

Identification of precambrian deformational phases in the region of Tejuçuoca - CE

Identificação de fases deformacionais pré-cambrianas na região de Tejuçuoca - CE

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Abstract: This study presents new geological and structural data from a detailed survey conducted in Tejuçuoca, Ceará State (NE Brazil). The study area is located within the Central Ceará Domain, 30 km southeast of the Santa Quitéria Magmatic Arc (SQMA), and is dominated by the Canindé do Ceará Complex (Paleoproterozoic) and the Ceará Group (Neoproterozoic). Field observations and petrographic analyses were integrated with satellite imagery and airborne geophysical data to produce a detailed lithostructural map. The resulting cartography and structural data reveal four distinct deformation phases (D1–D4) that record the Precambrian tectonic evolution of the region, with the latter three correlated to specific episodes of the Brasiliano Orogeny. The D1 phase represents a pre-Brasiliano event characterized by a relict foliation that was intensely reworked during subsequent stages. The D2 phase is associated with the early collisional stages of the Brasiliano Orogeny, generating structures parallel to the main SQMA axis. The D3 phase corresponds to an advanced collisional stage dominated by thrust tectonics and internal strain, which strongly reoriented the earlier fabric. Finally, the D4 phase records a post-collisional, transcurrent tectonic regime responsible for the final structural reaccommodation of the rock units.

Keywords: Geological mapping; Deformation phases; Brazilian Orogeny.

Resumo: Apresentamos novos dados obtidos em um levantamento geológico de detalhe realizado em Tejuçuoca-CE. A área de estudo se localiza no domínio Ceará Central, 30km ao sudeste do Arco Magmático Santa Quitéria (AMSQ), onde predominam as rochas do Complexo Canindé do Ceará (Paleoproterozóico) e do Grupo Ceará (Neoproterozóico). Dados de campo e estudos petrográficos foram integrados ao geoprocessamento de imagens de satélite e dados aerogeofísicos para produzir um mapa geológico litoestrutural de detalhe. A cartografia gerada, junto à análise dos dados estruturais, permitiu identificar quatro fases de deformação (D1–D4) que marcam a evolução tectônica pré-cambriana na região, sendo as três últimas correlacionáveis com episódios específicos do ciclo Brasiliano.

A fase D1 representa um evento deformacional pré-brasiliano, que originou uma foliação pretérita posteriormente retrabalhada nas fases subsequentes. A fase D2 está relacionada às etapas colisionais iniciais da Orogênese Brasileira, envolvendo a geração de estruturas com orientação paralela ao eixo do AMSQ. A fase D3 se vincula à etapa colisional avançada da orogênese, onde a tectônica dominada por cavalgamentos associados a processos de deformação interna, reorientaram a foliação. Por último, a fase D4 está relacionada ao desenvolvimento de uma tectônica transcorrente, que representou um estágio pós-colisional de reacomodação dos espaços ocupados pelas massas rochosas.

Palavras-chave: Mapeamento geológico; Fases de deformação; Orogênese Brasileira.

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1. Introduction

The study of polyphase deformation, with an emphasis on identifying structures generated by distinct tectonic events, is a fundamental step toward understanding the geological evolution of orogenic belts. In the Central Ceará tectonic domain, which belongs to the Borborema Province and is characterized by the presence of the Santa Quitéria Magmatic Arc, numerous studies have addressed deformation within the context of the Brasiliano Orogeny. However, these studies remain limited in terms of detail and spatial coverage, failing to fully encompass all areas affected by these tectonic processes. Given this scenario, this study aims to advance structural geology knowledge through a detailed analysis of a sector located in the Tejuçuoca municipality, which is embedded in this geotectonic framework but still lacks specific investigations. To date, the area has only been characterized by 1:100,000 scale geological maps: CPRM Tapera SB.24-V-B-II (CASTRO, 2014) and CPRM Iruçuba SA.24-Y-D-V (NALETO, 2014). However, these documents present inherent scale limitations and exhibit inconsistencies in both the delimitation and description of certain lithostratigraphic units and geological structures. Considering this state of the art, this study presents new data obtained from a detailed geological survey aimed at characterizing, mapping, and standardizing the local geology, thereby providing key constraints for a more precise understanding of the region's tectonic evolution.

2. Regional geological context

The Borborema Province (BP) represents the main portion of the Precambrian platform located in northeastern South America, forming a complex orogenic system composed of multiple tectonic terranes. These terranes include Archean nuclei, Paleoproterozoic gneissic-migmatitic basement rocks, and domains formed by meso- to neoproterozoic supracrustal metasequences (ALMEIDA *et al.*, 1981; CABY; ARTHAUD, 1998; ARTHAUD *et al.*, 2008). The intense tectonic activity of the Brasiliano–Pan-African Cycle (600–550 Ma), which involved the continental collision between the São Luís/West African and São Francisco/Congo cratons, gave rise to the current configuration of the BP. This configuration is characterized by the aforementioned mosaic of lithostructural frameworks and the intrusion of numerous syn- and post-orogenic granitoids (VAN SCHMUS *et al.*, 1995; ARTHAUD *et al.*, 2015). Additionally, as a result of the Brasiliano orogenic events, several transcurrent shear zones were generated, separating distinct crustal blocks that record thermotectonic events of varying ages (BRITO NEVES *et al.*, 2000; ALMEIDA *et al.*, 2021; SANTOS *et al.*, 2017; 2018; 2021; OLIVEIRA; MEDEIROS, 2018).

Among the different domains making up the BP, the study area is located within the Ceará Central Domain, which is characterized by the predominance of paleoproterozoic rocks from the Canindé of Ceará Complex and neoproterozoic rocks from the Ceará Group. This domain also features the Tamboril–Santa Quitéria Complex, consisting of metagranitoids, metadiorites, and metagabbros, alongside a significant component of metatexites and diatexites (Figure 1). The magmatic rocks of this complex are distributed along a NE-SW trending belt and, under the designation of the Santa Quitéria Magmatic Arc (SQMA), are interpreted as one of the main milestones of the Brasiliano Orogeny (CAXITO *et al.*, 2020; SANTOS *et al.*, 2023). Within this regional geological framework, the mapped area is located southeast of the SQMA, in a sector dominated by paleoproterozoic and neoproterozoic metamorphic rocks derived from igneous and sedimentary protoliths (Figure 2).

