UNIVERSIDADE FEDERAL DE SERGIPE
PRÓ-REITORIA DE PÓS-GRADUAÇÃO E PESQUISA

FÁCIES, ELEMENTOS ARQUITETURAIS E ANÁLISE DE PALEOCORRENTES DA FORMAÇÃO TACARATU: SEDIMENTAÇÃO ORDOVÍCIO-SILURIANA DA SUB-BACIA DE TUCANO NORTE, BRASIL

Mateus do Nascimento Santana

Orientador:
Dr. Felipe Torres Figueiredo

DISSERTAÇÃO DE MESTRADO

PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS E ANÁLISE DE BACIAS

São Cristóvão-SE
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Mateus do Nascimento Santana

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Dissertação apresentada ao Programa de Pós-Graduação em Geociências e Análise de Bacias da Universidade Federal de Sergipe como requisito para obtenção do título de Mestre em Geociências.

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"Rhaegar fought valiantly, Rhaegar fought nobly,
Rhaegar fought honorably. And Rhaegar died."

George R. R. Martin

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RESUMO

O registro sedimentar paleozoico do Nordeste do Brasil inclui as sucessões basais das bacias intracratônicas do Parnaíba, Araripe e Tucano-Jatobá, além de pequenas bacias interiores. A sedimentação nesse intervalo teve origem no Ordoviciano, a partir de sistemas aluviais continentais que drenaram os terrenos orogênicos neoproterozoicos do Gondwana. A Formação Tacaratu representa o intervalo basal dos estratos paleozoicos na Sub-bacia de Tucano Norte, Nordeste do Brasil. Esta unidade é predominantemente composta por depósitos siliciclásticos de granulação grossa, associados a sistemas fluviais entrelaçados. Este estudo teve como objetivo examinar o registro sedimentar da Formação Tacaratu, com foco em fácies, associações de fácies e paleocorrentes. Foi realizado um trabalho de campo detalhado em 10 localidades da Formação Tacaratu, com o objetivo de analisar fácies, geometria, superfícies limitantes e paleocorrentes dos depósitos sedimentares desta unidade. Foram identificadas onze fácies, que permitiram a individualização de quatro associações de fácies: FA1 - barras cascalhosas e arenosas, FA2 - barras arenosas e topos de barras, FA3 – barras cascalhosas de meio canal, e FA4 - depósitos finos de áreas de extravasamento. A análise de paleocorrentes revelou uma tendência predominante de paleofluxo para o norte, consistente com estudos anteriores, além de variações localizadas que sugerem morfologias de canais de baixa sinuosidade, previamente interpretadas como entrelaçadas. Esses resultados aprimoram a compreensão dos processos sedimentares que controlaram a deposição da Formação Tacaratu, ao mesmo tempo em que fornecem novas perspectivas sobre a história deposicional dos sistemas fluviais iniciais do Gondwana Ocidental.

Palavras-chave: Formação Tacaratu; Análise de fácies; Paleocorrentes; Morfologia de canal.

ABSTRACT

The Paleozoic sedimentary record of Northeastern Brazil includes the basal successions of the intracratonic basins of Parnaíba, Araripe, and Tucano-Jatobá, as well as smaller intracratonic basins. Sedimentation during this interval began in the Ordovician from continental-scale alluvial systems that drained the Neoproterozoic orogenic terrains of Gondwana. The Tacaratu Formation represents the basal Paleozoic interval in the Northern Tucano Sub-basin, Northeastern Brazil. This unit is predominantly composed of coarse-grained siliciclastic deposits associated with braided fluvial systems. This study investigates the sedimentary record of the Tacaratu Formation, focusing on facies, facies associations, and paleocurrents. Detailed fieldwork was conducted at 10 localities within the Tacaratu Formation, aiming to analyze facies, deposit geometry, bounding surfaces, and paleocurrents of the unit. Eleven facies were identified, allowing the distinction of four facies associations: FA1 - gravel and sandy bars, FA2 - sandy bars and bar tops, FA3 – coarse-grained middle channel bars, and FA4 - overbank fines. Paleocurrent analysis revealed a predominant northward paleoflow trend, consistent with previous studies, along with local variations suggesting low-sinuosity wandering channel morphologies, previously interpreted as braided. These findings refine the understanding of the sedimentary processes that controlled the deposition of the Tacaratu Formation, offering new insights into the depositional history of early fluvial systems of the Western Gondwana.

Keywords: Tacaratu Formation; Facies analysis; Paleocurrents; Channel morphology.

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CAPÍTULO I – INTRODUÇÃO

1.1. Apresentação

O registro sedimentar paleozoico do nordeste do Brasil compreende as sucessões basais das bacias intracratônicas do Parnaíba, Araripe e Tucano-Jatobá, bem como pequenas bacias interiores, como Mirandíba, São José do Belmonte e Fátima (Assine, 2007; Cerri et al., 2024; Milani et al., 2007; Pereira et al., 2018). O início da sedimentação nessa região é atribuído a sistemas aluviais de grande escala que drenaram os terrenos orogênicos neoproterozoicos do Gondwana durante o Ordoviciano (Cerri et al., 2024, 2022; Mabesoone, 1994; Milani et al., 2007).

A Formação Tacaratu representa a sequência sedimentar basal paleozoica das sub-bacias de Tucano Norte e Jatobá (Costa et al., 2007). Sua composição siliciclástica de granulação grossa é atribuída a sistemas aluviais entrelaçados (Rocha e Leite, 1999). Apesar de alguns estudos terem abordado o contexto sedimentar da Formação Tacaratu, incluindo fácies, paleocorrentes e sistemas deposicionais (Carvalho, 2015; Carvalho et al., 2018; Costa et al., 2007; Menezes-Filho et al., 1988; Santos e Souza, 1988), análises detalhadas de fácies, processos sedimentares e geometria dos depósitos — fundamentais para a definição de modelos deposicionais precisos (Bridge e Lunt, 2006) — ainda são escassos. Além disso, o arcabouço estrutural ao longo da margem flexural das bacias de Tucano e Jatobá tem dificultado a defnição de correlações estratigráficas entre as unidades paleozoicas (Milani et al., 2007). Essas limitações ressaltam a necessidade de pesquisas abrangentes para aprimorar a compreensão da história deposicional da Formação Tacaratu, especialmente considerando seu papel como o principal aquífero da região (Diniz et al., 2012).

Este estudo oferece uma investigação abrangente da Formação Tacaratu na região do Gráben de Santa Brígida, a leste da Sub-bacia de Tucano Norte. Esta área exibe afloramentos com ampla extensão lateral e vertical, proporcionando condições favoráveis para a análise de fácies, associações de fácies, elementos arquiteturais e paleocorrentes. Espera-se contribuir com novas informações sobre os processos sedimentares e os controles deposicionais que atuaram na história deposicional da unidade, aprimorando, assim, a compreensão sobre os sistemas aluviais durante os ciclos iniciais de sedimentação do Gondwana Ocidental.

Os resultados dessa pesquisa foram organizados em um artigo científico, intitulado "*UNRAVELING ORDOVICIAN-SILURIAN SEDIMENTATION: FACIES, PALEOCURRENTS, AND ARCHITECTURAL ANALYSIS OF THE TACARATU*

FORMATION, NORTHERN TUCANO SUB-BASIN, BRAZIL", submetido ao *Journal of South American Earth Sciences.*

1.2. Objetivos

O objetivo geral deste trabalho foi estudar detalhadamente o registro sedimentar da Formação Tacaratu, aflorante na região do Gráben de Santa Brígida, nos estados de Sergipe e Alagoas, a fim de contribuir com o entendimento sobre os processos sedimentares e os controles deposicionais que atuaram na unidade, assim como nos ciclos iniciais de sedimentação do Gondwana.

Para alcançá-lo foram definidos os seguintes objetivos específicos:

1. Descrever os depósitos sedimentares da Formação Tacaratu, em termos de fácies, associação de fácies, superfícies limitantes e elementos arquiteturais;
2. Determinar o sentido do fluxo ou dos fluxos de correntes associados à unidade;

1.3. Localização da área

A área de estudo engloba os afloramentos da Formação Tacaratu da Sub-bacia Bacia do Tucano Norte, à leste da região do Gráben de Santa Brígida, nos estados de Sergipe e Alagoas (Figura 1).

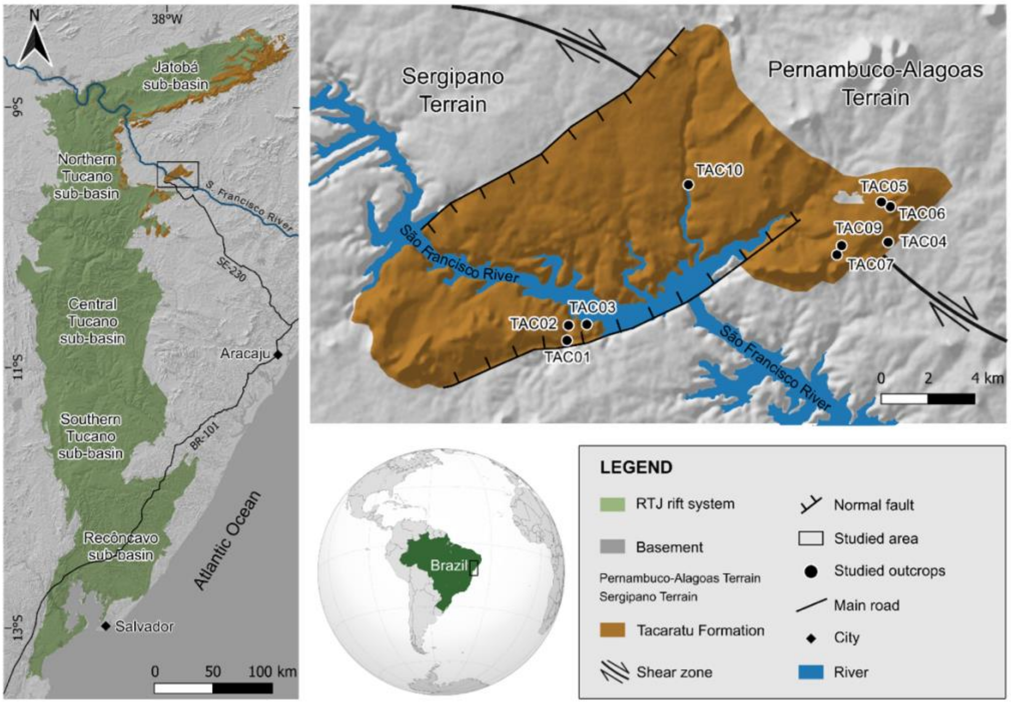

Figura 1: Localização esquemática da localidade de estudo na Bacia do Recôncavo-Tucano-Jatobá (Esquerda). Localização dos pontos estudados na Formação Tacaratu na área de estudo (direita).

Em Sergipe foram realizadas saídas de campo no município de Canindé de São Francisco (SE), nas proximidades dos Cânions de Xingó, sobretudo no Vale dos Mestres (TAC01, TAC02 e TAC03). Em Alagoas, os afloramentos objeto deste estudo estão próximos à cidade de Olho D'Água do Casado (TAC07 e TAC09) e nas localidades Serra da Onça (TAC04, TAC05 e TAC06) e Praia da Dulce (TAC10).

1.4. Método de trabalho

Para atingir os objetivos propostos, foram empregados os seguintes métodos.

