversal to channel axes reinforce the hypothesis that this facies association represents lateral channel overflows during fluvial floods, instead of distal portion of sheetfloods. The siltstones may have been deposited by gravitational settling of particles in suspension in the final flooding stages or in temporary floodplain ponds. The occurrence of laminated heterolites of fine-grained sandstones and siltstones interbedded with lenses of conglomerates can be interpreted as aqueous flows reworking segments of inactive and abandoned alluvial fans lobes (Blissenbach, 1954; Denny, 1967; Went, 2005). This evidence points to low competence flows related to the distal portion of alluvial fans systems. The occurrence of mud cracks and rain prints also suggests frequent subaerial exposure. Greenish mud layers are interpreted as volcanic tuffs deposited on the floodplain (Guadagnin et al., in prep.).

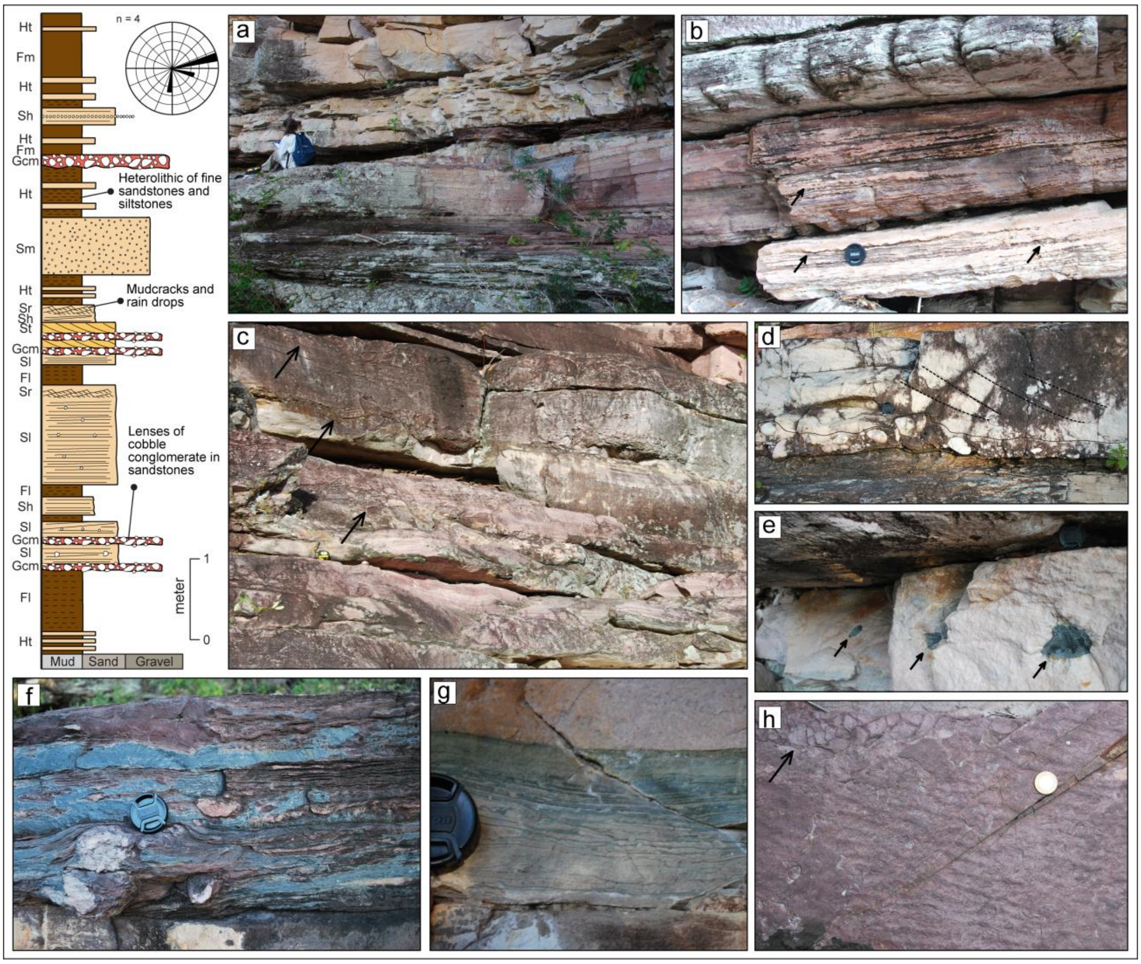


Fig. 10. Plate showing floodplain deposits facies association. In (a) horizontally-stratified fine-grained sandstones (facies Sh), in (b) ripple cross-laminated (facies Sr; arrows) interbedded, horizontally-stratified (facies Sh) sandstones, in (c) lenses of massive cobble conglomerates within sandstones (facies Gcm), in (d) conglomerate lag overlain by trough cross-stratified sandstones, in (e) dark volcanic (arrows) clast within sandstones, in (f) clast dispersed along the heterolithic sets, in (g) massive greenish mudstone, in (h) ripple marks and desiccation cracks present in siltstone.

4.8. Facies Association 8: Tide influenced shallow, sand-bed braided channel

Description

This facies association consists of lenticular medium-grained to conglomeratic sandstones, 1.5 to 2.3-m-thick, with multiple internal and basal erosion surfaces (Fig.11a), extending laterally by tens of meters. The sandbodies packages exhibit well-developed fining-upwards successions (Fig. 11b) of conglomeratic sandstones, bipolar cross-stratified sandstones **(Facies St)**, sigmoidal cross-stratified sandstones (**Facies Ss(t);** Fig. 11c) and rare low-angle stratified sandstones (**Facies Sl)**. The cross-sets in simple cross-strata vary from 0.5 to 1.0-m-thick and compound cross-strata vary from 0.5 to 1.5-m-thick. In places, the sandstones show regularly-spaced, concave, steeply dipping (25º) cross-stratification with reactivation surfaces (**Facies St(t)**; Fig 11d). Sigmoidal cross beds are recognized by downcurrent transitions in foreset angle from gently dipping to more steeply dipping (Fig. 11e), accompanied by increasing to decreasing thickness of cross-strata within the sets, which are bounded by reactivation surfaces. Rare ripple cross-laminated, fine-grained sandstones (**Facies Sr)** occur capping the sandbodies or climbing up the median-base portion of the foresets (Fig. 11f) with direction opposite to the main flow. The palaeocurrent data derived from cross-strata and ripple cross-laminations exhibit dispersion among the sections. The sections located at the North show a predominance of palaeocurrents to W-SW and subordinate palaeocurrents to E-NE, while in the sections located at the South the main palaeocurrents present SSW-SSE direction and subordinate palaeocurrent to NNW-NNE.