3. Methodology

In order to achieve a detailed geological characterization, a geological mapping survey was conducted over an 80 km² area, integrating field observations with the interpretation of base cartographic material generated through the processing of satellite imagery and airborne magnetic and radiometric data. The data sources included the Northern Ceará Airborne Geophysical Project (CPRM, 2009) –executed from October 18, 2008, to July 8, 2009, by the Geological Survey of Brazil– and Landsat 8 images acquired by the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) (USGS, 2020).

Geophysical data processing was performed using the Oasis Montaj 8.8 software (GEOSOFT, 2016). Based on the processing of the airborne magnetic data, magnetic anomaly maps (total field and reduction-to-the-pole), spatial derivative maps, and an analytic signal map were generated. From the processing of the airborne gamma-ray spectrometric data, individual channel maps (K, eTh, eU), a ternary composite map (RGB), an F-factor map, and an eTh/K radiometric ratio map were obtained.

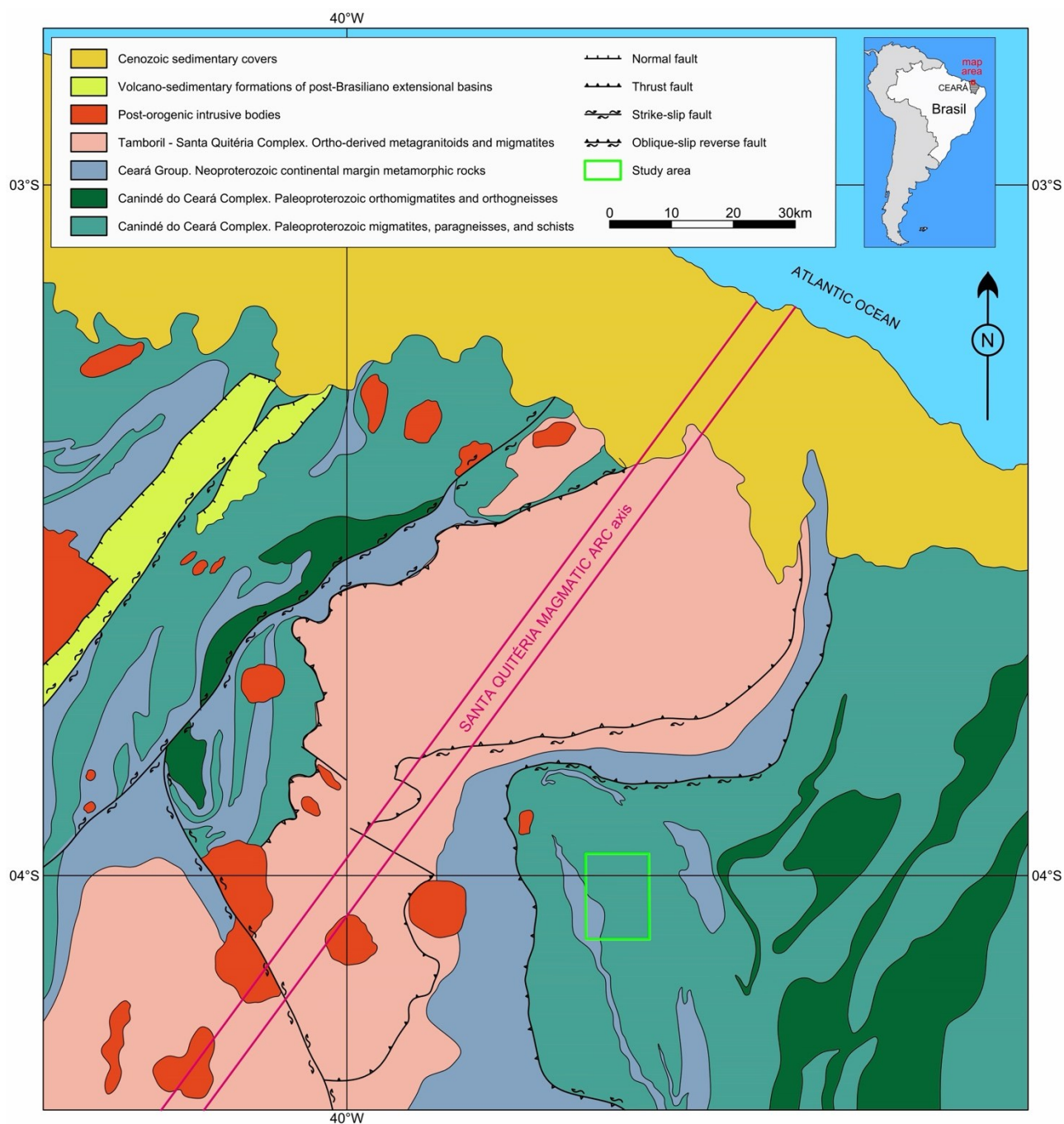


Figure 1 – Situation map of the studied area in the regional geological context. Geodetic coordinates (WGS84).
Source: Pinéo *et al.* (2020).

Landsat imagery processing was performed using QGIS 3.36 software (QGIS Development Team, 2024), which included atmospheric correction and the generation of RGB band combinations designed to enhance spectral differences among the distinct lithological units.

Fieldwork –encompassing lithological characterization, sampling, geometric and kinematic structural analyses, and structural measurements– was carried out during two campaigns conducted from November 27 to December 1, 2023, and from July 23 to July 27, 2024. Field equipment included geological hammer, chisel, Brunton-type compass, and a 15×

hand lens. For georeferencing, data storage, and photographic records of the surveyed field stations, smartphones equipped with the Avenza Maps 4.4 application (AVENZA SYSTEMS INC., 2023) were used. Additionally, all data collected at each station were documented manually in a field notebook.

Following field observations and macroscopic inspection, 12 samples were selected from a broader collection for petrographic analysis. Transmitted and reflected light microscopy was conducted on polished thin sections to identify mineral phases and determine textural and structural characteristics. The thin sections were prepared at the Thin Section Laboratory (LAMIN) of the Department of Geology at the Federal University of Ceará (UFC).

Based on field data and processed imagery products, the main lithologies were delineated: orthogneisses were mapped according to the interpretation of the ternary gamma-ray spectrometric (RGB) map, corresponding to areas with low concentrations of thorium (Th), potassium (K), and uranium (U), and on airborne magnetic maps in zones showing high magnetic response due to the presence of magnetite in the rock composition. Regions with higher Th, K, and U contents coincided with paragneisses, marbles, and amphibolites, whose boundaries were delineated primarily based on field observations.

Structural data were systematically organized into spreadsheets and processed using Stereonet software (ALLMENDINGER *et al.*, 2013; CARDOZO; ALLMENDINGER, 2013). Stereograms were constructed using a Schmidt equal-area net with lower-hemisphere projection; contour lines were plotted using a counting method with 1% area circles (SCHMIDT, 1925). Best-fit values for the construction of π -diagrams were obtained through eigenvector analysis of the directional data, assuming cylindrical folding (MARDIA; JUPP, 2000).