A análise das características sedimentares da unidade será executada através do levantamento de seções, análise de fácies, associação de fácies e de elementos arquiteturais. A análise de paleocorrentes será usada para inferir a área fonte e o padrão de dispersão dos sedimentos e a morfologia fluvial.

1.4.1. Análise de fácies

O levantamento de perfis estratigráficos é um método padrão em pesquisas sedimentológicas e estratigráficas. Tal procedimento envolve a descrição e anotação detalhada de cada aspecto que compõem uma fácies sedimentar, representada na escala centimétrica e métrica ao longo de uma seção vertical de rocha ou sedimentos através dos métodos elaborados por Miall (1977, 1996, 2000), Collinson (1996) e Bridge (2006). Seu uso permite observar as variações verticais e auxiliar na correlação lateral das fácies descritas (Tucker 2011). Por sua vez, a análise de fácies utiliza os atributos individuais da rocha (características litológicas e texturais, seleção granulométrica, estruturas sedimentares e conteúdo fossilífero) a fim de compreender as circunstâncias envolvidas na sua formação (Nichols, 2009).

1.4.2. Análise de associações de fácies e elementos arquiteturais

Os elementos arquiteturais representam os produtos deposicionais e erosivos acumulativos na escala de dezenas à centenas de anos e são descritos com base na natureza da superfície limitante, geometria externa, escala e geometria interna, que podem variar na escala de campo e em subsuperfície na escala de centenas a milhares de metros (Miall 1996, 1985). Em campo, caso específico desta proposta, será feito uso da comparação direta entre fotomosaicos dos afloramentos e os perfis verticais, para compreender as variações de extensão, espessura e litológicas entre as camadas de rocha.

1.4.3. Análise de paleocorrentes

A análise de paleocorrentes utiliza a medição de estruturas sedimentares que refletem as condições hidrodinâmicas e aerodinâmicas do fluxo, a fim de verificar a direção e, por vezes, o sentido da corrente responsável pela sua formação (Figueiredo, 2013). Os resultados obtidos na análise de paleocorrentes contribuem para a definição da área fonte, bem como na reconstrução paleogeográfica da bacia (Figueiredo, 2013).

As medidas de paleocorrente foram obtidas utilizando um Apple® iPhone 11 equipado com o aplicativo *FieldMove Clino* (Petroleum Experts Limited, 2022), seguindo as recomendações de Allmendinger et al. (2017). No total, 210 medidas foram obtidas. Para analisar e visualizar os dados de paleocorrentes, incluindo o vetor médio, o diagrama de rosetas e a variância circular, foram utilizadas as bibliotecas *NumPy*, *Matplotlib* e *SciPy* do Python. O código utilizado para essa análise está disponível no material suplementar. Os resultados estatísticos foram calculados com base na metodologia descrita por Fisher (1993).

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CAPÍTULO II – ARTIGO "UNRAVELING ORDOVICIAN-SILURIAN SEDIMENTATION: FACIES, PALEOCURRENTS, AND ARCHITECTURAL ANALYSIS OF THE TACARATU FORMATION, NORTHERN TUCANO SUB-BASIN, BRAZIL"

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Mateus do Nascimento Santana [a*], Pedro Victor Oliveira Gomes [b], Felipe Torres Figueiredo [a]

[a] Programa de Pós-Graduação em Geociências e Análise de Bacias, Universidade Federal de Sergipe (UFS), Avenida Marcelo Deda Chagas, S/N, Rosa Elze, São Cristóvão, SE, 49107-230, Brasil

[b] Programa de Pós-Graduação em Ciências do Sistema Terra e Sociedade, Instituto de Geociências, Universidade de São Paulo (USP), Rua do Lago, 564, São Paulo, SP, 05508-080, Brasil

*Corresponding author.

Email address: mateusnsantana@outlook.com (M. Santana).

Abstract

This study investigates the sedimentary record of the Ordovician-Silurian Tacaratu Formation in the Northern Tucano Sub-basin, Brazil, with a focus on facies, facies associations, architectural elements and paleocurrents. The Tacaratu Formation represents the basal Paleozoic interval of the Northern Tucano and Jatobá sub-basins, predominantly composed of coarse-grained siliciclastic deposits associated with braided fluvial systems. Detailed fieldwork at 10 localities into the Northern Tucano sub-basin was conducted to analyze facies, geometry, bounding surfaces, and paleocurrents, aiming to provide new insights into sedimentary processes and depositional controls that shaped its formation. Eleven facies were identified, grouped into four main facies associations: FA1 - gravel and sandy bars, FA2 - sandy bars and bar tops, FA3 - coarse-grained middle channel bars, and FA4 - overbank fines. Paleocurrent analysis revealed a predominant northward paleoflow trend, aligning with previous studies, but also indicated variations suggestive of low-sinuosity wandering channel morphologies previously interpreted as braided. These findings contribute to a deeper understanding of sedimentary processes and depositional controls in the Tacaratu Formation, offering new perspectives on the early fluvial systems of the Western Gondwana.

Keywords: Tacaratu Formation; Facies Analysis; Paleocurrents; Channel Morphology.

1. Introduction

The Paleozoic sedimentary record of northeastern Brazil comprises the basal successions of the Parnaíba, Araripe, and Tucano-Jatobá intracratonic basins, as well as small relict basins, such as Mirandíba, São José do Belmonte, and Fátima (Mabesoone, 1994; Assine, 2007; Milani et al., 2007; Pereira et al., 2018; Cerri et al., 2024b). The onset of sedimentation in this region is attributed to continental-scale alluvial systems that drained the Neoproterozoic orogenic terrains of Gondwana in the Ordovician (Mabesoone, 1994; Milani et al., 2007; Cerri et al., 2022, 2024b).

The Tacaratu Formation represent the Paleozoic basal sedimentary sequence of the Northern Tucano and Jatobá sub-basins (Costa et al., 2007). Its coarse-grained siliciclastic composition is attributed to braided alluvial systems deposition over the Pernambuco-Alagoas Massif (Rocha and Leite, 1999; Costa et al., 2003). Its chronostratigraphic position was previously suggested to be Siluro-Devonian (Regali, 1964; Braun, 1966), however, recent detrital zircon analysis indicated an older Ordovician age for this unit (Cerri et al., 2024b, 2024a).

The correlation of the Tacaratu Formation with other basal Paleozoic units in Northeast Brazil plays an important role to understand the development of these alluvial systems and epicontinental seas in Western Gondwana (Medeiros et al., 2019; Cerri et al., 2024a, 2024b). Although previous studies have addressed aspects of the Tacaratu Formation, such as facies, paleocurrents, and depositional environments (Menezes-Filho et al., 1988; Santos and Souza, 1988; Costa et al., 2007; Carvalho, 2015; Carvalho et al., 2018), detailed analyses of facies, sedimentary processes, and deposit geometry remain lacking. Such analyses are crucial for developing accurate depositional models (Bridge and Lunt, 2006). Additionally, its structural framework along the flexural margins of the Tucano and Jatobá sub-basins has hampered the definition of stratigraphic correlations (Costa et al., 2007; Milani et al., 2007). These observations underscore the need for comprehensive research to better understand the Tacaratu Formation depositional history, especially given its role as the main aquifer system of the region (Diniz et al., 2012).

This study provides a comprehensive investigation of the Tacaratu Formation in the Santa Brígida Low region (Fig. 1), east of the Northern Tucano sub-basin. This area exhibits large vertical and horizontal outcrops suitable for analysis of facies associations, architectural elements, and paleocurrents. We aim to provide new insights into sedimentary processes and depositional controls that shaped its formation, thereby enhancing our understanding of alluvial systems during the initial sedimentation cycles in Western Gondwana.

2. Geological setting

The Recôncavo-Tucano Jatobá rift system (RTJ) is a rift basin located in the Northeast Brazil, which origin is related to the opening of South Atlantic Ocean during Early Jurassic (Fig. 1) (Milani, 1985; Magnavita and Cupertino, 1988). Basement structural features controlled the evolution of the rift, subdividing the basin into five sub-basins: Recôncavo, Tucano (Southern, Central, and Northern), and Jatobá (Magnavita and Cupertino, 1988). Unlike the basins of the Brazilian continental margin, the opening of the RTJ rift was aborted in the Early Cretaceous (Milani, 1985).

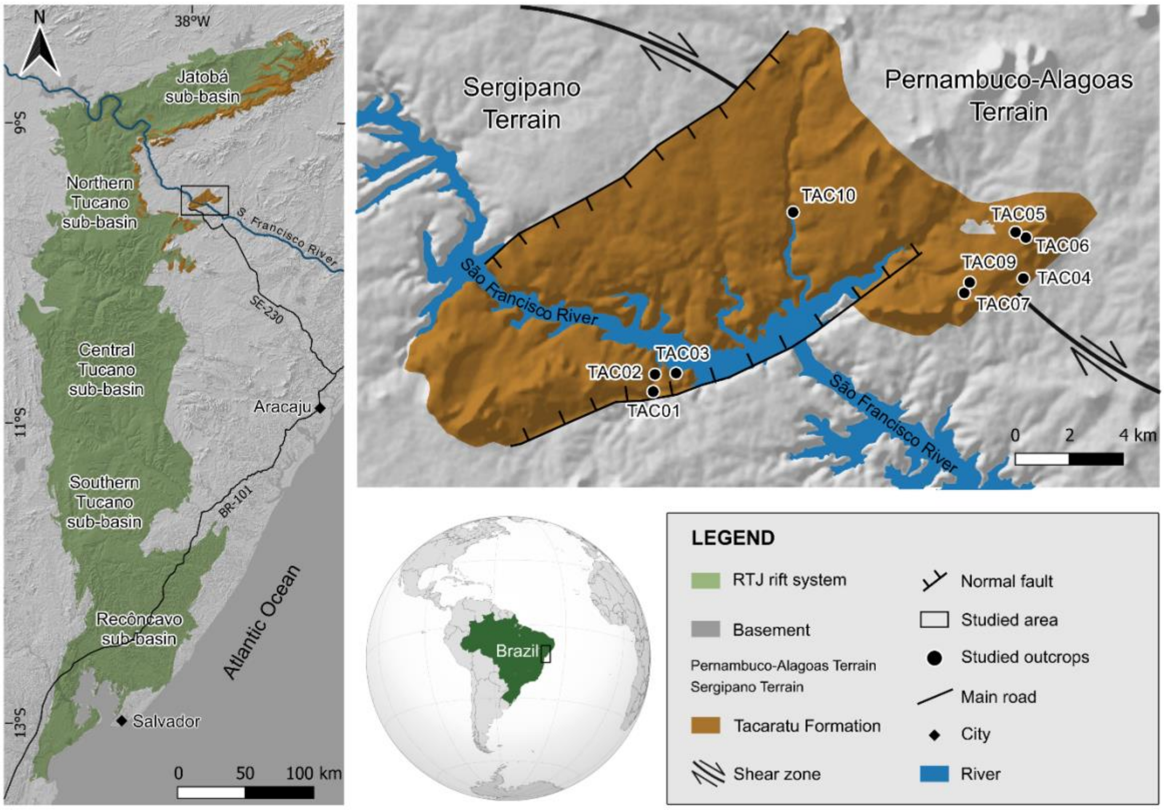

Fig. 1: Schematic map of the studied location area on the Recôncavo-Tucano-Jatobá rift system (RTJ) (left). Distribution of studied outcrops of Silurian-Devonian Tacaratu Formation in the studied area (top right) (modified from ANP, 2024; Mendes et al., 2017; Menezes-Filho et al., 1988; Neumann et al., 2017; Santos and Souza, 1988).