Interpretation

The conglomeratic and medium-grained sandstones disposed in fining-upwards succession, the predominantly unidirectional palaeocurrents together with the channel-shape and significant internal and basal erosion surfaces suggest deposition in fluvial channels (Bristow, 1993; Collinson, 1996). The absence of macroforms, the lack of lateral accretion beds and the rare overbank deposits suggest shallow fluvial channels with relatively low sinuosity (Miall, 1996). The multiple erosion surfaces indicate repeated episodes of channel incision and infill. The occurrence of bipolar cross-strata indicating reversing currents suggest that the deposits of shallow, sand-bed braided channel were reworked by tidal currents (Shanley et al., 1992; Plink-Björklund, 2005; Martinius and Gowland, 2011). The reactivation surfaces on steeply dipping cross-strata indicate that bedform lee-side is changed into the stoss-side by reversals in flow direction (Shanley et al., 1992) or superimposition of the other bedforms (Dalrymple, 1984; Shanley et al., 1992). The sigmoidal beds with increasing to decreasing foreset angle and cross-strata thickness are interpreted as representing accelerating flow conditions, followed by deceleration within a single ebb tide (Shanley et al., 1992). The difference in foresets thickness is interpreted as changes in the acceleration of dune migration caused by neap-spring-neap tide fluctuations (Kreisa and Moiola, 1986; Martinius and Gowland, 2011). This deceleration happens when the tide has greater strength against the river. At the spring moment, the ebb current is "broke" more intensely by the flood current. The reactivation surfaces within the individual sigmoidal beds have been attributed to the migration of superimposed bedforms (Dalrymple, 1984; Shanley et al., 1992). The low-angle cross-stratification was deposited by high velocity currents. The ripple cross-laminated deposits that cap the sandbodies represent abandonment of channels, or were deposited in interchannel areas (Plink-Björklund, 2005). The ripple cross-laminations that climb up the middle-basal portion of the foresets with direction opposite to the main flow indicate reversing to much weaker, subordinate currents. The bipolar cross-strata indicating reversing currents display a dominant south to south-westward fluvial palaeocurrents and subordinate north to northeast tide palaeocurrents.

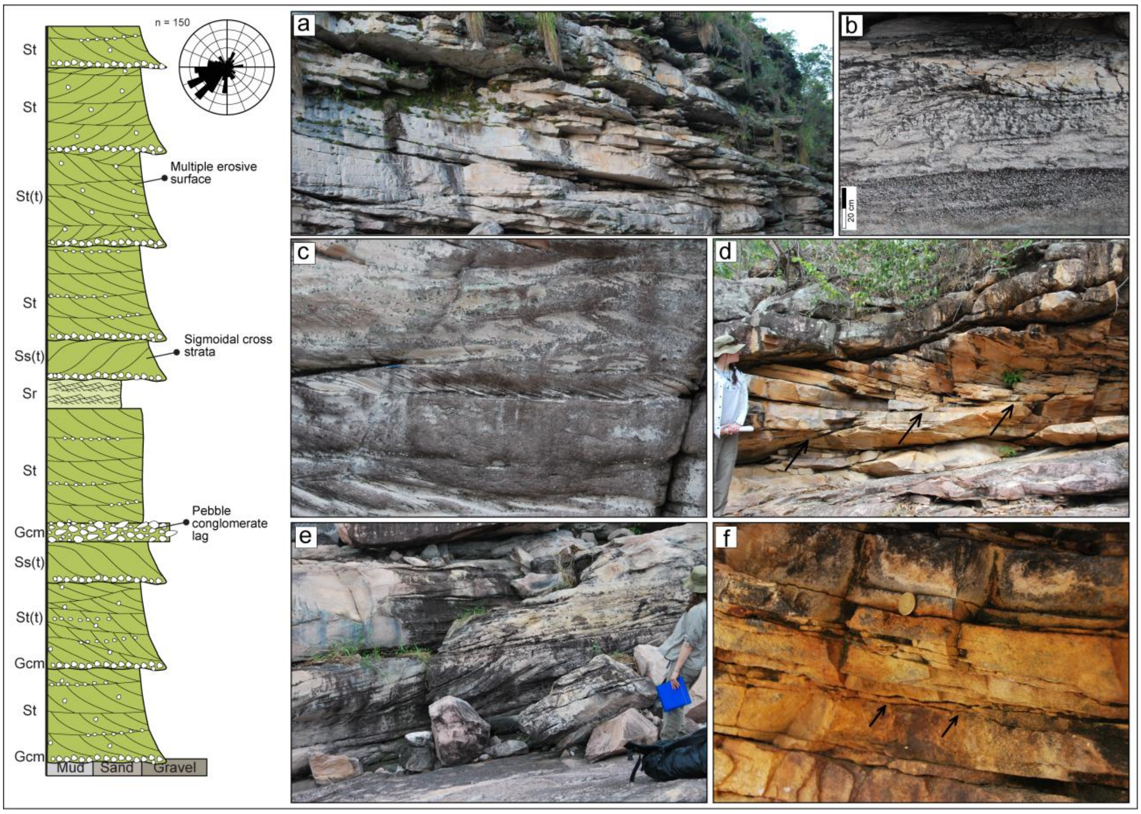


Fig. 11. Plate showing tide-influenced, shallow, sand-bed braided channel facies association. In (a) lenticular geometry with multiple internal and basal erosive surfaces, in (b) fining-upwards succession of massive pebble conglomerate and cross-stratified sandstones, in (c) sigmoidal cross-bedded sandstones, in (d) sandstones with regularly-spaced concave reactivation surfaces (arrows), in (e) downcurrent transition in foreset angle from steeply dipping for gently dipping, in (f) ripple cross-lamination climbing (arrows) up the median-base portion of the foreset with direction opposite to the main flow.

4.9. Facies Association 9: Upper flow regime tidal sand flat

Description

This facies association is dominated by amalgamated sandsheets (Fig. 12a), up to 2-m-thick and tens of meters laterally extense. The sandstones are medium- to coarse-grained and are generally moderately to poorly-sorted (Fig. 12b). Individual beds have sharp, slightly undulating, erosive bases. Sets are characterized by horizontal stratification **(facies Sh; Fig. 12c)**, ripple cross-lamination **(facies Sr; Fig. 12d)**, trough cross-stratification **(facies St)** and rarely wavy lamination **(facies Sw; Fig. 12e)**. Occasionally, these sandbodies are interlayered with thin massive mudstone beds **(facies Sm)**. These deposits are arranged in 0.3 to 0.7-m-thick sets, with frequent alternation of facies Sh and Sr or St and Sr. The trough cross-stratifications define a palaeocurrent to NW-SW, while the ripple cross-laminations show paleoflow direction to NE-SE.