4. Results

4.1. Local geology

As a result, a lithostructural geological map was produced at a scale of 1:12,500 (Figure 2), providing a significantly higher level of detail compared to the previously available regional cartography (1:100,000 Irauçuba and Tapera Sheets). According to the current regional cartography integrated in the Geological Map of Ceará (PINÉO *et al.*, 2020), the studied territory is largely dominated by paleoproterozoic rocks belonging to the Migmatitic Paragneiss Unit of the Canindé do Ceará Complex, with a subordinate occurrence of neoproterozoic rocks from the Ceará Group in the NW and SW sectors. In the present study, the identified rocks were classified into five lithofacies of the Canindé do Ceará Complex (para-derived migmatites and gneisses, orthogneisses, amphibolites, calc-silicate rocks, and goudites) and three lithofacies of the Ceará Group (paragneisses and micaschists, marbles, and quartzites). Additionally, an Fe-occurrence (magnetite gneiss), pegmatite bodies, and hydrothermal quartz veins were identified.

4.1.1 Canindé do Ceará Complex - Migmatitic Paragneiss Unit

- Para-derived migmatites and gneisses

Outcrops of this lithological unit occur mainly as grayish pavements. The rocks display gneissic banding with varying degrees of partial melting, alternating between gneissic intervals, metatextitic migmatites, and, more rarely, diatextitic domains (Figures 3A and 3B). The bands range from millimeter to centimeter thickness and exhibit fine- to medium-grained textures. A granoblastic texture predominates in the leucocratic portions, whereas the melanocratic bands are characterized by a lepidoblastic structural pattern. The essential mineral assemblage consists of quartz (5% to 10%), biotite (10% to 15%), microcline (20% to 25%), plagioclase (30% to 40%), and muscovite (10% to 15%), with garnet (1%), magnetite (1%), and zircon (1% to 2%) as accessory minerals (Figures 4A and 4B). Sericite (3% to 5%) and epidote (1%) occur as alteration minerals.

- Orthogneisses

The orthogneisses in the region occur primarily as light gray slabs. They present a foliated structure with moderately to well-defined, thin- to medium-thickness banding (Figure 3C). It is possible to differentiate granoblastic-textured felsic bands, composed mostly of plagioclase (30% to 40%), microcline (10% to 20%), and quartz (10% to 20%), from lepidoblastic-textured mafic bands that concentrate biotite (10% to 20%) and occasionally hornblende (Figures 4C and

4D). Accessory minerals such as magnetite (1%) and zircon (1%) are present in both compositions. Overall, the minerals occur as fine- to medium-grained, anhedral to subhedral crystals.

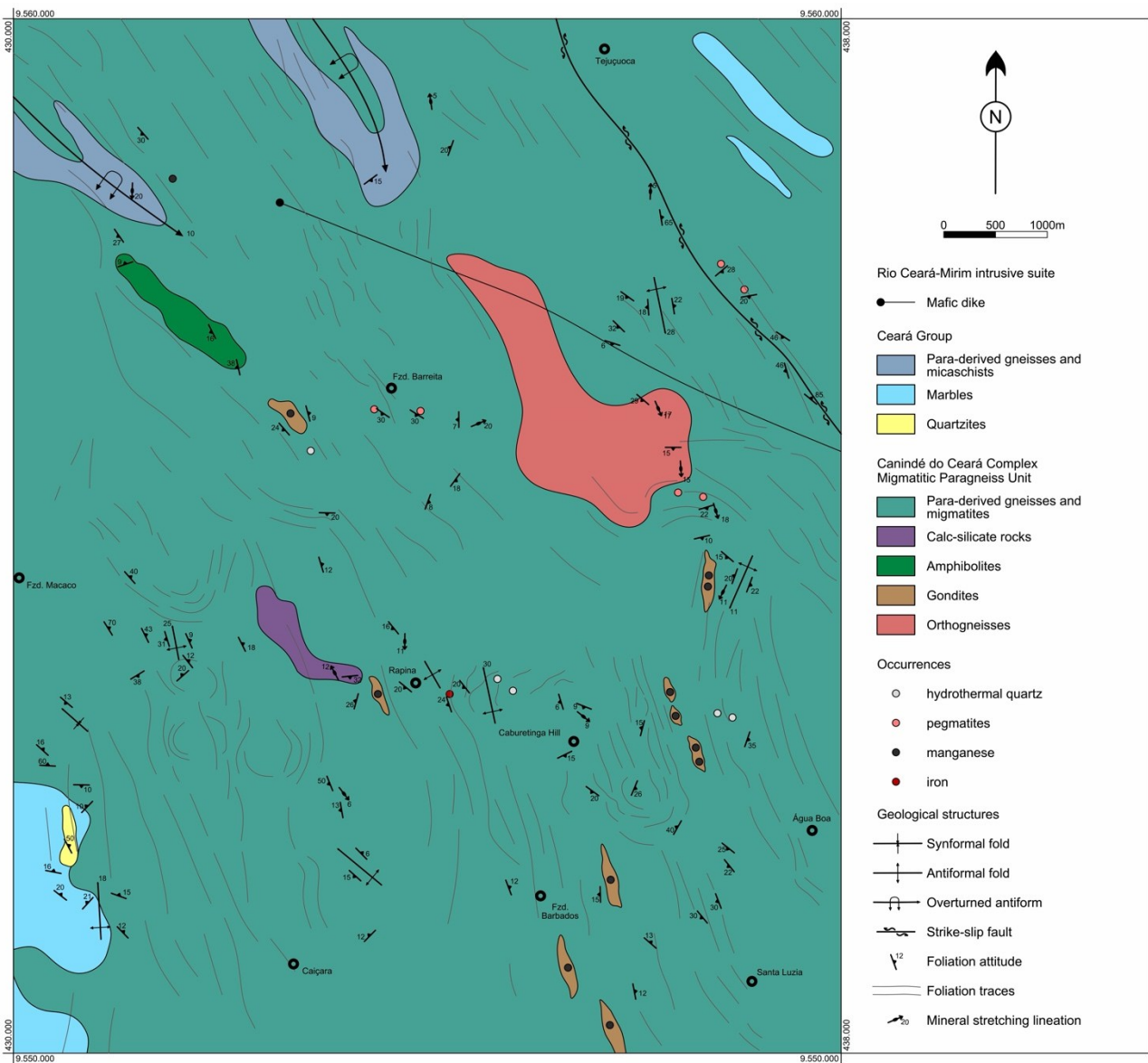


Figure 2 – Geological map of the studied area. UTM coordinates zone 24M (WGS84).
Source: Authors (2026).