Due to similarities in their sedimentary fill and evolutionary history, the Northern Tucano and Jatobá sub-basins share the same stratigraphic framework (Fig. 2) (Santos et al., 1990; Costa et al., 2007).The Paleozoic record is represented by four lithostratigraphic units developed prior to the rift phase within an intracratonic basin setting: the basal Ordovician fluvial Tacaratu

Formation, the Devonian shallow-marine Inajá Formation, the Carboniferous glacial Curituba Formation, and the Permian shallow-marine Santa Brígida Formation (Fig. 2) (Costa et al., 2007).

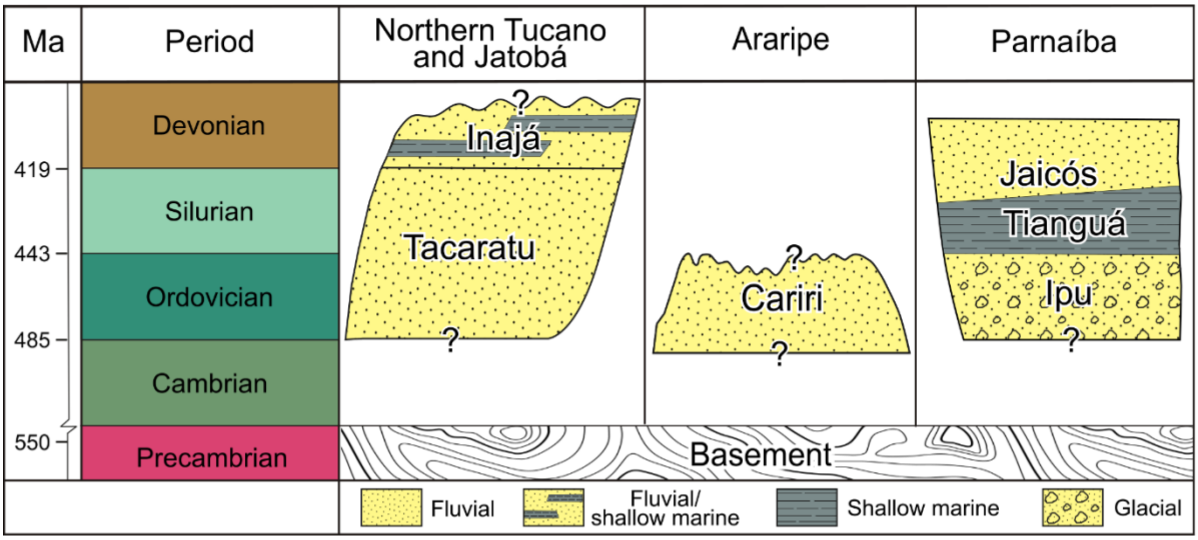

Fig. 2. Simplified chronostratigraphic correlations between Northern Tucano and Jatobá, Araripe, and Parnaíba Paleozoic units (Assine, 2007; Costa et al., 2007; Vaz et al., 2007; Carvalho et al., 2018; Fambrini et al., 2020; Cerri et al., 2022, 2024b, 2024a)

The Tacaratu Formation was formalized by Braun (1966) based on the analysis of the quartz-rich sandstone from the Serra de Tacaratu in Pernambuco State. The Tacaratu Formation exhibit extensive sandy plateaus with steep escarpments on the eastern and southern edges of the Northern Tucano and Jatobá Basin (Rocha and Leite, 1999). Along the eastern boundary of the Northern Tucano sub-basin, the unit crops out discontinuously in scattered areas throughout the region known as Santa Brígida graben (Menezes-Filho et al., 1988; Santos and Souza, 1988; Neumann, 2017; Neumann et al., 2017).

The alluvial deposits of the Tacaratu Formation are characterized by conglomerates, conglomeratic sandstones, and coarse-grained sandstones with trough and planar cross bedding, along with subordinated siltstones and mudstones (Rocha and Leite, 1999; Carvalho et al., 2018). Its depositional environment is described as braided rivers and alluvial fans systems (Menezes-Filho et al., 1988). Petrographic analysis allows these sandstones to be classified as quartzarenites, sublithic, subarkoses, and arkoses, with main sources from metamorphic and igneous rocks, and provenance linked to interior stable cratons and continental transitional terrains (Neumann et al., 2013; Carvalho et al., 2018; Batista et al., 2022).

The age of the Tacaratu Fomation has not been determined through biostratigraphic methods, since no material has been recovered to determine its chronostratigraphic position. Hence, its age has been tentatively assigned to the Silurian-Devonian periods, with a possible extension into the Ordovician (Regali, 1964; Braun, 1966; Ghignone, 1979; Carvalho et al., 2018), based on its stratigraphic position – underlying the Devonian Inajá Formation – and its lithological similarities with the Serra Grande Group (Jaicós Formation) in the Parnaíba Basin, the Cariri Formation in the Araripe Basin, and Karapotó Formation in Sergipe-Alagoas Basin (Braun, 1966; Mabesoone, 1994; Costa et al., 2007; Souza-Lima et al., 2014; Guzmán et al., 2015; Carvalho et al., 2018; Cerri et al., 2024b).

Recently, the correlation of these units was confirmed by Cerri et al. (2024b) through U-Pb detrital zircon analysis of basal Paleozoic units in the basins of Northeast Brazil. Their findings indicate an Early Ordovician age to the Tacaratu Formation, which was part of a large-scale river system transporting sediments from orogenic areas in the south of the Borborema Province. Using a similar approach, Cerri et al. (2024a) proposed that Cambrian-Ordovician sedimentary successions recorded in Northern Africa and the Middle East may represent analogous alluvial systems dispersing sediments towards the northern and northwestern margins of Western Gondwana.

3. Methods

The fieldwork was conducted between August 2022 and January 2023. An investigation was carried out at 10 distinct locations within the Tacaratu Formation in the Santa-Brígida Low area, (Serra do Retiro area of Santos and Souza (1988)), east of Northeast Tucano sub-basin (Fig. 1). Vertical sections were constructed according to Tucker (2011) to analyze the sedimentary succession. The facies were examined according to models established for braided rivers by Miall (1977, 2006), Collinson (1996), and Bridge (2006). To assess the lateral variation, identify bounding surfaces and architectural aspects, photomosaics of the outcrops were constructed, as described by Miall (2006, 2000, 1985). Paleocurrents measurements were obtained on the foreset of planar and trough crossbedding structures to determine the direction of sedimentary transport, as described by Miall (2000). The dip-direction measurements were taken using an Apple® iPhone 11 equipped with the *FieldMove Clino* application (Petroleum Experts Limited, 2022), following the recommendations of Allmendinger et al. (2017). A total of 203 dip-directions measurements in seven locations were taken. To analyze and visualize the paleocurrent data, including the mean vector, rose diagram, and circular variance, we employed the Python libraries *NumPy*, *Matplotlib*, and *SciPy*. The code used for this analysis is provided in the supplementary material. The statistical results were calculated based on the methodology described by Fisher (1993).

4. Results

4.1. Facies, facies association and bounding surfaces

Eleven facies were identified in the Tacaratu Formation (Table 1) leading to the establishment of four facies associations (Table 2): FA1 – Gravel and sandy bars; FA2 – Sandy bars and bar tops, FA3 – Coarse-grained middle channel bars; and FA4 – Overbank fines.

Table 1: Facies description and interpretation according to Miall (1977, 2006), Bridge (2006), and Collinson (1996).

Code	Facies	Description	Interpretation
Gm	Massive conglomerate	Sandy-matrix-supported pebbly massive conglomerate. Pebbles are mostly composed of vein and smoke quartz. Exhibit irregular contacts with Sm.	Product deceleration of a high-density, cohesionless sediment-water mixture during bar migration under laminar or turbulent flow conditions.
St	Sandstone with trough cross-bedding	Coarse to very coarse sandstone with distinct trough cross-bedding. The trough cross-bed sets can reach up to 2 meters in thickness in large-scale beds. Most sets are 3 to 10 cm thick and are organized into cosets measuring between 10 and 50 cm in thickness. The grains exhibit low sphericity and are angular. Contacts with the Sp facies are erosive or irregular, occasionally marked by pebble lags.	Migration of sinuous-crested to linguoid 3D dunes under a lower flow regime.
Sp	Sandstone with planar cross-bedding	Coarse to very coarse sandstone with planar cross-bedding stratification. Granules and pebbles are abundant and consist of vein quartz. Peables are 1.0-1.5 cm long. Sets range between 15 to 80 cm thick and display finning upward sequences.	Product of straight-crest, transverse and linguoid 2D dunes migration.
Sm	Massive sandstone	Fine-grained massive sandstone, occasionally silty. The beds exhibit a slightly irregular pebbly lag contact with the St facies and vertically transition into Sh facies. Contacts with the St, Sp, and Scr facies display planar, lenticular, or concave upward geometries.	Product of sediment deposition in gravity flow conditions.
Sh	Sandstone with horizontal lamination	Fine sandstone with horizontal lamination.	Result of deposition in upper plane bed flow regime.
Sc	Sandstone with compound cross bedding	Very coarse sandstone with compound cross bedding. Peabbles are rare and sparse. Sets range up to 3-4cm internally. Beds are up to 75cm thick.	Result of superimposed dune migration (small bedforms) on the surface of a compound bar (large bedforms).

Sd	Sandstone with convoluted bedding	Medium, well sorted sandstone with convoluted bedding. Sparse granules are present. Convoluted fold beds measure up to 2cm.	Resulting from plastic deformation of liquefied sediments post-deposition.
Sl	Sandstone with low-angle planar cross-bedding	Sandstone with low-angle planar cross-bedding.	Formation of antidunes under supercritical flow conditions.
Scr	Sandstone with climbing ripple cross lamination	Fine, sorted to very sorted sandstone with climbing ripple cross-lamination. Sparse granules are present.	Migration of current ripples in supercritical climb regime.
H	Heterolithic sandstone	Medium to fine heterolithic sandstone with climbing ripple cross-lamination. The beds are wavy and show variations in silt content. Ripple sets reach up to 3 cm in height.	Deposition due alternating decantation and traction processes.
Fl	Laminated siltstone	Horizontal laminated white siltstone. The sets can be up to 20cm thick. Contacts occur with fine and coarse massive sandstone (Sm).	Deposition of fine sediments by decantation in overbank areas, abandoned channels, or drape deposits.

Table 2: Facies associations.