Interpretation

The occurrence of sandstones with bipolarity in the palaeoflow direction suggests tidal deposits. Sandstones with horizontal stratification formed under upper flow regime succeeded by sandstones with ripple cross-lamination are common in high-energy tidal flats (Dalrymple et al., 1985; Dalrymple et al., 1990; Dalrymple, 1992; Plink- Björklund, 2005). The sandstones with horizontal stratification are interpreted as deposits formed in upper flow regime associated to the dominant tide, and the climbing ripples are developed in conditions of subordinate tide flows. The sandstones with trough cross-stratification represent the migration of sinuous crested dunes deposited in conditions of weaker dominant tide. The sandstones with wavy ripples represent the oscillatory flow under the influence of waves in low energy conditions (Tirsgaard, 1993) and massive mudstone is interpreted as the product of suspension fallout in low energy conditions.

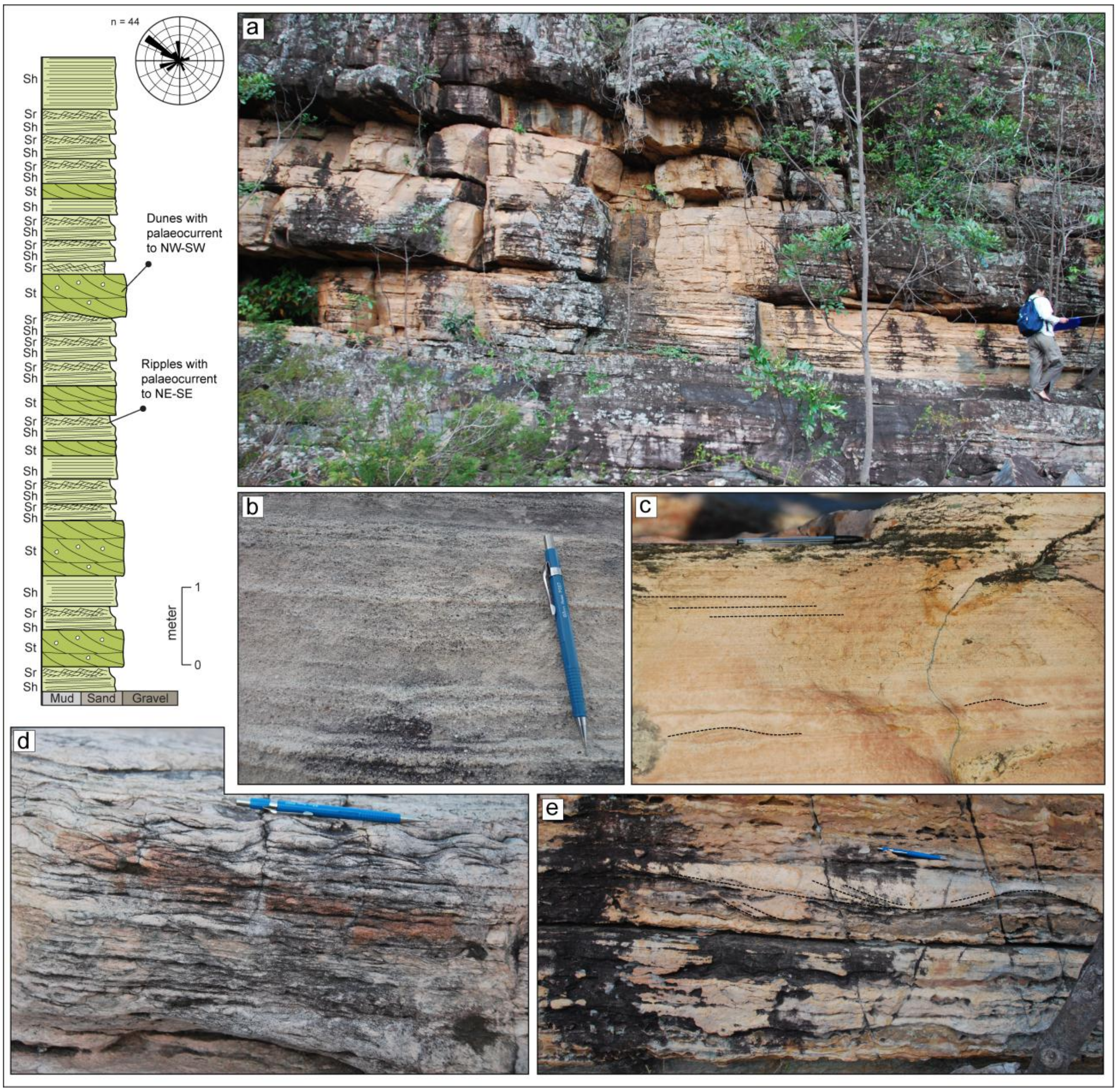


Fig. 12. Plate showing upper flow regime tidal sand flat facies association. In (a) tabular, laterally-extensive fine-grained sandstones, in (b) poorly-sorted with granular sandstones, in (c) climbing ripples overlain horizontally-stratified sandstones, in (d) alternation of horizontally- and ripple cross-laminated sandstones, in (e) wavy laminated sandstone.

4.10. Facies Association 10: Shoreface (Caboclo Formation)

Description

This facies association consists of tabular sandstone and siltstone bodies, 0.2 to 2-m-thick and several meters laterally extense. These deposits are dominated by fine- to medium-grained sandstones with horizontal stratification **(facies Sh;** Fig. 13a**)**, wavy-lamination (**facies Sw;** Figs. 13b and 13c), and ripple cross-lamination (**facies Sr;** Fig. 13d). The beds have sharp bases that are bedding-parallel to slightly wavy or erosive. Interbedded with wavy-laminated sandstones occur laminated mudstones (**facies Fl;** Figs. 13e and 13f) or massive mudstone (**facies Fm;** Fig. 13g). These deposits are arranged in sets up to 20-cm-thick and the facies succession displays a general fining upwards trend. Paleocurrents from ripple cross-lamination indicates varied directions (Fig. 13d).

Interpretation

The presence of sandstones with wavy-lamination suggests deposition in the shoreface. The sandstones with horizontal stratifications intercalated with wavy ripples are interpreted as flat bedforms developed in conditions of upper flow regime and reworking by waves (Simpson et al., 2002). The alternation of wavy ripples and current ripples are products of combined flows in which the current ripples are generated by traction currents, and the wavy ripples are generated by oscillatory flows. The laminated and massive mudstones are interpreted as the product of suspension fallout below wave base. The heterolithic sediments that succeeded the sand package represent rhythmic alternation between mudstones deposited from suspension in more distal zones of the shoreface, and wavy-laminated sandstones deposited from flows imprinted by storm waves (McCormick and Grotzinger, 1993).