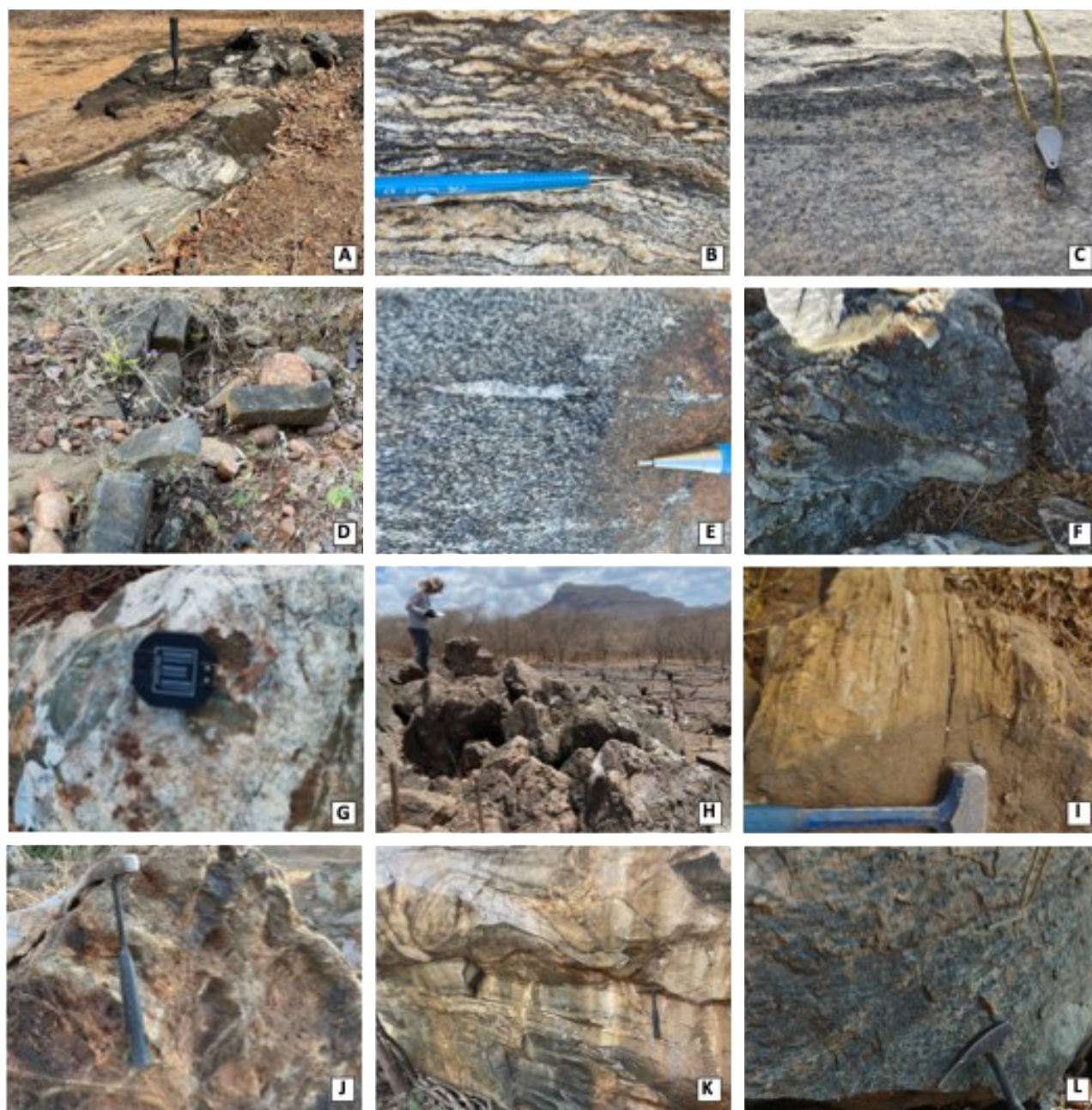


Figure 3 – Outcrop photographs and macroscopic perspectives of lithotypes from the Migmatitic Paragneiss Unit of the Canindé do Ceará Complex. A) and B) Migmatites and paragneisses; C) Orthogneisses; D) and E) Amphibolites; F) and G) Calc-silicate rocks; H), I), and J) Manganese occurrences; K) and L) Iron occurrence.

Source: Authors (2026).