Facies association	**Description**	**Interpretation**
FA1 – Gravel and Sandy bars	FA1 is characterized by granule-rich sandstones with tabular and trough cross-bedding, with occasional fine-grained sandstones. The thickness of these sandstone sets ranges from 10 cm to 1.5 m, forming tabular and sheet-like bodies that extend laterally up to approximately 40 m. Massive conglomerates (Gm) occur as lenses within massive sandstones (Sm).	This association represents gravel and sandy bars within a high-energy fluvial system. The presence of large-scale cross-stratified sandstones and conglomerate lenses indicates the migration of sinuous-crested dunes and deposition in braided river channels
FA2 – Sandy bars and bar tops	This association represents gravel and sandy bars within a high-energy fluvial system. The presence of large-scale cross-stratified sandstones and conglomerates indicates the migration of sinuous-crested dunes and deposition by mass plastic debris flow in braided river channels	FA2 reflects the deposition of sandy bars and bar tops in a fluvial system. The tabular and sheet-like bodies formed in this association indicate sedimentation during more stable flow conditions, with evidence of falling stages and the formation of abandoned bar
FA3 – Coarse-grained middle channel bars	This facies association is characterized by massive conglomerates (Gm) and coarse-grained sandstones with planar and trough cross-bedding (Sp and St facies). The lateral extent of these sets can reach up to 70 m, with predominantly tabular geometries and erosive horizontal bounding surfaces. Pebble lags and internal gradation within the conglomerate layers are also observed.	FA3 represents the deposits of coarse-grained middle channel bars within a fluvial system. The erosive surfaces and pebble lags suggest high-energy conditions, with deposition influenced by fluctuations in flow velocity and sediment supply.
FA4 – Overbank deposits	FA4 is characterized by laminated siltstones (Fl) and fine to very fine massive sandstones (Sm). These	FA4 represents floodplain and overbank deposits formed in overbank areas of the fluvial

	deposits are limited in both vertical and lateral distribution within the Tacaratu Formation. The laminated siltstones can reach up to 20 cm in thickness and are interbedded with fine-grained massive sandstones, displaying horizontal bounding surfaces and tabular geometries.	system. The fine-grained nature of these sediments indicates deposition by decantation during flood events, within low-energy environments such as floodplains.

4.1.1. Facies Association 1 - FA 1 – Gravel and sandy bars

The gravel and sandy bar facies association is represented by granule-rich sandstones with tabular and trough cross-bedding (Sp and St) and rarely fine-grained sandstones (Fig. 3). The thickness of the sandstones sets ranges from 10 cm up to 1.5 m, and these sets form tabular and sheet-like bodies that extend laterally up to approximately 40 m (Fig. 4). The Sp facies exhibit cosets organized into tabular sets of 5 to 10 cm of coarse to very coarse sandstones, showing tangential top and bottom foresets (Fig. 3E). In some levels, Sp and St facies sets display large-scale cross-stratification (Fig. 3C-D, Fig. 4). Locally, convolute sandstones (Sd facies) are also present (Fig. 3G).

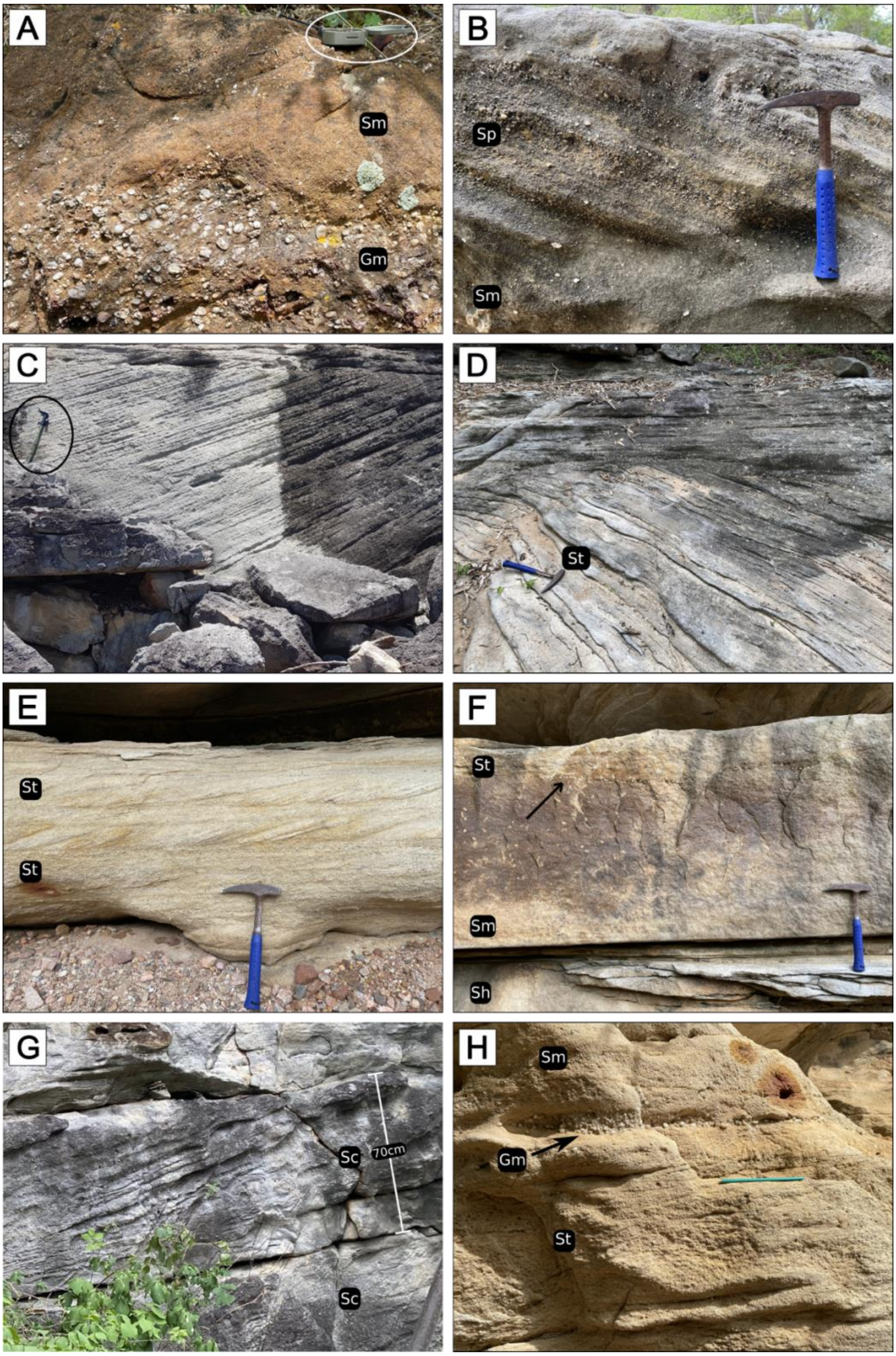

Fig. 3: Gravel sandy facies association (FA1) at TAC01 location. **(A)** Massive conglomerate (Gm) overlying massive sandstone (Sm). **(B)** Massive sandstone (Sm) and planar cross stratified sandstone (Sp) bounded by erosive surface. **(C-D)** Large-scale planar cross-stratified sandstone (Sp). **(E)** Coset of trough-cross stratified sandstones (St). **(F)** Succession of sandstone with horizontal lamination (Sh), massive sandstone (Sm) and trough-cross stratified sandstone (St) facies. Note pebbly lags bounding Sm and St beds (black arrow). **(G)** Convolute sandstone (Sc) sandstone with low-angle planar stratification and trough-cross stratified sandstones **(H)** Conglomerate lenses (Gm) in massive sandstone (Sm). Scale: Switchblade (10 cm long), hammer (33 cm high), compass (7 cm), and walking stick (35 cm high).

The bounding surfaces of the cosets observed are mostly horizontal. Massive conglomerates facies (Gm) occur as lenses into massive sandstones (Sm) (Fig. H). The lower boundary of FA1 was not observed, while upper limit with FA2 is marked by a concave-up pebbly lag erosional surface, which is overlain by massive and laminated stratified sandstone (Sm and Sh facies) (Fig.4F; Fig. 6). Paleocurrent measurements from the foresets surfaces indicate an NNE paleoflow direction (Fig. 4). The vertical profile of the FA1 facies associations is provided in Section 1 at TAC01 locality (Fig. 4).

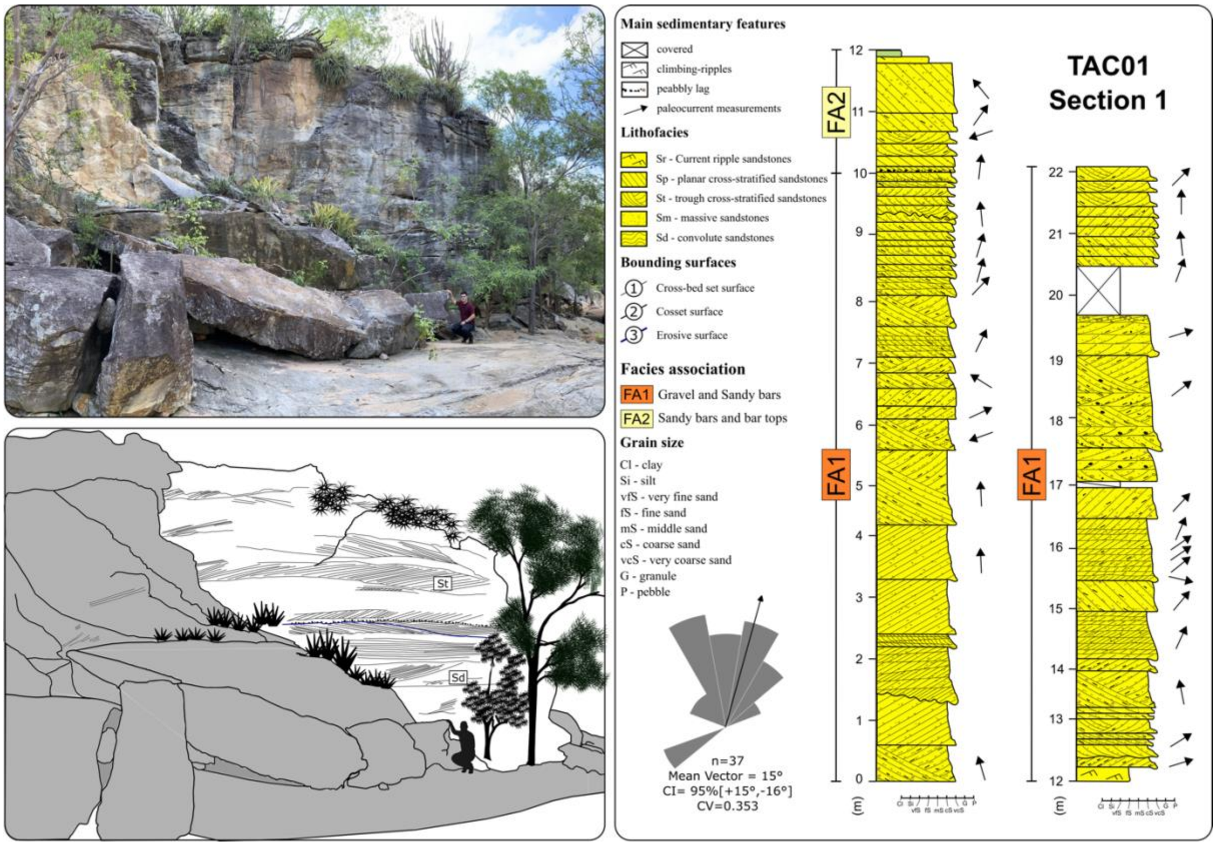

Fig. 4: FA1 - Gravel and Sandy bars facies association at TAC01 location. TAC 01 locality section, paleocurrents and main sedimentary features (right). Interpretation of FA2 facies association and bounding surfaces at TAC01 location (left).