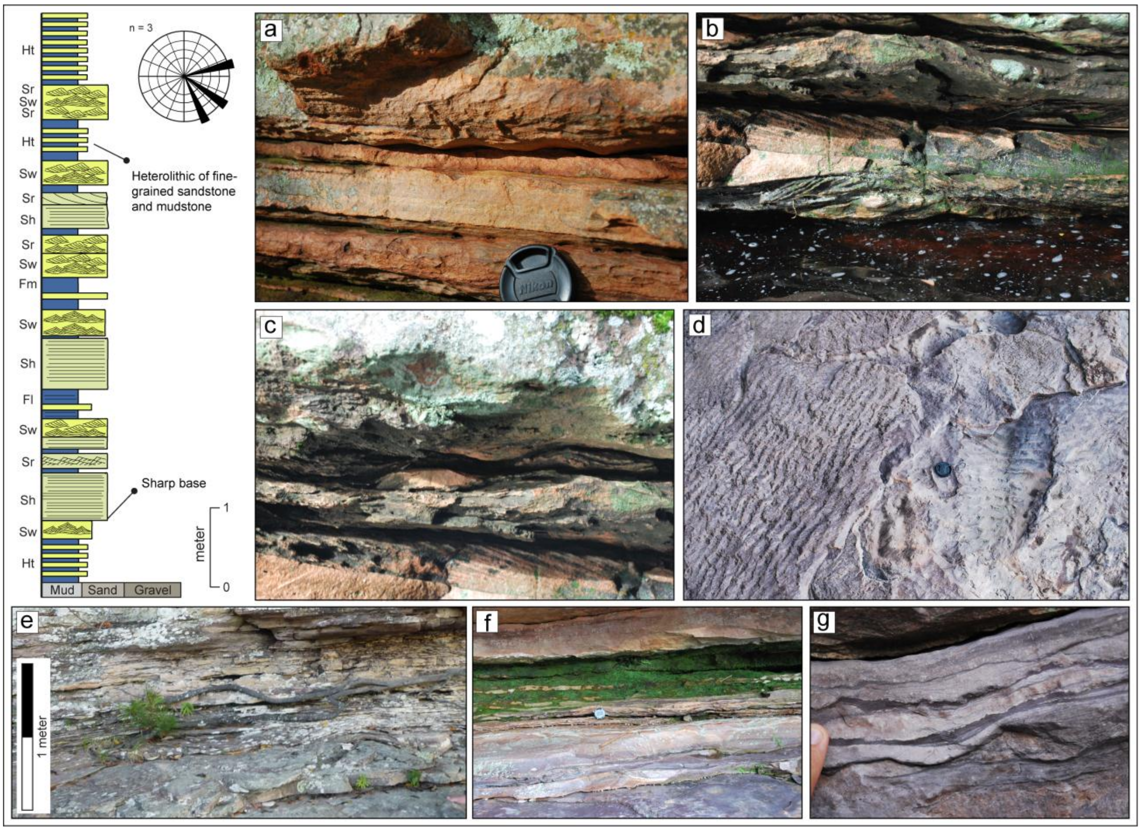


Fig. 13. Plate showing shoreface facies association. In (a) horizontally-laminated sandstones with wavy ripples on the top, in (b) wavy-laminated sandstones, in (c) wavy-rippled sandstones (arrows), in (d) ripple marks indicate the various flow direction (arrows), in (e) and (f) intercalation of wavy rippled sandstones and laminated mudstones, in (g) drapes of massive mudstones interlayered with wavy-laminated fine-grained sandstones.

5. Stratigraphic Framework

The Tombador Formation presents thickness ranging from 150 to 600 meters with the largest thickness in the Lençóis region and the smallest thickness close to the Jacobina region (Silva Born, 2011). At the Sincorá Range, the Tombador Formation exhibits thicknesses of up to 600 meters and is subdivided into lower and upper intervals, with distinct stratigraphic signatures. The lower interval, predominantly fluvial and estuarine, overlies with an angular unconformity the Açuruá Formation (Derby, 1906; Pedreira, 1994). The upper interval, the focus of the present work, is characterised by alluvial fan, fluvial braidplain and aeolian systems covered by fluvio-estuarine deposits on the top (Fig. 14).

The upper interval can be subdivided in three depositional sequences limited by regional unconformities (Fig. 14): (i) Sequence I, characterised by fluvio-aeolian deposits; (ii), Sequence II, composed of essentially alluvial deposits; and (iii) Sequence III, consisting of fluvio-estuarine and shallow marine deposits. The studied interval was analysed based only on recognition of unconformities. Mitchum et al. (1977) define depositional sequence as genetically related stratigraphic units bounded by unconformities or their correlative conformities. The criteria used to identify unconformities in outcrops include: (1) an abrupt change in the facies, which may involve both a change in the depositional systems or alterations in the architecture of the facies within a specific depositional system; (2) an abrupt change in the texture and grain size across the unconformity; and (3) changes in the palaeocurrent patterns.