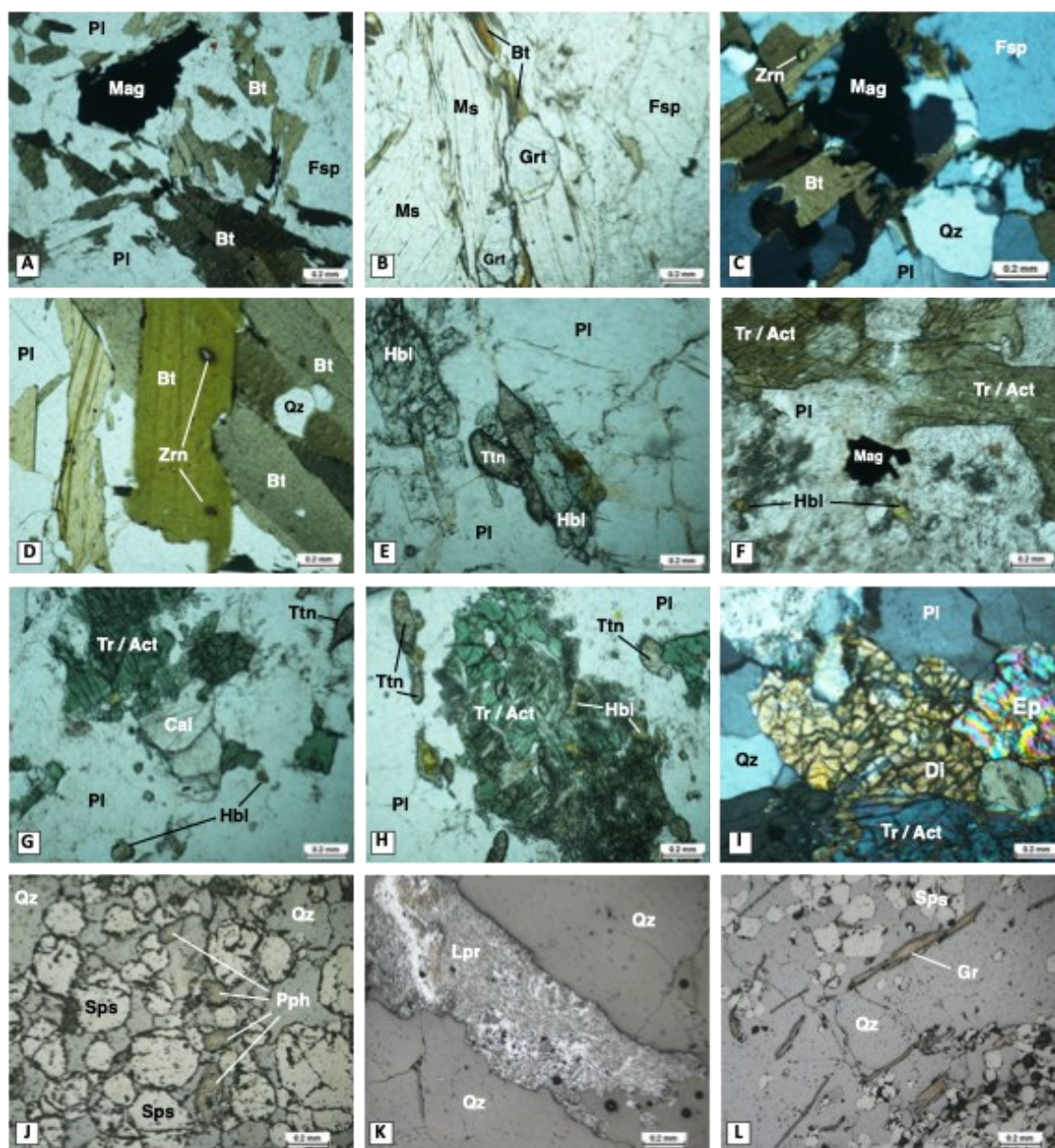


Figure 4 – Photomicrographs of lithotypes from the Migmatitic Paragneiss Unit of the Canindé do Ceará Complex. TL: Transmitted Light – RL: Reflected Light – XPL: Crossed Polarizers – PPL: Plane-Polarized Light. A) and B) Migmatites and paragneisses (TL - PPL); C) Orthogneiss (TL - XPL); D) Orthogneiss (TL - PPL); E) and F) Amphibolites (TL - PPL); G) and H) Calc-silicate rocks (TL - PPL); I) Calc-silicate rocks (TL - XPL); J) Gondites (TL - PPL); K) and L) Gondites (RL - PPL). Mineral abbreviations according to Warr (2021): actinolite (Act), biotite (Bt), calcite (Cal), diopside (Di), epidote (Ep), feldspar (Fsp), garnet (Grt), graphite (Gr), hornblende (Hbl), lithiophorite (Lpr), magnetite (Mag), muscovite (Ms), pyrophanite (Pph), plagioclase (Pl), quartz (Qz), spessartine (Sps), titanite (Ttn), tremolite (Tr), zircon (Zrn).
Source: Authors (2026).

- Amphibolites

These are dark gray rocks that occur in areas with dark brown clayey soils, forming small erratic outcrops of rounded blocks (Figure 3D). They exhibit a fine- to medium-grained, equigranular granoblastic or nematoblastic texture, dominated by anhedral to subhedral crystals (Figure 3E). They are composed mainly of hornblende (20% to 30%), plagioclase (10% to 20%), and augite (10% to 15%), accompanied by titanite (4% to 5%) and magnetite (1%) as accessory minerals (Figures 4E and 4F). Tremolite/actinolite (10% to 20%) and sericite (4% to 5%) are recognized as products of retrometamorphic and/or alteration processes.

- Calc-silicate rocks

These are light gray to whitish rocks that occur isolated or as intercalations within the amphibolitic rocks, displaying a medium- to coarse-grained granoblastic texture dominated by anhedral and subhedral crystals (Figures 3F and 3G). The essential mineral assemblage consists of hornblende (20% to 30%), plagioclase (15% to 20%), microcline (6% to 7%), quartz (8% to 10%), diopside (10% to 15%), and tremolite/actinolite (15% to 20%). The accessory mineral suite may include titanite, apatite, garnet, clinozoisite, biotite, calcite, epidote, and magnetite (Figures 4G, 4H, and 4I).

- Gondites

The gondites constitute Mn proto-ore occurrences that outcrop prominently in the SE sector of the study area, intercalated within the paragneisses as small hillocks with irregular morphology (Figures 3H, 3I, and 3J). The outcrops exhibit a dark brown color and occasionally display a fine- to medium-grained foliation. They occur as narrow, aligned bodies forming boudinaged and stretched lenses trending NNW. The gondites are composed of spessartine (40% to 60%), manganese oxides/hydroxides (8% to 10%), and quartz (30% to 40%) (Figures 4J, 4K, and 4L). Pyrophanite (3%), graphite (5%), biotite (3%), lithiophorite (3%), and sulfides (1%) can be found as accessory minerals. A prominent feature of these rocks is the abundance of quartz veins of varying thickness forming stockwork structures (Figure 3J).

- Iron occurrence - Magnetite gneiss

Hosted by the migmatitic paragneisses of the Canindé do Ceará Complex, an iron occurrence was documented on the western slope of the Caburetinga Hill, near the Rapina Farm. It occurs across an area of approximately 30 × 30 m, where large boulders of a gneissic-structured lithotype outcrop. These rocks contain gray bands composed essentially of fine- to medium-grained magnetite with either massive or disseminated textures (Figures 3K and 3L). On average, the rock composition consists of magnetite (40%), plagioclase (40%), quartz (18%), and garnet (2%).

4.1.2 Ceará Group

- Para-derived gneisses and micaschists

The cartographic representation of this lithotype defines elongated and folded lenticular bodies, characterized by variations between micaschists and aluminous paragneisses that are occasionally migmatized. The rocks outcrop as pavements and boulders with a light gray color, in which preserved primary bedding with intercalations of metapelitic and metapsammitic facies can occasionally be recognized (Figure 5A). They display granoblastic and lepidoblastic textures, and a composition dominated by biotite, plagioclase, and quartz, with variable proportions of muscovite, garnet, and sillimanite (Figure 6A).