4.1.2. Facies Association 2 - FA 2 – Sandy bars and bar tops

The sandy bars and bar tops facies association is characterized by tabular and trough cross-bedding sandstones (St and Sp facies), alongside minor massive and ripple cross-laminated sandstones (Sm and Scr facies) (Fig. 5). The thickness of the sets ranges from 10 cm to 2.0 m in some large-scale Sp sets. Lateral extension can reach up to 70 m, though this is occasionally disrupted by lateral displacement of blocks due faults and fractures (Fig. 6).

The vertical succession of the FA2 (Section 2 of Fig. 6) comprises St and Sp facies in the lower part of the section (7-11 m). In this interval, reactivation surfaces are observed bounding granule-rich massive sandstones (Ms) and trough cross-bedded sandstones (St) strata (Fig. 5C). This succession is overlain by small-scale massive and ripple cross-laminated sandstones (Sm and Scr facies) in the midsection of the profile (18-20 m). At this level, Sm facies consist of massive silty sandstones, occurring as discontinuous small lenses that can extend laterally from 40 to 150 cm within Scr and low-angle planar cross-bedding sandstones (Sl) (Fig. 5A-B). The Scr facies occasionally exhibit rhythmic deposition of fine sediments over the ripple crests (Fig. 5B). The top of the section is marked by the reappearance of large-scale Sp, St an Sm strata, extending from 20 to 26 m. Bounding surfaces are mostly horizontal and erosive, resulting in tabular and sheet-like bodies (Fig. 6). The central portion of photomosaic highlights downstream-dipping coset surfaces with downlap terminations bounding a major erosive surface (2nd and 4rd order of Miall (1996) respectively), interpreted as lateral accretion bar macroforms (LA element of Miall (1985)) (Fig. 6). The paleocurrents measures in FA2 reveal a southeastward trend, indicating a significant paleoflow shift compared to FA1 (Fig. 6).

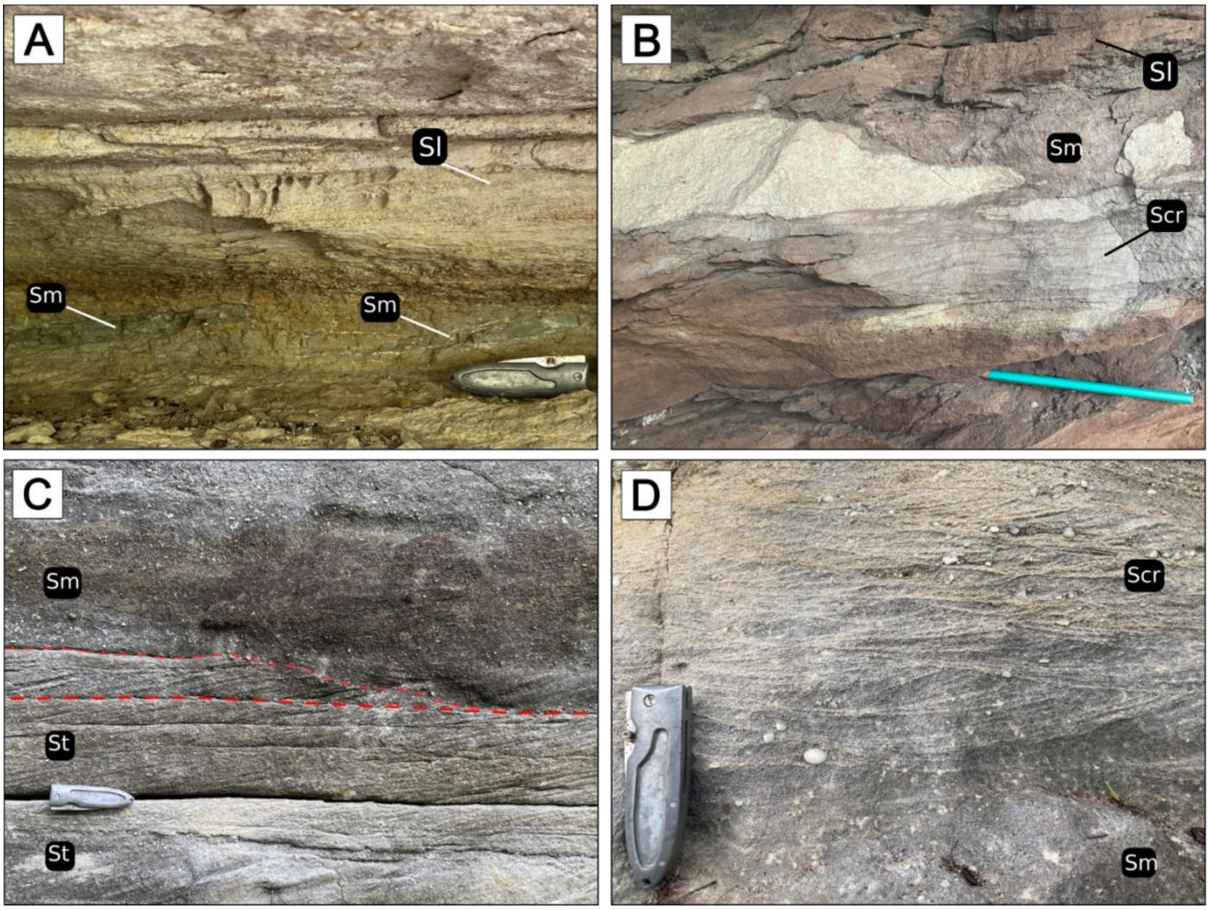

Fig. 5: Sandy bars and bar tops facies association (FA2) at TAC01 location. **(A)** Lenses of massive silty sandstone (Sm) within low-angle planar cross-bebbed sandstone (Sl) **(B)** Climbing ripple cross-laminated sandstones (Scr), low-angle planar cross-bedding sandstone (Sl), and massive sandstone (Ms) stratas. Note the reddish alteration caused by the accumulation of fine sediments in the top of the ripples **(C)** Massive sandstone (Sm) overlying trough cross-bedded sandstone (St) showing internal reactivation surface (dashed red line) (D) Sandstone with climbing ripple underlying massive sandstone (Sm) Scale: Switchblade (10 cm long) and pencil (35 cm).

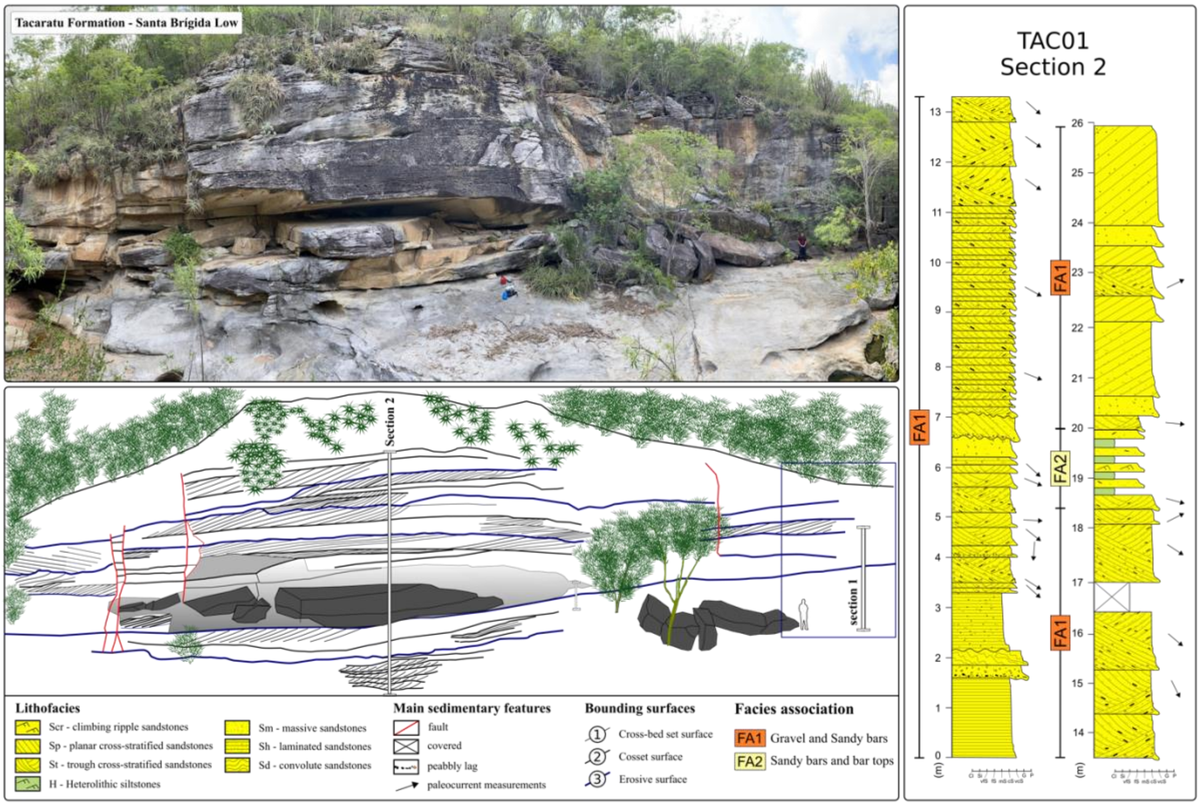

Fig. 6: FA2 - Sandy bars and bar tops facies association at TAC01 location. TAC 01 locality section 2, paleocurrents and main sedimentary features (right). Interpretation of FA2 facies association and bounding surfaces at TAC01 location (left). Scale: Geologist is 1.76 m.

4.1.3. Facies Association 3 - FA3 – Coarse-grained middle channel bars

This coarse-grained middle channel bar facies association was described at the TAC07 location. It is characterized by massive conglomerates (Gm), as well as planar and trough cross-bedded sandstones (Sp and Sp facies) (Fig. 7). Laterally, the sets can reach up 70 m (Fig. 8), with predominantly tabular geometries and bounding surfaces that are both erosive and horizontal. Conglomerates are coarse-sand matrix supported with granules and pebbles composed of vein quartz. The Sp and St facies presents in FA2 are characterized by large-scale, granule-rich coarse sandstones strata with sparse pebbles (Fig. 7A, C-F), with set thicknesses varying laterally from 30 cm to 1.3 m (Fig. 8).