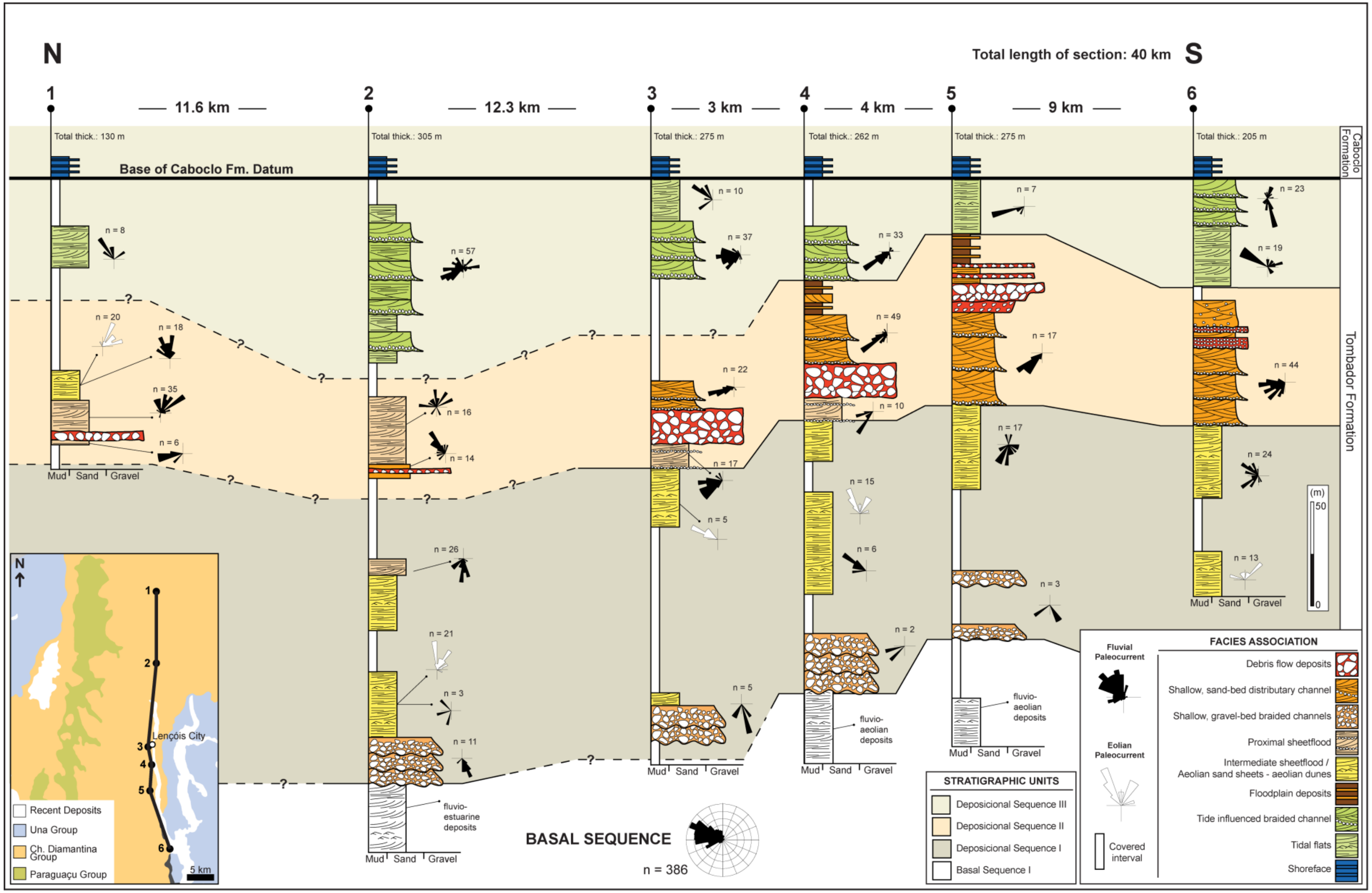

N
Total length of section: 40 km
S
1
11.6 km
2
12.3 km
3
3 km
4
4 km
5
9 km
6
Total thick.: 130 m
Total thick.: 305 m
Total thick.: 275 m
Total thick.: 262 m
Total thick.: 275 m
Total thick.: 205 m
Base of Caboclo Fm. Datum
Caboclo Formation
Tombador Formation
Mud Sand Gravel
fluvio-estuarine deposits
fluvio-aeolian deposits
BASAL SEQUENCE
n = 386
Recent Deposits
Una Group
Ch. Diamantina Group
Paraguaçu Group
Lençóis City
5 km
STRATIGRAPHIC UNITS
Deposicional Sequence III
Deposicional Sequence II
Deposicional Sequence I
Basal Sequence I
Fluvial Paleocurrent
Eolian Paleocurrent
Covered interval
FACIES ASSOCIATION
Debris flow deposits
Shallow, sand-bed distributary channel
Shallow, gravel-bed braided channels
Proximal sheetflood
Intermediate sheetflood / Aeolian sand sheets - aeolian dunes
Floodplain deposits
Tide influenced braided channel
Tidal flats
Shoreface
(m)
50
0

Fig. 14. Correlation of the six vertical sections showing the three depositional sequences of the Upper Tombador Formation. The fluvio-estuarine basal sequence shows mean vector direction to north-westward. The first boundary coincides with an abrupt change of the palaeocurrent, with a mean vector direction to the south, and with a grain size increase. The second boundary is marked by an abrupt grain size, with a high dispersion in the palaeocurrents typical of alluvial fan systems. The third sequence boundary is accompanied by an establishment of fluvio-estuarine systems. The location map indicates the vertical sections.

5.1. Sequence I

Sequence I, with thickness ranging from 100 to 120 m, comprise a fluvio-aeolian systems in which 25% of the total sequence thicknesses are shallow, gravel-bed braided channels concentrated on the base, and the remainder of the section includes intercalations of the intermediate sheetfloods and aeolian deposits. The lower boundary is characterized by an intra-Tombador angular unconformity, that is marked by the abrupt entrance of conglomerates and conglomeratic sandstones interpreted as shallow, gravel-bed braided fluvial deposits overlying fine- to coarse-grained sandstones linked to fluvio-estuarine systems (vertical section 2) or fluvio-aeolian systems (vertical sections 4 and 5). The unconformity is clearly due to the change in the fluvial paleocurrent from WNW in the lower interval to SSE at the base of Sequence I (Fig. 14). On top of gravel-bed braided fluvial deposits at the base of Sequence I, aeolian and intermediate sheetflood sandstones occur interbedded. In general, the palaeowind data indicate an average transport vector to the northeast with dispersion from northwest to east. The intermediate sheetfloods, in turn, have a wide dispersion of palaeocurrent directions with an average vector to the west. The palaeocurrents of the sheetfloods that occur interlayered with aeolian dunes point to a sediment transport perpendicular to the migration of aeolian dunes.

5.2. Sequence II

This sequence shows thicknesses ranging from 40 to 70 m and its lower boundary is marked by an abrupt change in grain size from intermediate sheetfloods and aeolian sandstones (Sequence I) to debris flow conglomerates and proximal sheetfloods or shallow, sand-bed braided channel sandstones (Sequence II, Fig. 14). The dispersion of palaeocurrent data and the facies associations of Sequence II are typical of alluvial fans system (Fig. 15). Thus, each vertical section displays distinct vertical stacking due to lateral facies variations within the alluvial fan (Figs. 14 and 15). Vertical sections 3 and 4 exhibit similar stratigraphic succession, in which the base is composed of proximal sheetfloods and debris flow deposits approximately 18-m-thick covered by shallow, sand-bed braided channels and floodplain deposits on the top. Vertical section 5 exhibits sand-bed braided channels underneath debris flow intercalated with floodplain deposits. Vertical section 6, in turn, presents amalgamated sand-bed braided channel with no occurrence of debris flows and floodplain deposits. Vertical sections 1 and 2 suggest a facies distribution related to distal portions of the alluvial fans. Vertical section 2 comprises thin beds of debris flow and sand-bed braided channels overlain by amalgamated proximal sheetfloods while vertical section 1 exhibit thin-bedded debris flow deposits overlain by proximal sheetfloods deposits and aeolian sand sheets and dunes. Palaeocurrents show various directions, common in alluvial fan systems presenting semi-radial geometry. In general, two domains are observed in the palaeocurrents obtained from sand-bed braided channel and sheetfloods deposits. The fluvial deposits of the Southern sections (vertical sections 3, 4, 5 and 6) suggest transport of sediments ranging from South to West, while the fluvial strata of the Northern (vertical sections 1 and 2) show dominant palaeocurrents to Northwest and North (Figs. 14 and 15).

5.3. Sequence III

This sequence is formed by deposits belonging to two distinct lithostratigraphic units. The base comprises sandstones from the Tombador Formation while the top show mudstones from the Caboclo Formation. Ranging from 20 to 70 m thick, Sequence III is bounded at its base by an abrupt entrance of fluvio-estuarine systems characterised by tide-influenced, shallow sand-bed braided channel and upper flow regime tidal flats deposits, over continental deposits of Sequence II (Fig. 14). The tidally-influenced braided channels show palaeocurrents with a dominant ebb direction to the South-Southwest and flood tide direction to the North-Northeast. The tidal flats facies association shows bidirectional palaeocurrents to West-Northwest and East-Northeast, the first possibly related to flood tide and the second to ebb tide. Those lithofacies associations are succeeded by shallow marine deposits (mudstones of the Caboclo Formation) but the upper boundary of Sequence III was not defined in the present study.