- Marbles

They outcrop as extensive pavements with a white or grayish-white color, which frequently exhibit intense systematic fracturing (Figure 5B). The marbles present a fine- to medium-grained granoblastic texture composed of anhedral to subhedral crystals of calcite (30% to 40%), dolomite (20% to 30%), tremolite (10% to 20%), and phlogopite (10% to 20%). Accessory minerals such as scapolite and graphite occasionally contribute to the composition in proportions below 1%. Epidote alterations replacing tremolite, and talc filling fractures are recognized (Figures 6B and 6C).

- Quartzites

They are found in a restricted sector associated with the marbles that dominate the SW portion of the mapped area. They are observed in small pavements with incipient foliation or as scattered, loose white blocks (Figure 5C). Fine-grained quartz predominates in the composition of these rocks, with a subordinate presence of muscovite.



Figure 5 – Outcrop photographs of the Ceará Group lithotypes. A) Para-derived micaschists; B) Marbles; C) Quartzites.

Source: Authors (2026).

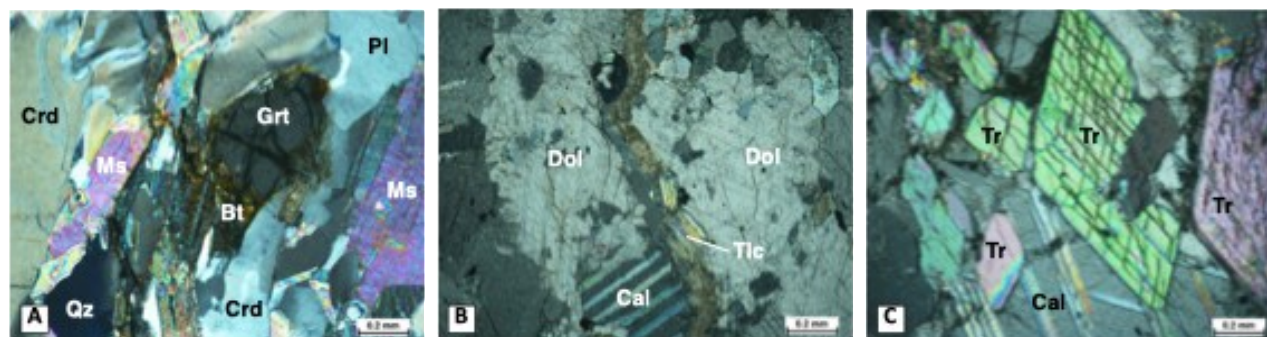


Figure 6 – Photomicrographs of the Ceará Group lithotypes. TL: Transmitted light – RL: Reflected light – XPL: Crossed polarizers – PPL: Plane-polarized light. A) Paragneisses (TL - XPL); B) and C) Marbles (TL - XPL). Mineral symbols according to Warr (2021): biotite (Bt), calcite (Cal), cordierite (Crd), dolomite (Dol), garnet (Grt), muscovite (Ms), plagioclase (Pl), quartz (Qz), talc (Tlc), tremolite (Tr).

Source: Authors (2026).

4.2 Structural geology

Based on the field survey of structures, combined with the interpretation of cartographic products generated through geoprocessing and the integration of information from previous studies, a structural database was generated for the study area (Figure 2). The structural analysis of these data was conducted considering the spatial distribution of the information, the geometric and kinematic characterization of the structures, and the results obtained from statistical processing.

The main structural framework strikes northwest, with a predominance of foliations dipping at low to medium angles toward the SW and NE; other directions occur locally, associated with superposed folding. In addition to foliations, the main macroscopic structural features observed in the area are folds and a strike-slip shear zone in the NE sector.

As a result of the conducted studies, four ductile deformation phases were identified, represented by sets of tectonic structures with consistent structural styles and orientations. The structural elements comprising each phase are described below.

- First deformation phase (D1)

S1: foliation materialized by a gneissic banding characterized by the alternation of leucocratic and melanocratic bands of variable thickness. It affects the paleoproterozoic lithologies that compose the Canindé do Ceará Complex; due to being modified and reworked by subsequent deformational phases, it does not preserve a measurable structural attitude.

No stretching lineations associated with D1 were recorded.

- Second deformation phase (D2)

S2: foliation that partially modifies the orientation of S1 due to the generation of gentle folds with axial planes oriented in a NE direction. As a consequence of this folding, the S2 foliation locally manifests with a NE strike and gentle dips alternating toward the NW and SE.

F2: folds with subvertical axial planes oriented in a NE direction and axes plunging at low angles (12° to 19°) in two opposite directions: NE and SW (Figure 7A).

No stretching lineations associated with D2 were recorded.



Figure 7 – Photographs of folds observed in outcrops.

Source: Authors (2026).

- Third deformation phase (D3)

S3: foliation with NNW strike and low- to medium-angle dips in variable directions toward the SW and NE, produced by the reorientation of the S2 foliation. The S3 foliation is present in all lithologies of the area, defining schistosity and/or banding characterized by alternating mafic and felsic bands with variable thicknesses ranging from millimeter to centimeter scale. The banded structure occurs mainly in paragneisses, the dominant lithotype in the study area, and frequently displays evidence of migmatization.

F3: folds with axes plunging at low angles (0° to 30°) in two opposite directions: NNW and SSE. Axial planes are oriented NNW, parallel to the strike of the S3 foliation. In the northwestern sector, overturned antiforms occur, with an axial surface parallel to the main foliation (S3) and axes gently plunging to the southeast. In the central-southern sector, the folds present subvertical axial planes striking NNW and axes plunging at low angles (0° to 30°) toward the NNW (Figure 7B).

L3: mineral stretching lineation recognized within the fabric of the gneissic rocks, with low-angle plunges (05° to 30°) toward the NNW and SSE. *Boudin* structures defined by the lenticular outcrops of goudites indicate stretching along the NNW-SSE direction.

- Fourth deformation phase (D4)

Represented by a NW-striking strike-slip shear zone located in the northeastern quadrant of the study area. The characteristic feature of this structure is a steeply dipping mylonitic foliation (S4) with a NW strike, which obliterates previous structures. According to Naleto (2018), in the Fazenda do Carlos region, the structure displays sinistral kinematics, evidenced by the orientation of asymmetric sigma-type porphyroclasts and S-C surfaces (Figure 8).