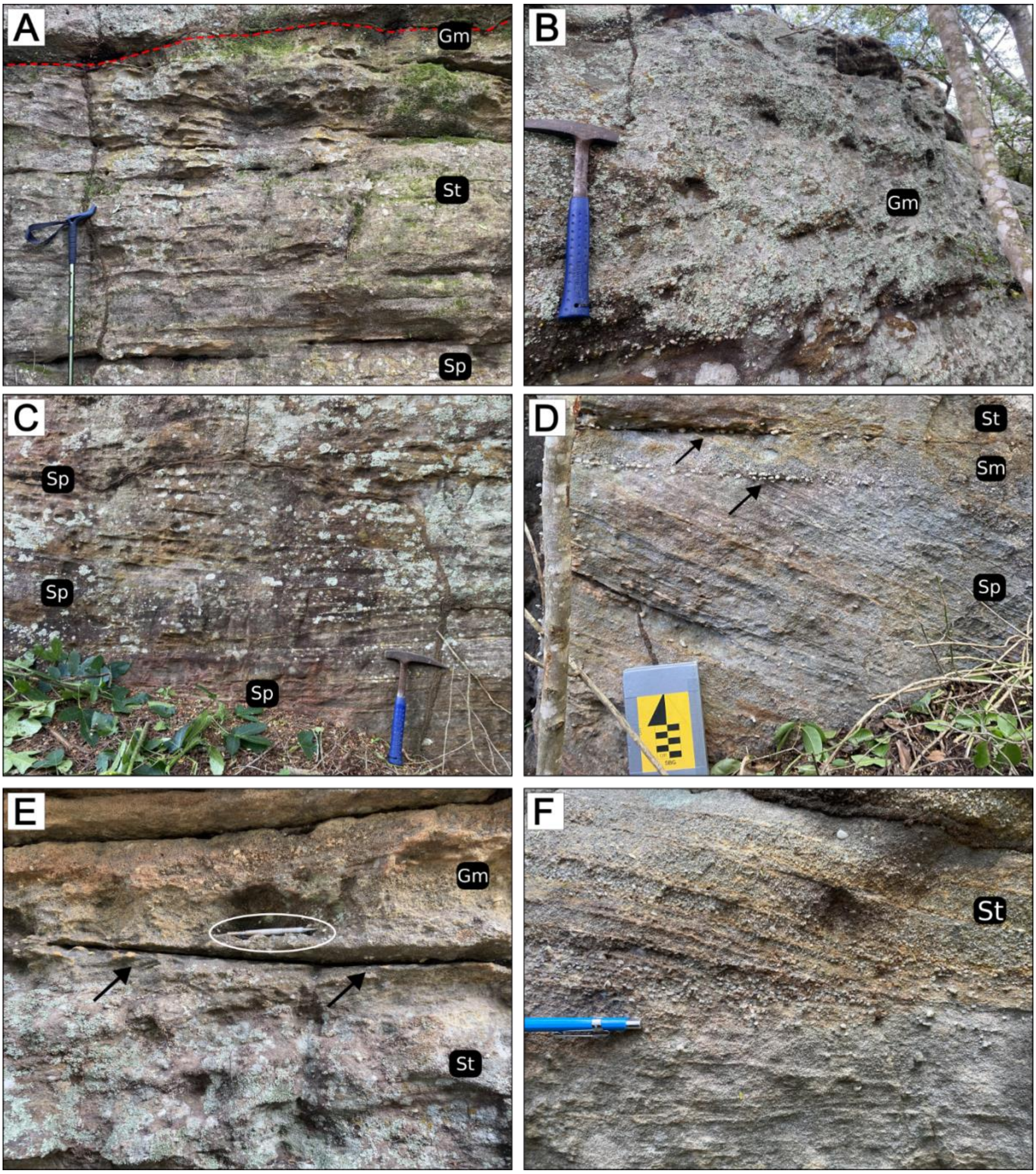

Fig. 7: Coarse-grained middle channel bars facies association (FA3) at TAC07 location. **(A)** Trough cross-bedded sandstone (St) and massive conglomerate (Gm) bounded by erosive surface (red dashed line) **(B) (C)** Large-scale trough cross-bedded sandstones (St) **(D)** Planar cross-bedded sandstones (Sp) and massive sandstone (Sm) limited by pebbly lag **(E)** Massive conglomerate (Gm) overling trough cross-bedded sandstone (St) by erosive concave-upward surface (black arrow). **(F)** Detail of fining upward sequence. Scale: walking stick (50 cm height), hammer (33 cm height), pencil (15 cm long), and notebook (19 cm height).

The bottom of the section is marked by a succession of St and Sp sets (0-2 m) mainly bounded by erosive and horizontal surfaces (Fig. 8), whose pebbly lags accumulations are common (Fig. 7A, D). An erosive bounding surface delimited the bottom of the section, which evolves to massive conglomerate dominated facies towards the top (2-4 m) (Fig. 8). At this point, bounding surfaces between sets are slightly erosive and exhibit concave upwards geometry in some places

(Fig. 7E) (Fig. 7A; Fig. 8), Some Gm sets show internal gradation organized in centimetric-thick layers of different proportions of sand, granules, and pebbles. An NNW paleoflow trend was obtained from paleocurrents measurements (Fig. 8).

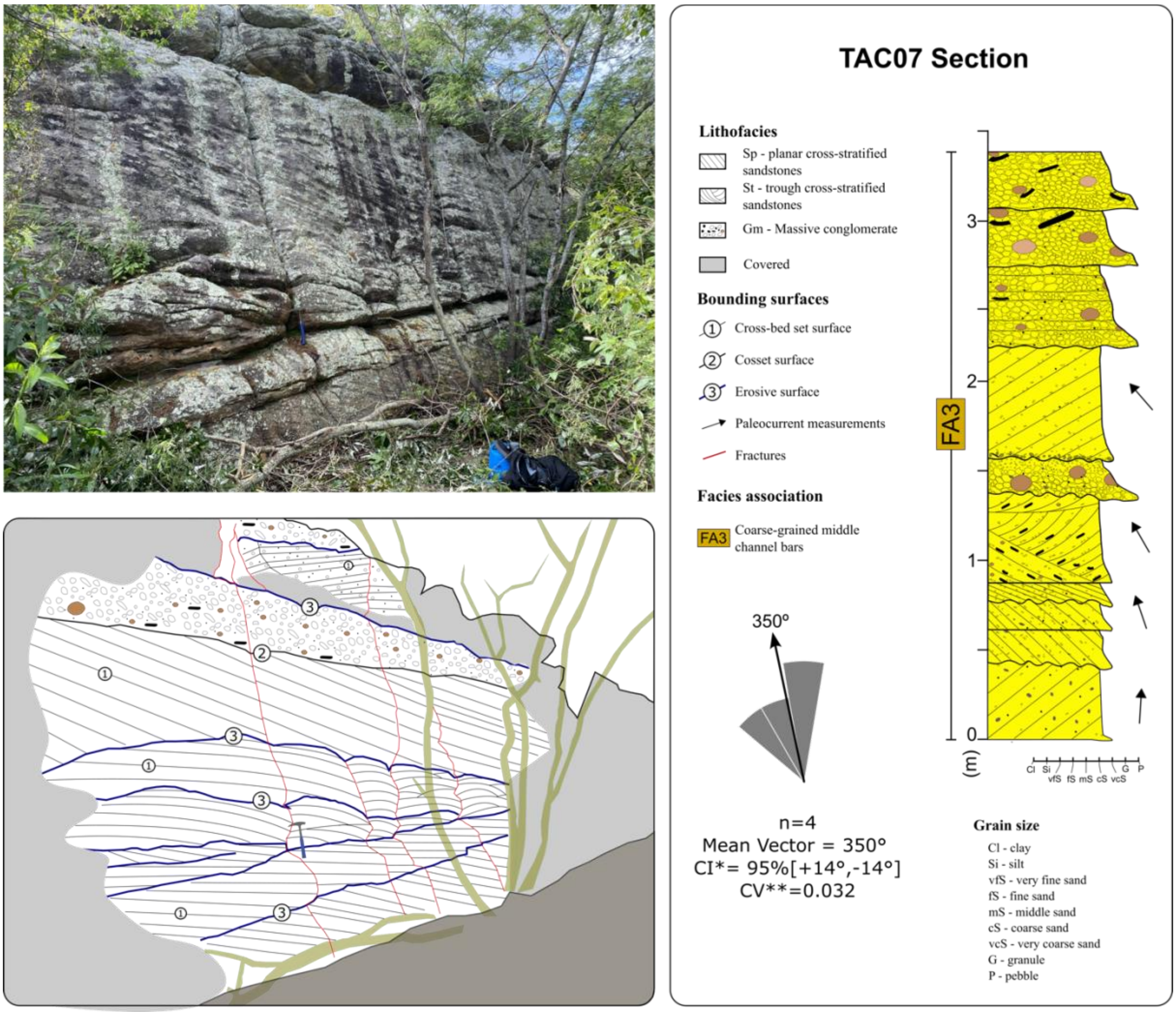

Fig. 8: Coarse-grained middle channel bars facies association (FA3). Interpretation of FA3 facies association geometry and bounding surfaces at TAC07 location (left). Vertical section and paleocurrent trend from FA3 in locality TAC07 (right). Scale: hammer (33 cm height).

4.1.4. Facies Association - FA 4 – Overbank deposits

The Overbank facies association occurs in a restricted interval, both vertical and lateral, within Tacaratu Formation. It is characterized by laminated siltstone (Fl) and coarse to very fine massive sandstone (Fig. 9). The laminated siltstone sets (Fl) can reach up to 20 cm in thickness and extend horizontally for a few meters. In TAC09 section (Fig. 9), Fl sets are interbedded with very fine-grained massive sandstones (Sm), showing horizontal bounding surfaces and tabular geometries. The upper limit of FA4 is marked by an erosive bounding surface, overlain by a thin coarse-grained massive sandstone layer (Sm) and large-scale St facies, which are interpreted as belonging to FA3. This set contains small, rounded intraclasts up to 3 cm in size

(Fig. 9). Paleocurrent measurements from the upper part of the section indicate a NE paleoflow trend (Fig. 9).

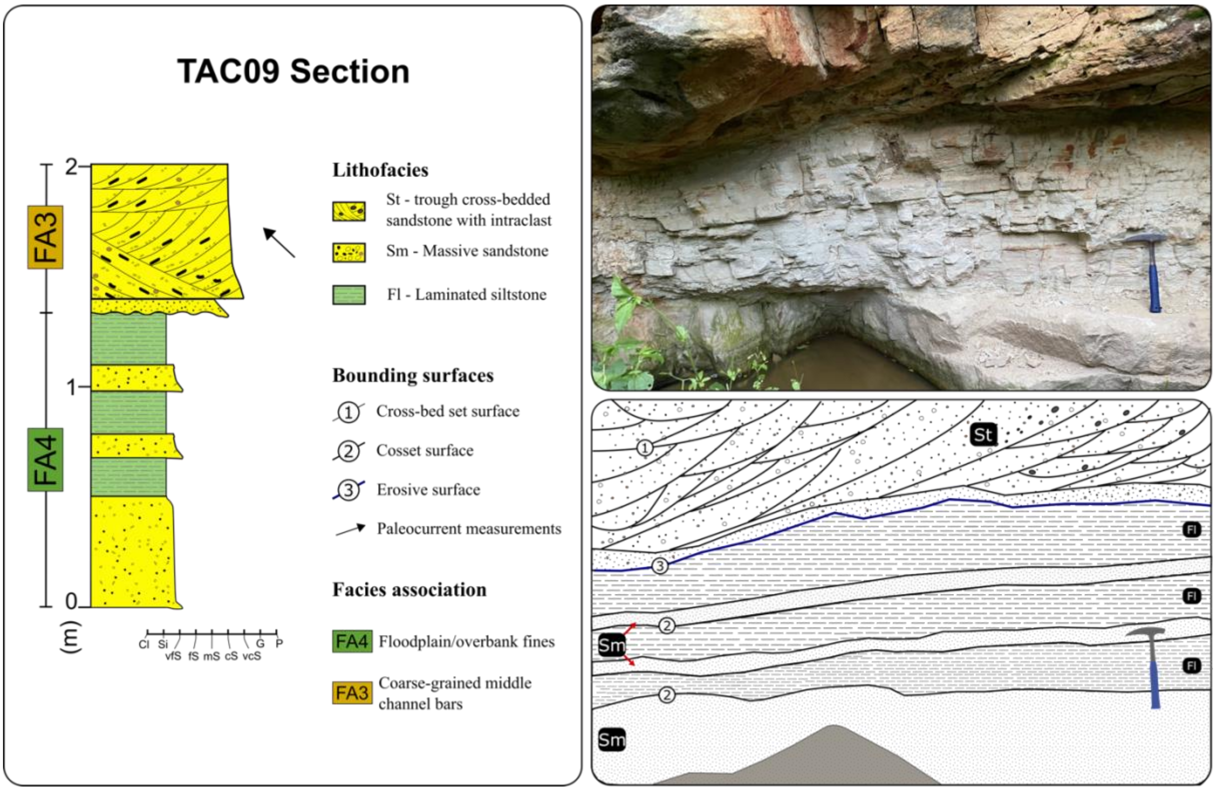

Fig. 9: FA4 - Overbank facies association at TAC09 location. TAC 09 locality section, paleocurrents and main sedimentary features (left). Interpretation of FA 4 facies association and bounding surfaces at TAC09 location (right). Note the intraclasts scours at the top right. Scale: hammer is 33 cm long.