6. Stratigraphic Evolution: Discussion

The upper portion of the Tombador Formation is characterised by three depositional sequences bounded by regional unconformities (Fig. 14), deposited in a wide intracratonic sag basin developed on the Congo-São Francisco Craton (Dussin and Dussin, 1995; Schobbenhaus, 1996; Guimarães et al., 2008).

Sequence I is characterised in the base by conglomerates and conglomeratic sandstones deposited by shallow, gravel-bed braided channels, which are overlain by fine- to coarse-grained sandstones associated to intermediate sheetfloods and aeolian dunes and aeolian sand sheets. The lower boundary of this sequence is marked by an angular regional erosive surface, evidenced by an abrupt change of facies and fluvial palaeocurrents (Magalhães et al., 2012). Below the sequence boundary dominate fine- to medium-grained sandstones linked to fluvio-estuarine systems with a dominant fluvial palaeocurrent to the West (Magalhães et al., 2012; Fig. 14); above the unconformity, conglomeratic deposits of the shallow, gravel-bed braided channels on the base of Sequence I exhibit an average palaeocurrent to the South. This change in the fluvial palaeocurrent suggests a regional reorganization of the drainage basin. Conglomerates of the Tombador Formation are predominantly composed of white and green quartzites, being the green quartzites rich in fuchsite (chromium mica) from the Jacobina Group. Pedreira (1994) suggested that the Jacobina Group outcropped eastward from the Sincorá Range and was the source for sediments of the Tombador

Formation in the Mesoproterozoic. The composition of the clasts and the existence of a high-energy braided fluvial system with sediment transport to the South suggest a tectonic rearrangement of the drainage systems coming from high areas to the East, and may be related to alluvial fan systems.

The high-frequency intercalation between ephemeral fluvial and aeolian deposits observed in Sequence I is extremely common in Proterozoic successions. Such intercalation between fluvial and aeolian deposits may be due to autocyclic or allocyclic factors. The autocyclic factors result from the short term interrelationship between coexisting underwater and aeolian depositional processes. The absence of vegetation in the Precambrian resulted in wide interfluve areas reworked by aeolian deposits under all types of climatic conditions (Dalrymple et al., 1985; Kocurek et al., 1992; Simpson and Eriksson, 1993; Trewin, 1993). Allocyclic factors are associated with mechanisms external to the basin, such as climate, sea level change, sediment supply and basin tectonics (Kocurek, 1996, 1999). In this case, the absence of well-defined drying or wetting upward cycles, the small thickness, and low lateral continuity of the aeolian packages suggest coexistence between fluvial sheetfloods and aeolian deposits, excluding the hypothesis of allocyclic factors controlling the fluvio-aeolian interaction.

A new abrupt entrance of conglomeratic deposits related to alluvial fans systems overlying the fluvio-aeolian successions marks the lower boundary of Sequence II. The development of this sequence boundary and the establishment of an alluvial fan system may be related to a new tectonic reactivation. The presence of tuff layers within floodplain deposits of Sequence II (Guadagnin et al., in prep.) indicates a volcanic event in the basin or in adjacent area. According to Guadagnin et al. (in prep.) these tuffs may be related to magmatism resulting from collisional or extensional tectonics at the eastern margin of the Congo-São Francisco palaeoplate that might have affected the interior of the plate and hence influencing the sediment dynamics of the Tombador Formation (Magalhães et al., 2012).

Therefore, the lower unconformity of Sequence II, as well as its sedimentary succession, would reflect tectonic uplift and subsidence resulting from the intraplate stress that occurred within the Congo-São Francisco palaeoplate (Guadagnin et al., in prep.) The entrance of conglomeratic sediments of Sequence II may be related to uplift of source areas in response to a sin-depositional tectonics (Allen and Heller, 2012). Several studies indicate that intraplate stresses can be transmitted for hundreds of kilometres within oceanic and continental plates, causing uplift or subsidence in intracratonic basins. Different authors argue that tectonic movements within intracratonic basins are related to processes acting at the plate margins. The intraplate stresses are increasingly used to explain the beginning or reactivation of large intracratonic structures, even though the main locus of extension or compression is located at long distances (Cloetingh et al., 1985; Kominz and Bond, 1991; Heller et al., 1993).

The lateral facies variability between vertical sections within Sequence II corresponds to distinct segments of the alluvial fan system (Fig. 15). The predominance of debris flows deposits in the proximal portions, and the occurrence of traction flow deposits in the distal segments can be explained by initial debris flows that segregate and evolve to diluted flows, in a way similar to that described by Sohn (1999). Thus, the debris flows deposits at the base of vertical sections 3 and 4 correspond to proximal zones deposited in the main trench of the alluvial fans or in other larger channels within the alluvial fan system (Went, 2005). In the studied sections, debris flow deposits between 1 to 10 m thick were deposited in the main trench. The deposits arranged in fining-upwards cycles that occur overlying debris flows deposits at the base of sequence II in vertical sections located to the South are interpreted as shallow, sand-bed braided channels that correspond to fluvial distributary channels at the intermediary segments of the alluvial fans. The changes in grain size and lateral facies variability suggest that the proximal deposits of alluvial fans fed the fluvial, sand-bed braided channels in more distal portions (Hadlari et al., 2006). To the North (vertical sections 1 and 2), the predominance of fluvial sheetflood and aeolian dunes and aeolian sandsheets over shallow, sand-bed braided channels and debris flows suggest deposition at distal zones of alluvial fans.