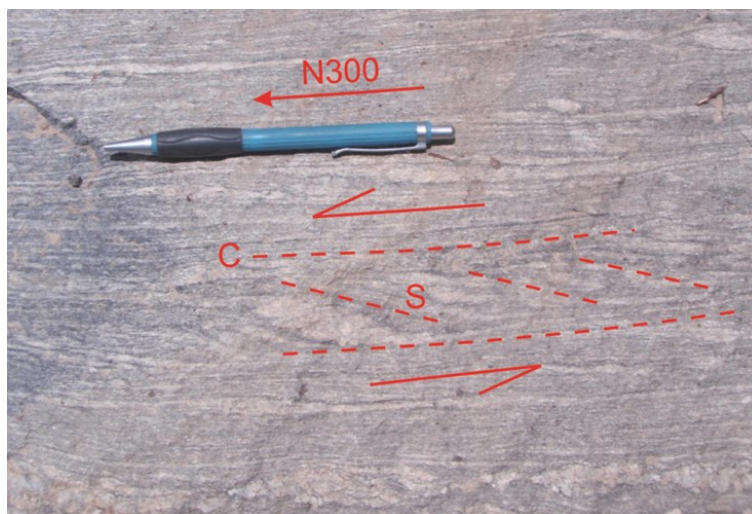


Figure 8 – S-C surfaces with sinistral kinematics in a strike-slip shear zone.
Source: Naleto (2018).

4.2.1 Fold Analysis

The folds observed in the area exhibit decimetric to metric dimensions and can be observed in several outcrops. However, their structural analysis, using cartographic representations and stereonet, allows the identification of lower-order folds of larger dimensions, involving wavelengths of several hundred meters.

Table 1 and Figures 9 and 10 present the detailed analysis of the two fold generations recognized in the area. The first generation (F2) displays subvertical axial planes striking NE and axes plunging at low angles (12° to 19°) in two opposite directions: NE and SW. The second generation (F3) presents subvertical axial planes striking NNW and axes plunging at low angles (0° to 30°) toward the NNW and SSE. In both cases, a gentle folding pattern dominates, with an interlimb angle greater than 120° .

The plunge in opposite directions recognized for both F2 and F3 axes results from the superposed folding produced after the third deformation phase. Due to this superposed folding, the cartography shows that the foliations measured in the area exhibit dip directions in all orientations and, in certain sectors, the foliation traces hint at "dome and basin" refolding features (Figure 10). Nevertheless, it is worth noting that the statistical analysis conducted by integrating all collected foliation data ($n=146$) generally reflects the structural configuration generated during the D3 phase, which is dominated by NNW-striking foliations and folds with axes following this same trend (Figure 11).

Additionally, it should be highlighted that in several sectors, the gneisses include intrafolial folds (Figure 7C), which can be interpreted as higher-order parasitic folds associated with the main folds that dominate the area.

Table 1 – Parameters and location of the folds analyzed in Figure 10. Indicated elements: axis attitude, axial plane attitude (DIP AZ / DIP format), interlimb angle, and number of measurements used in the analysis (n). UTM zone 24M coordinates (WGS84).

Point	Easting	Northing	Axis	Axial plane	Interlimb ang.	n	Phase
1	435966.051	9557285.800	197/15	111/76	168	4	D2
2	433318.038	9553636.701	232/14	143/90	174	2	D2
3	431582.438	9553867.242	037/12	126/87	164	4	D2
4	430537.098	9553369.104	043/13	313/89	165	4	D2
5	430885.075	9551396.935	010/18	281/88	127	2	D2
6	434200.363	9550841.631	302/03	033/90	151	2	D3
7	433355.933	9551778.832	310/00	040/83	163	2	D3
8	431264.639	9553657.303	336/03	246/87	108	11	D3
9	434596.050	9553461.753	319/30	231/86	55	8	D3

Source: Authors (2026).

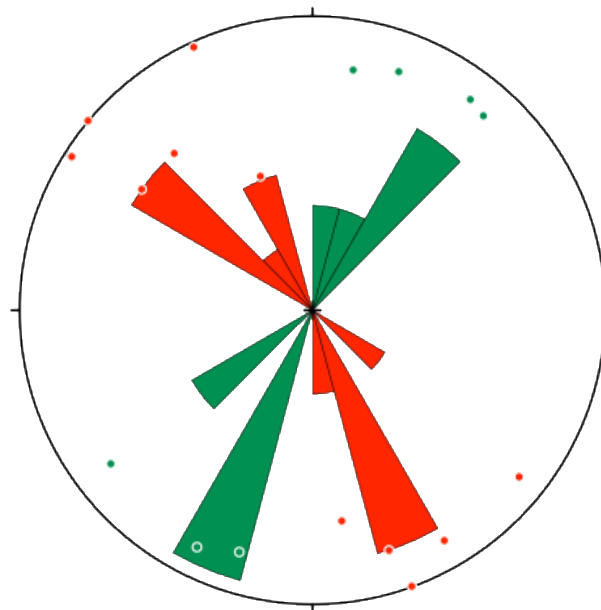


Figure 9 – Rose diagram showing fold plunge directions. Overlaid stereonet showing axis representation. F2 ($n=7$, green) and F3 ($n=11$, red).

Source: Authors (2026).