4.2. Paleocurrents Analysis

Paleocurrent measurements were conducted at seven sites within the Tacaratu Formation (Fig. 10). Table 3 presents the local values for number of measurements, mean vector, and trend for each locality. The results indicate a predominant paleoflow direction towards the north, with localized deviations towards NNW and NNE, consistent with the paleoflow patterns reported by Carvalho et al. (2018) for the for exposures of the Tacaratu Formation in the southern sector of the Jatobá sub-basin. Among our data, only site TAC 03 showed a significant deviation, with a paleocurrent direction trending southeast. The circular variance of the mean vector (C_{var}) the studied points was intermediate (C_{var} = 0.335; see Galeazzi et al. (2021) for a detailed explanation of circular variance and channel morphology).

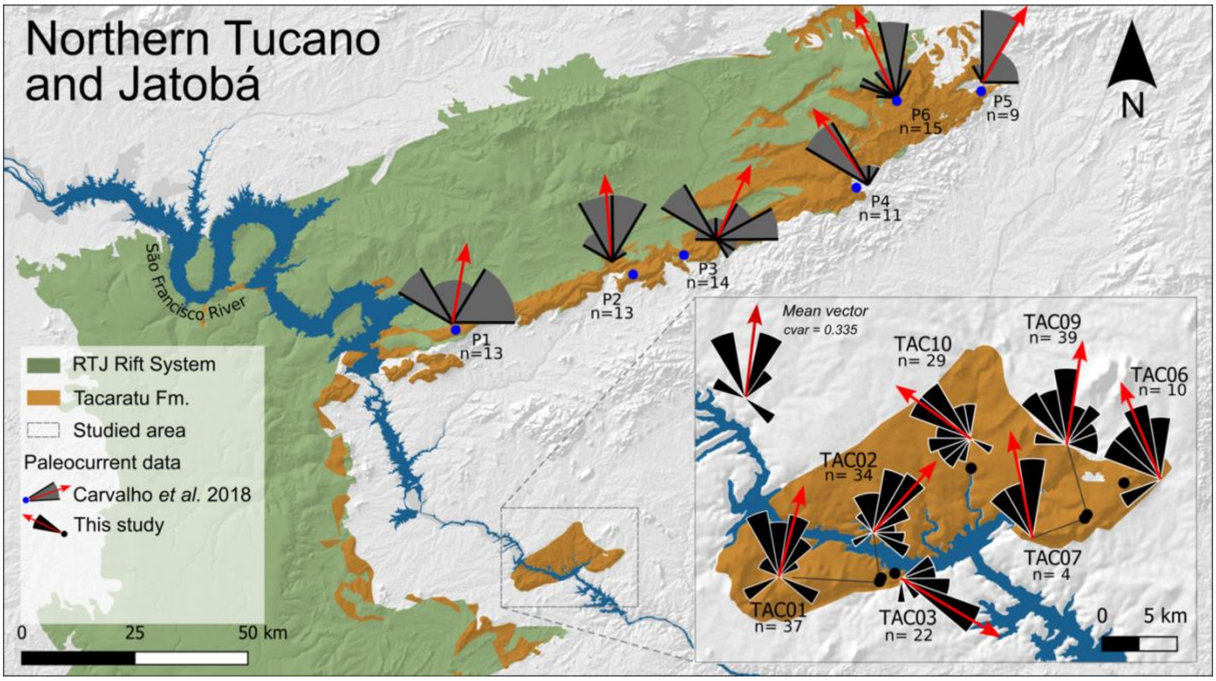

Fig. 10: Schematic map showing the distribution of paleocurrent patterns results in the Tacaratu Formation as observed in this work (black rose diagrams) compared to those reported by Carvalho et al. (2018) (grey rose diagrams). Note that the rose diagram "Mean vector" represents the mean vector of each point and the respective circular variance.

Table 3: Paleocurrent trends, number of measurements, mean vector for each locality of Tacaratu Formation.

Locality	N	Mean vector	Trend
TAC01	37	15	NNE
TAC02	34	43	NE
TAC03	22	121	ESE
TAC06	10	337	NNW
TAC07	4	350	N
TAC09	39	11	N
TAC10	29	304	NW

5. Discussion

5.1. Facies, facies associations and boundary surfaces

The facies and facies associations described herein for the Tacaratu Formation exhibit a variability predominantly composed of coarse-grained cross-bedded siliciclastic facies in association with subordinate fine-grained clastic facies.

The FA1 - gravel and sandy bar facies association, along with FA2 - sandy bars and bar tops, occurs at the TAC01 location within the Vale dos Mestres Trail in the municipality of Canindé do São Francisco (SE) (Figueiredo et al., 2023). Gravel bars and sandy bedforms (GB and SB elements) are commonly interbedded architectural mesoforms, characterized by tabular and sheet bodies that fill channels and form minor bars (Miall, 1996). FA1 displays variability in the thickness of Sp and St facies, ranging from centimeter-thick sets to large-scale cross-bedded sets (Fig. 4). Bridge (2006) emphasized the correlation between the scale of stratigraphic sets, such as cross-bedded sets, and the overall size of the channel. The significant enlargement or reduction in size of the individual elements in ancient alluvial deposits can be understood as a result of changes in the energy conditions over time and space, which could be attributed to shifts in tectonic activity, topography, or climate (Collinson et al., 2006). The Sp ans St sandstones can develop into convolute sandstones, generated by the deformation of liquefied sediments during deposition (Collinson et al., 2006). The small-scale cross-laminated sandstones (Scr) and low-angle planar cross-bedded sandstones (Sl), interbedded with silty massive sandstone characterize the FA2 assemblage. These facies tend to be preserved at top of larger bedforms during falling stages (Miall, 1996) or abandoned bars (Nichols, 2009).

The FA3 Coarse-grained middle channel bars is dominated by massive conglomerates (Gm) and coarse-grained cross-bedded sandstones (Sp and St facies) with abundant granules and pebbles and tabular geometries, suggesting a high-energy fluvial flow. The sets are bounded by erosive and horizontal surfaces and exhibt pebble lag surfaces (Fig. 7D), wich are indicative of erosion by fluid scour (Collinson et al., 2006). The internal gradation within the Gm sets, organized into distinct layers of sand, granules, and pebbles, points to fluctuations in flow velocity and sediment supply during deposition. Mid-channel bars tend to form within the channel as the flow gradually splits (Collinson, 1996).

Interbedded fine-grained facies of massive sandstone (Sm) and laminated siltstone (Fl) represent the FA4 – overbank fines facies association. They have little vertical and horizontal distribution in the study area. These deposits are characterized by sedimentation in overbank areas of the channel during floods, such as floodplains (Collinson et al., 2006; Miall, 1996; Nichols, 2009). They are organized into planar strata within large sequences of large-scale strata (Bridge and Lunt, 2006) and could be interpreted as LS (laminated sand) and OF (overbank fines) architectural elements of Miall (1985). An erosive bounding surface separates FA2 from a thin coarse-grained massive sandstone and a large-scale St set with intraclasts at the base of the trough. Miall (1996) claims that such succession is commonly found above fluvial erosive surfaces. Menezes-Filho et al. (1988) and Santos and Souza (1988) reported kaolinitic lenses in the Tacaratu Formation without providing additional depositional context.

Coarse-grained bedload streams tend to exhibit moderate to strong braiding, high mobility, and significant erosion of the banks and riverbed. These conditions are typically promoted in proglacial, semi-arid, and non-vegetated environments (Collinson, 1996; Went, 2005). Although the earliest evidence of land vegetation dates to the Ordovician (Rubinstein et al., 2010), the Silurian period is recognized for the onset of plant colonization on land (Melchin et al., 2020). The vegetation exerts major controls in erosion, sedimentary supply and bank stability in alluvial contexts (Went, 2005). These conditions, similar to those in modern semi-arid environments, likely raised the development of braided fluvial systems, persisting until the end of the Paleozoic (Collinson, 1996; Miall, 1996).

5.2. Paleocurrent Analysis

The paleocurrent analysis reveals a predominant northward trend, with localized variations toward the NNW and NNE (Fig. 10). This trend is consistent with several studies that predominantly identified a northwestward paleoflow direction in the Tacaratu Formation in Northern Tucano and Jatobá sub-basins (Menezes-Filho et al., 1988; Santos and Souza, 1988; Rocha and Leite, 1999; Souza-Lima et al., 2014; Carvalho, 2015; Carvalho et al., 2018; Cerri et al., 2024b). Our results, however, show a slightly eastward deviation compared to the findings of Carvalho et al. (2018) in the Jatobá sub-basin and other previous literature (Fig. 10). A similar eastward shift, from Parnaíba to Tucano-Jatobá basins, was observed by Cerri et al. (2024b) when analyzing and comparing paleocurrent partners across several Paleozoic basins in NE Brazil, including findings from Carvalho et al. (2018), Assis et al. (2019), and Cerri et al. (2020). Similar eastward shift in paleoflow to the southern portion of Gondwana is reinforced by the N-NE trend observed by Souza-Lima et al. (2014) in the correlated Karapotó Formation in the Sergipe-Alagoas Basin. Cerri et al. (2024b) suggested that these changes are related to the proximal and distal position of the paleodrainage courses in this region of Gondwana.

Paleocurrent patterns are valuable indicators for determining source areas and paleoslope regions (Miall, 2000). Menezes-Filho et al. (1988) paleocurrent directions are consistent with glacial striations found in Sergipe-Alagoas basin, suggest the source area as an alluvial fan system originating from Africa to the Tacaratu-Serra Grande facies. However, Ghignone (1979) proposed a cratonic source in the São Francisco Craton. Our results are similarly to Carvalho et al. (2018), who suggest source areas along south and southeast of the São Francisco Craton and Pernambuco-Alagoas terrain, according to provenance studies. This southern source area was futher corroborated by Cerri et al. (2024b) through isotopic, sedimentological and paleocurrent data.