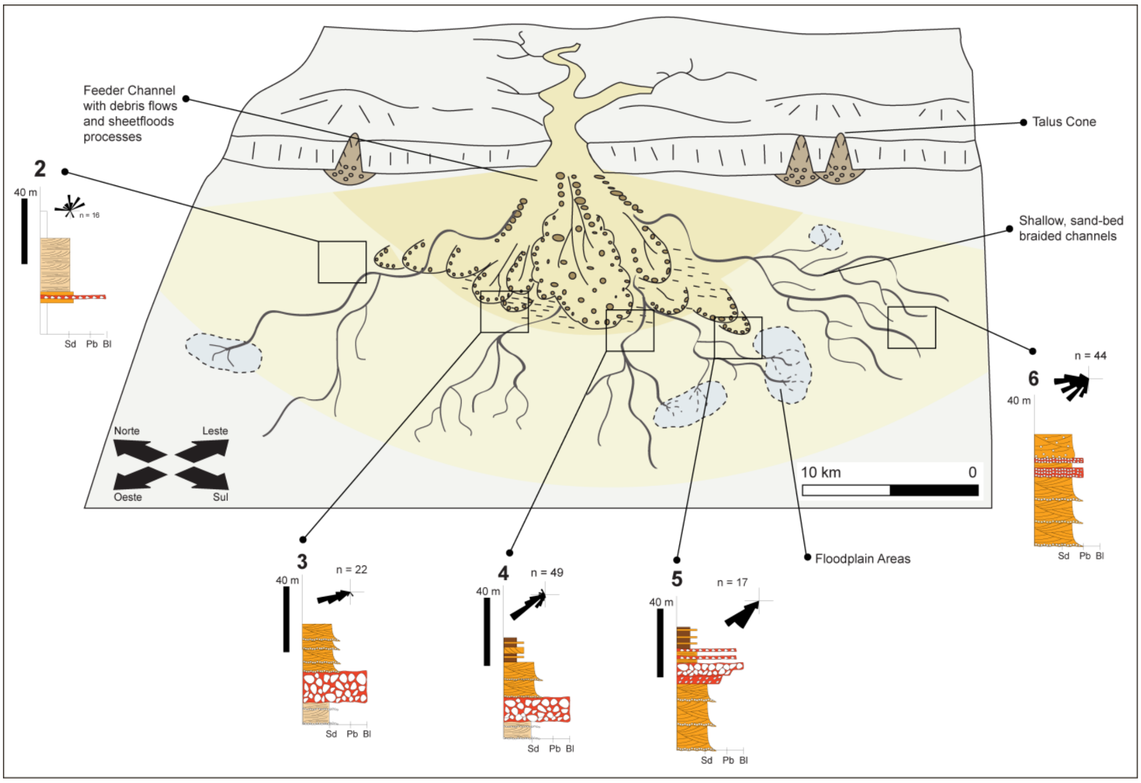


Fig. 15. Palaeogeomorphology map during deposition of the Sequence II, showing alluvial fan depositional system. Squares show the position of the vertical sections.

Debris flows deposits cutting fluvial sand-bed braided channels can be interpreted as the migration of the main feeder channel over old channels (Went, 2005). The floodplain deposits interbedded with thin conglomerates layers at the top of Sequence II may result from sporadic building of alluvial lobes over floodplains (Went, 2005). They also suggest sporadic traction flows reworking the surface of feeder channels of alluvial fans or other abandoned deposits, transported and redeposited at the distal segments of alluvial fans (fan toes) (Blissenbach, 1954; Denny, 1967). The radial pattern of fluvial palaeocurrentes, with wide dispersion and mean vector to the southwest, suggest that these systems came from highlands located at the northeast of the Sincorá Range. The stratigraphic correlation along the vertical sections suggests the alluvial fan had a minimum coverage radius of 40 km, the total distance of vertical sections.

Integration of data from the present work with those of Silva Born (2011) indicates that Sequence II extended further to the North nearby Jacobina city

(Fig. 16), where this unit shows thickness of up to 150 meters. Silva Born (2011) concluded that proximal alluvial fan deposits dominated by gravity flows located to the North graded southwards to fluvial sheetfloods and aeolian sandstones. Therefore, the occurrence of Sequence II further to the North suggests an increase of its depositional area in relation to that of Sequence I (Fig. 16). However, there are compositional differences between the conglomerates of Sequence II in the Jacobina and Lençóis regions. In the Jacobina area, conglomerates present meta-sedimentary subrounded clasts with medium sphericity of green and white quartzite, while nearby Lençóis conglomerates show angular clasts with low sphericity composed of 70% sedimentary rocks and 30% metasedimentary rocks. This difference in clast composition suggests some differences of source area for the alluvial fans. In Jacobina, the basement that served as source rock (Fig. 16) for the northern systems was the Jacobina Group whereas in nearby Lençóis, the dominance of clasts of sedimentary rocks with high textural immaturity suggests the source area for conglomerates were sedimentary rocks most likely from Rio dos Remédios and/or Paraguaçu Group (Fig. 16) that may have been uplifted in the edge of the basin.

Based on palaeocurrent data in the Jacobina and Lençóis area, it was possible to estimate the dimensions of the alluvial fan systems and to understand the spatial distribution of the main facies associations that compose Sequence II. The stratigraphic framework including both areas indicates that the base of Sequence II is primarily composed of debris flows conglomerates and shallow, sand-bed braided channels, with greater thicknesses in the North and South extremities (Fig. 16). Fluvial sheetfloods and aeolian sandstones are thicker in the central area located between Lençóis and Jacobina. Palaeocurrent data in both areas indicate a radial pattern with dominant transport to Southwest and variations to Northwest and Southeast. The geographic position of the vertical sections and the projection of palaeocurrents with respect to proximal deposits suggest that the alluvial fans had a minimum coverage radius of at least 40 km and that the proximal fan were located approximately 20 to 40 km to the east from the vertical sections.