The braided fluvial depositional context assigned to the Tacaratu formations was primarily defined through descriptive methods, such as outcrop facies analysis (Menezes-Filho et al., 1988, 2013; Santos and Souza, 1988; Santos et al., 1990; Carvalho et al., 2018). However, Galeazzi et al. (2021) adopted a quantitative approach, using preserved barforms in the alluvial plains of modern rivers as proxies to infer paleoflow directions at the channel-belt scale. These barforms provide ranges of paleocurrent circular variance that effectively aid in identifying channel patterns in the geological record. Our findings indicate that the paleocurrent circular variance data from the Tacaratu Formation (Fig. 10 – circular variance = 0.335) aligns with low-sinuosity wandering (LSW) channel morphologies. The wandering channel pattern is considered an intermediate style between meandering and braided styles, occurring when the braiding of channels tends to decrease (Miall, 1996; Collinson et al., 2006). These changes in channel morphology could explain the steep variation in paleoflow values observed at the TAC03 locality (Table 3), which may result from lateral accretion on mid-channel bars, as discussed by Almeida et al. (2024). The authors propose that paleocurrent variations of up to 180º can occur in rivers exhibiting a wandering morphology. Furthermore, the facies association from which the paleocurrent data for this point were obtained, similar to those find in the TAC01 and TAC02 localities, suggests that these are not floodplain deposits. This further supports the interpretation that the channel morphology explains the variation in the mean vector observed at TAC03. Galeazzi et al. (2021) emphasize the need for a substantial amount of paleocurrent data to achieve more robust outcomes. Despite the relatively small dataset, the similarity between the size of the study area and the scale of the river channel analyzed supports the consistency of the results.

6. Conclusions

The sedimentary characteristics of the basal Tacaratu Formation of Northern Tucano sub-basin, within Santa Brígida low area, were analyzed using facies, facies association, architectural elements and paleocurrent analysis. The findings of this study reveal that the Tacaratu Formation exhibits previously unrecognized depositional characteristics, including both channel and overbank alluvial elements, as well as a distinct fluvial style. The facies, facies association, and architectural elements outcomes allow us to distinguish four facies associations in the studied area. The coarse-grained cross-bedded FA1, FA2 and FA3 facies associations show genetic relations with channel macroforms, such as gravel-sand rich bars. The fine-grained FA4 facies association is related to floodplain deposition at overbank areas of the channel. These characteristics reinforce the interpretation of the Tacaratu Formation as a gravel and sand-rich alluvial system, exhibiting a low-sinuosity wandering fluvial style.

Paleocurrent findings indicate a general northward paleoflow trend in the Tacaratu Formation within the studied area, consistent with previous studies. Additionally, our circular variance data provided insights about channel morphology within the unit, suggesting a low-sinuosity wandering morphology. Further analysis with a more robust dataset, particularly using stratigraphic controls, could strengthen these conclusions and clarify style changes over time.

This research expanded the knowledge of facies and sedimentary processes over previous studies in Tacaratu Formation. Detailed studies are essential for understanding the sedimentary evolution of the Tacaratu Formation throughout the stratigraphic column, given the complexities of the structural framework within the Paleozoic units of the RTJ rift. Despite the relatively small size of the research area compared to the entire regional extent of the Tacaratu Formation in the RTJ rift system, the findings provide valuable insights into facies and associated processes, sediment dispersion, and channel dynamics. These insights may also contribute to a better understanding of the early sedimentation processes in the Western Gondwana intracratonic Paleozoic basins of Northeast Brazil.

Credit author statement

Mateus do Nascimento Santana: investigation, data analysis, writing, and editing.

Pedro Victor Oliveira Gomes: investigation, data analysis, writing and review.

Felipe Torres Figueiredo: orientation, conceptualization, methodology, investigation, writing – review, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work the author(s) used *ChatGPT* and *QuillBot* to enhance code, grammar, and readability. After using these tools, the author(s) thoroughly reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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Supplementary Material

Python code used in paleocurrent analysis

```
import numpy as np
import matplotlib.pyplot as plt
import scipy.stats as stats

# Data
PalcData = np.array([258, 348, 28, 357, 357, 245, 68, 300, 25, 49, 14, 56, 121,
                     124, 24, 20, 358, 356, 24, 344, 4, 7, 322, 250, 7, 4, 344,
                     24, 356, 358, 20, 24, 124, 121, 53, 14, 49, 250, 36, 322,
                     78, 89, 55, 60, 347, 26, 40, 56, 103, 56, 49, 49, 24, 11,
                     37, 43, 74, 20, 351, 1, 35, 1, 45, 120, 124, 120, 113, 27,
                     43, 23, 347, 130, 126, 135, 124, 183, 130, 94, 112, 134, 111,
                     114, 120, 128, 127, 134, 156, 133, 126, 62, 107, 97, 66, 6,
                     329, 249, 317, 0, 357, 360, 357, 6, 317, 329, 3, 341, 331, 5,
                     320, 350, 293, 339, 345, 336, 333, 7, 349, 357, 328, 5, 334,
                     5, 13, 10, 14, 355, 91, 11, 20, 100, 341, 10, 64, 51, 78, 52,
                     93, 24, 22, 18, 101, 1, 57, 13, 338, 51, 297, 314, 136, 298,
                     356, 312, 329, 331, 312, 271, 323, 332, 316, 320, 309, 302,
                     307, 9, 335, 210, 16, 264, 257, 267, 220, 230, 243, 285, 330,
                     343, 279, 297, 336, 295, 261, 275, 330, 302, 303, 279, 56, 321,
                     319, 331, 341, 2, 356, 325, 336, 336, 351, 9, 328, 5, 10, 0, 24])

# Convert degrees to radians
radians_data = np.deg2rad(PalcData)

# Calculate the mean direction
mean_angle = np.angle(np.mean(np.exp(1j * radians_data)))
mean_angle = mean_angle % (2 * np.pi)  # Normalize to the range of 0 to 2*pi

# Calculate the confidence interval for the mean direction
n = len(radians_data)
R = np.abs(np.mean(np.exp(1j * radians_data)))
circular_variance = 1 - R

alpha = 0.05
z = stats.norm.ppf(1 - alpha / 2)
delta = z * np.sqrt((1 - R**2) / (n * R**2))
lower_bound = (mean_angle - delta) % (2 * np.pi)  # Normalize to the range of 0 to 2*pi
upper_bound = (mean_angle + delta) % (2 * np.pi)  # Normalize to the range of 0 to 2*pi

# Convert back to degrees
mean_angle_deg = np.rad2deg(mean_angle)
lower_bound_deg = np.rad2deg(lower_bound) % 360
upper_bound_deg = np.rad2deg(upper_bound) % 360

# Circular variance
circular_variance_value = circular_variance
```

```
# Text to display
std_dev = np.rad2deg(delta)
text_to_display = f"n: {n}, Mean vector: {mean_angle_deg:.0f}°, Circular variance:
{circular_variance_value:.3f}"
# To plot the mean vector ± 2x the standard deviation, use the line below:
# text_to_display = f"n: {n}, mean vector: {mean_angle_deg:.1f}° ± {std_dev:.1f}° (2σ),
Circular variance: {circular_variance_value:.3f}"

# Plotting
fig, ax = plt.subplots(figsize=(18/2.54, 18/2.54), subplot_kw={'projection': 'polar'})
# Dividing by 2.54 converts the 18 cm to inches, which is the unit Python understands

# Adjust the angle so that 0° points North and increases clockwise
ax.set_theta_direction(-1)
ax.set_theta_offset(np.pi / 2.0)

# Plot the histogram with dark gray bins
hist_data, bins, _ = ax.hist(radians_data, bins=30, density=True, alpha=0.75, color='darkgray')

# Ensure the confidence interval weight is less than the bin with the highest weight in the data
max_bin_weight = hist_data.max()
confidence_interval_weight = max_bin_weight * 0.9

# Plot the mean direction as a black arrow with length proportional to R
ax.annotate('', xy=(mean_angle, R), xytext=(0, 0),
        arrowprops=dict(facecolor='black', shrink=0.05, width=2, headwidth=8))

# Fill the confidence interval with light blue and 50% transparency
ax.fill_betweenx([0, confidence_interval_weight], lower_bound, upper_bound,
color=(87/255, 153/255, 198/255), alpha=0.5)

# Add text with the mean vector, confidence interval, and circular variance at the top of the
figure
plt.text(0.5, 1.1, text_to_display,
      horizontalalignment='center', verticalalignment='center', transform=ax.transAxes,
      fontsize=12, fontname='Arial', color='black')

# Replace radial ticks with percentage values
ax.set_yticks(np.linspace(0, hist_data.max(), 5))
ax.set_yticklabels([f"{int(p)}%" for p in np.linspace(0, 100, 5)])

#plt.savefig('pc.png', dpi=700)
plt.show()

(mean_angle_deg, lower_bound_deg, upper_bound_deg, circular_variance_value)
```

CAPÍTULO III – CONCLUSÃO

As características sedimentares da Formação Tacaratu, base da sub-bacia do Tucano Norte, dentro da área do Gráben de Santa Brígida, foram analisadas com base em fácies, associações de fácies, elementos arquiteturais e análise de paleocorrentes. Os resultados deste estudo mostram que a Formação Tacaratu exibe um conjunto de características deposicionais não observados anteriormente, incluindo elementos de canal e planície, bem como estilos de canal distintos. A análise conjunta de fácies, associações de fácies e elementos arquiteturais permitiu distinguir quatro associações de fácies na área estudada. As associações de fácies FA1, FA2 e FA3 englobam rochas siliciclásticas de granulação grossa, ricas em estratificações cruzadas, e relação genética com macroformas do interior de canal (barras). A associação de fácies FA4 apresenta rochas siliciclásticas de granulação fina, relacionadas à deposição em planícies de inundação nas áreas de extravasamento do canal. Tais características reforçam a intepretação de um sistema aluvial rico em cascalho e areia, com estilo fluvial entrelaçado, atribuído à Formação Tacaratu.

Os resultados da análise de paleocorrentes indicam uma tendência geral de paleofluxo para o norte na Formação Tacaratu na área estudada, consistente com estudos anteriores. Além disso, os dados de variância circular forneceram informações sobre variações na morfologia dos canais dentro da unidade, sugerindo uma morfologia do tipo *wandering* de baixa sinusidade. Análises adicionais com um conjunto de dados robusto, especialmente utilizando controle estratigráfico, podem aprimorar essa interpretação e esclarecer as mudanças de estilo de canal ao longo do tempo.

Esta pesquisa ampliou o conhecimento sobre fácies e processos sedimentares na Formação Tacaratu em relação aos estudos anteriores. Análises detalhadas são essenciais para compreender a evolução sedimentar da Formação Tacaratu ao longo da coluna estratigráfica, considerando a complexidade do arcabouço estrutural das unidades paleozoicas no RTJ. Apesar do tamanho relativamente pequeno da área de pesquisa em comparação com a extensão regional da Formação Tacaratu no RTJ, os resultados obtidos fornecem contribuições significativas em termos de fácies, processos sedimentares, dispersão de sedimentos e morfologia dos canais na unidade. Esses achados auxiliam na compreensão dos padrões iniciais de sedimentação nas bacias intracratônicas paleozoicas do Gondwana Ocidental no Nordeste do Brasil.

ANEXO I

Comprovante de aceite do artigo no *Journal of South American Earth Sciences*.

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Para: Mateus do Nascimento Santana mateusnsantana@outlook.com

Manuscript Number: **SAMES-D-24-00497R1**

UNRAVELING ORDOVICIAN-SILURIAN SEDIMENTATION: FACIES, PALEOCURRENTS, AND ARCHITECTURAL ANALYSIS OF THE TACARATU FORMATION, NORTHERN TUCANO SUB-BASIN, BRAZIL

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