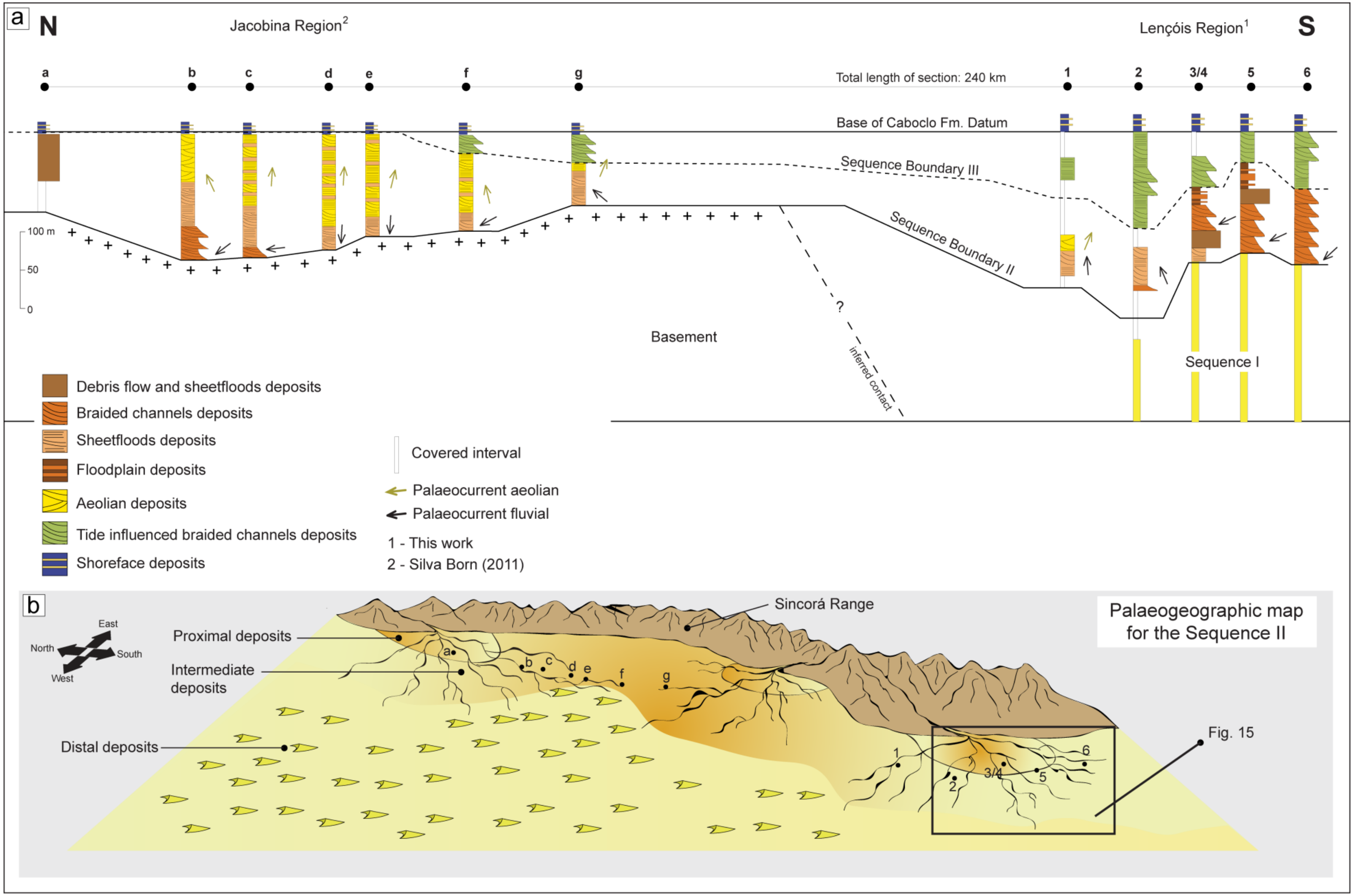

a
N
Jacobina Region[2]
Lençóis Region[1]
S
a
b
c
d
e
f
g
Total length of section: 240 km
1
2
3/4
5
6
Base of Caboclo Fm. Datum
Sequence Boundary III
Sequence Boundary II
100 m
50
0
?
Basement
inferred contact
Sequence I
Debris flow and sheetfloods deposits
Braided channels deposits
Sheetfloods deposits
Floodplain deposits
Aeolian deposits
Tide influenced braided channels deposits
Shoreface deposits
Covered interval
Palaeocurrent aeolian
Palaeocurrent fluvial
1 - This work
2 - Silva Born (2011)
b
East
North
South
West
Proximal deposits
Intermediate deposits
Distal deposits
Sincorá Range
Palaeogeographic map for the Sequence II
Fig. 15

Fig. 16. In (a) stratigraphic cross section showing integrated data with Jacobina region (Silva Born, 2011), in (b) palaeogeographic map of the Sequence II with the location of vertical sections of both areas, black square shows place of Fig. 15.

An erosive surface on top of continental deposits of Sequence II marks the lower boundary of Sequences III (Figs. 14 and 16). The base of Sequence III is characterised by tide-influenced, shallow, sand-bed braided channels with fluvial palaeocurrent to the South- Southwest or by tidal flat medium-grained sandstones with bipolar paleocurrent and eventual wave reworking. The fluvial palaeocurrents with preferential direction to South-Southwest indicate a coastline with Northwest-Southeast direction.

The occurrence of tide-influenced, shallow, sand-bed braided channels is rare in the geological record because most of the fluvial systems influenced by tide in the Phanerozoic are linked to meandering channels located in the proximal portion of estuaries (Shanley et al., 1992; Plink-Björklund, 2005). During the Precambrian, however, the absence of vegetation affected the fluvial styles and braided fluvial and deltaic systems dominated, even in distal portions of alluvial plains (Tirsgaard, 1993; Eriksson et al., 1995). In the study area, the occurrence of tidal facies associations in all vertical sections indicates a tide-influenced palaeoshoreline. The lateral facies correlation suggests that the braided fluvial systems were not active along the palaeoshoreline, and that inactive areas would be eventually covered by tidal flats deposits (Tirsgaard, 1993).

Tide-influenced braided fluvial deposits and tidal-flat deposits are overlain by shallow marine deposits of the Caboclo Formation, defining a general transgressive trend for the base of Sequence III. The upper boundary of sequence III, although not defined in the present study, may correspond to the second order sequence boundary defined by Alkmim and Martins-Neto (2011), which marks the contact between the Caboclo and Morro do Chapéu formations. Dating of stromatolitic limestones of the Caboclo Formation yielded a 1,140 ± 140 Ma age (Babinski et al., 1993), and recent dating on volcanic tuff on top of Sequence II of the Tombador Formation estimated an age of 1,416 ± 28 Ma (Guadagnin et al., in prep). With that in mind, the boundary between

Sequences II and III comprises a hiatus of up to 200 Ma, what suggests a tectonic origin for this sequence boundary although its genesis could not be linked to any tectono-magmatic event in the basin or adjacent areas.

7. Conclusions

Three depositional sequences bounded by regional unconformities were identified for the upper interval of the Tombador Formation. Sequence I is characterised by deposits of shallow, gravel-bed braided fluvial channels that are overlain by fluvial sheetflood and aeolian dunes and aeolian sand sheets. Sequence II is formed of debris flows, fluvial sheetfloods, shallow, sand-bed braided fluvial channels and floodplain deposits that constituted an alluvial fan system. Moreover, Sequence II occur further to the North and was deposited in a larger depositional area compared to that of Sequence I. The composition of conglomerates clasts revealed distinct source areas for Sequence II, one at the North related to the Jacobina Group and another to the South related to the Rio dos Remédios and/or Paraguaçu Group. Sequence III is characterised by tide influenced shallow, sand-bed braided channels and tide flats deposits overlain by shallow marine deposits of the Caboclo Formation.

The three depositional sequences display significant palaeo-geographical variations, linked to probable tectonic movements of the basin. Thus, tectonics was the main controlling factor of the accumulation and development of sequence boundary unconformities. Sequences I and II are marked by the entrance of coarse clastic sediments that probably reflect the uplift of source areas in response to tectonic movements linked to compressional or extensional events at the eastern margin of the Congo-São Francisco palaeoplate. The establishment of a gravel braided fluvial system of Sequence I along with a change of palaeocurrents with respect to the lower sequence suggest a regional restructuring of the drainage systems. The development of alluvial fans systems from highlands to the East and consequent widening of the depositional area of Sequence II suggest sediments deposited under syn-depositional tectonics conditions. The unconformity marks at the base of Sequence III reveals a significant hiatus close to the top of the Tombador Formation what suggests a tectonic origin for this unconformity. Sequence III shows fluvio-estuarine systems being progressively covered by shallow marine systems, hence defining a regional transgression. The top of Tombador Formation (fluvio-estuarine) and the base of the Caboclo Formation (shallow marine) form a single depositional sequence. The upper boundary of Sequence III was not identified in the study area and they separate the Caboclo and Morro do Chapéu formations.

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