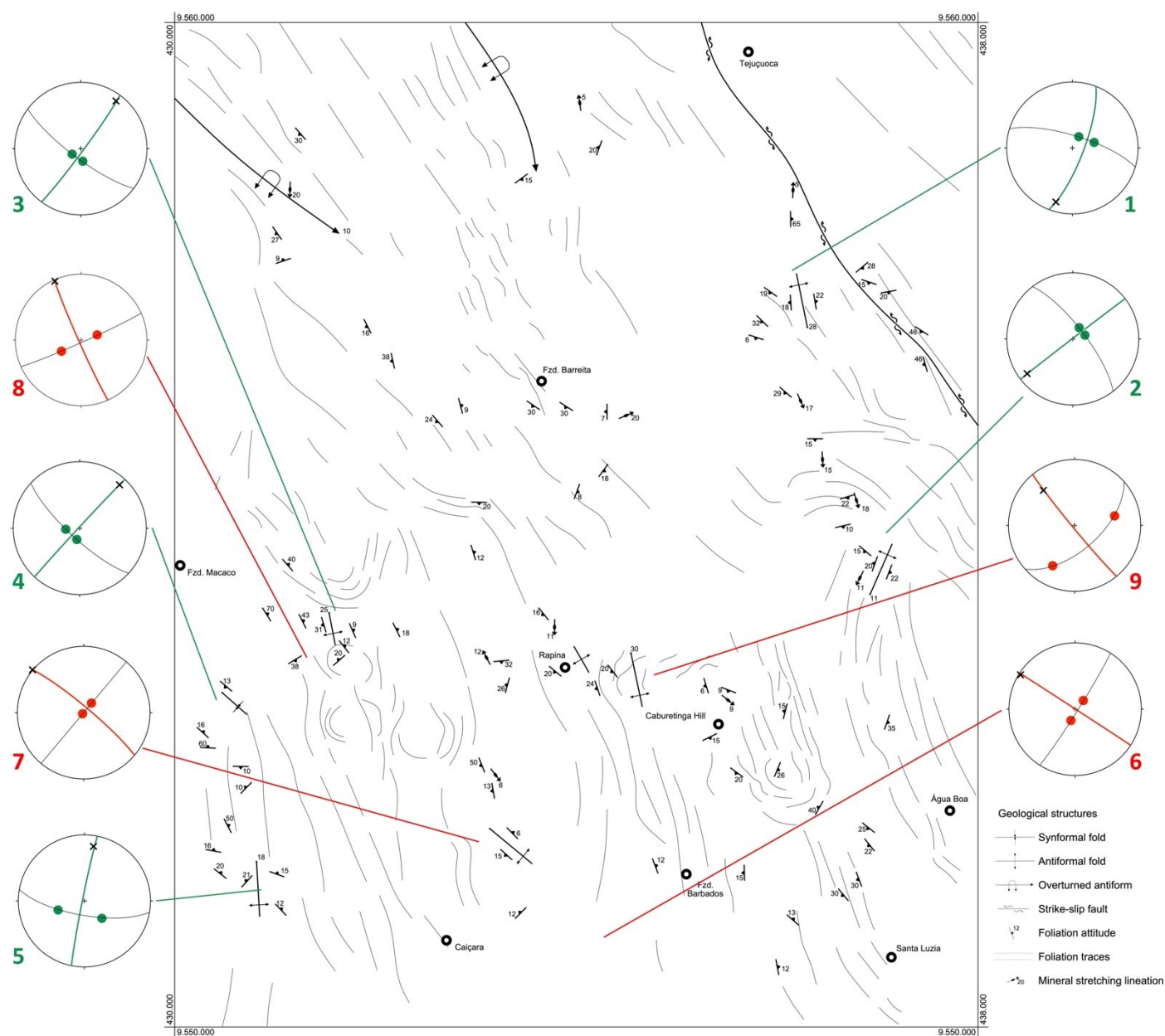


Figure 10 – Distribution and analysis of F2 (green) and F3 (red) folds. The stereonet representation of the folds includes the π -circle (black line), limbs (colored dots), axial plane (colored line), and axis (X). The parameters and location of each fold are detailed in Table 1. UTM zone 24M coordinates (WGS84).

Source: Authors (2026).

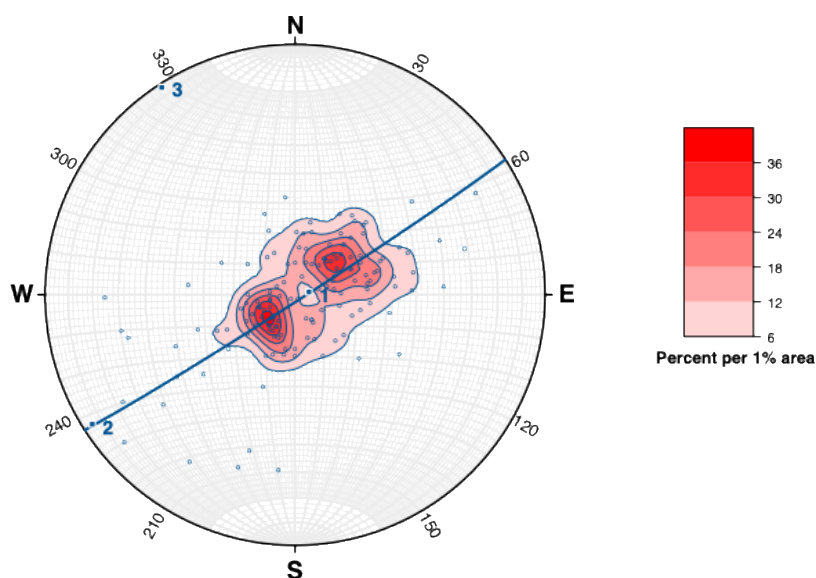


Figure 11 – Stereonet representing all foliations measured in the area ($n=146$), with contour diagram, π -circle, and π -axis.

Source: Authors (2026).

5. Discussion

5.1 Mapping criteria adopted

In order to maintain coherence and consistency, the nomenclature of the lithologies mapped in the geological map presented in Figure 2 is in agreement with the lithological descriptions of the Irauçuba Sheet CPRM SA.24-Y-D-V (NALETO, 2014) and the Geological Map of Ceará (PINEO *et al.*, 2020). In this regard, to facilitate correlation with other areas and avoid ambiguous designations, the denominations used in the Taparuaba Sheet CPRM SB.24-V-B-II (CASTRO, 2014) were disregarded due to their discrepancies and limited scope. As previously stated, five lithological units assigned to the Canindé do Ceará Complex were mapped in the region (para-derived migmatites and gneisses, orthogneisses, amphibolites, calc-silicate rocks, and gondites), alongside 3 units belonging to the Ceará Group (para-derived gneisses and micaschists, marbles, and quartzites). Additionally, occurrences of Fe ore, Mn ore, pegmatitic bodies, and hydrothermal quartz veins were marked on the geological map.

5.2 Synthesis of the precambrian tectono-metamorphic evolution

The description and analysis of the structural arrangement of the study area, in line with the local and regional lithostratigraphic characteristics, indicate the existence of four deformational phases.

The D1 phase represents a pre-Brasiliano deformational event that generated the prior foliation (S1), which was reworked by subsequent phases. The origin of the S1 foliation can be attributed to the Rhyacian-Orosirian metamorphic event that affected the Canindé do Ceará Complex between approximately 2,090 Ma and 1,950 Ma, reaching the metamorphic peak under granulite facies conditions and subsequently undergoing retrograde metamorphism to amphibolite facies (MUNIZ *et al.*, 2022).

The D2 phase is related to the initial collisional stages of the Brasiliano-Pan-African Orogeny, generating structures whose orientation follows the trend of the Santa Quitéria magmatic arc axis (Figure 12). Locally, these structures are represented by the S2 foliation, which displays moderate dips to the northwest and southeast, and by F2 folds, whose axes are oriented in a NE-SW direction. As illustrated in Figure 12, it is interpreted that during this phase, the compressive stresses were oriented NW-SE. It is also noted that this orientation of the principal compressive stress tensor is consistent with the distribution of the Paleoproterozoic lithologies of the Canindé do Ceará Complex, which display a structural

framework with a longitudinal development perpendicular to the D2 compression direction, suggesting that these units were intensely affected during this phase.

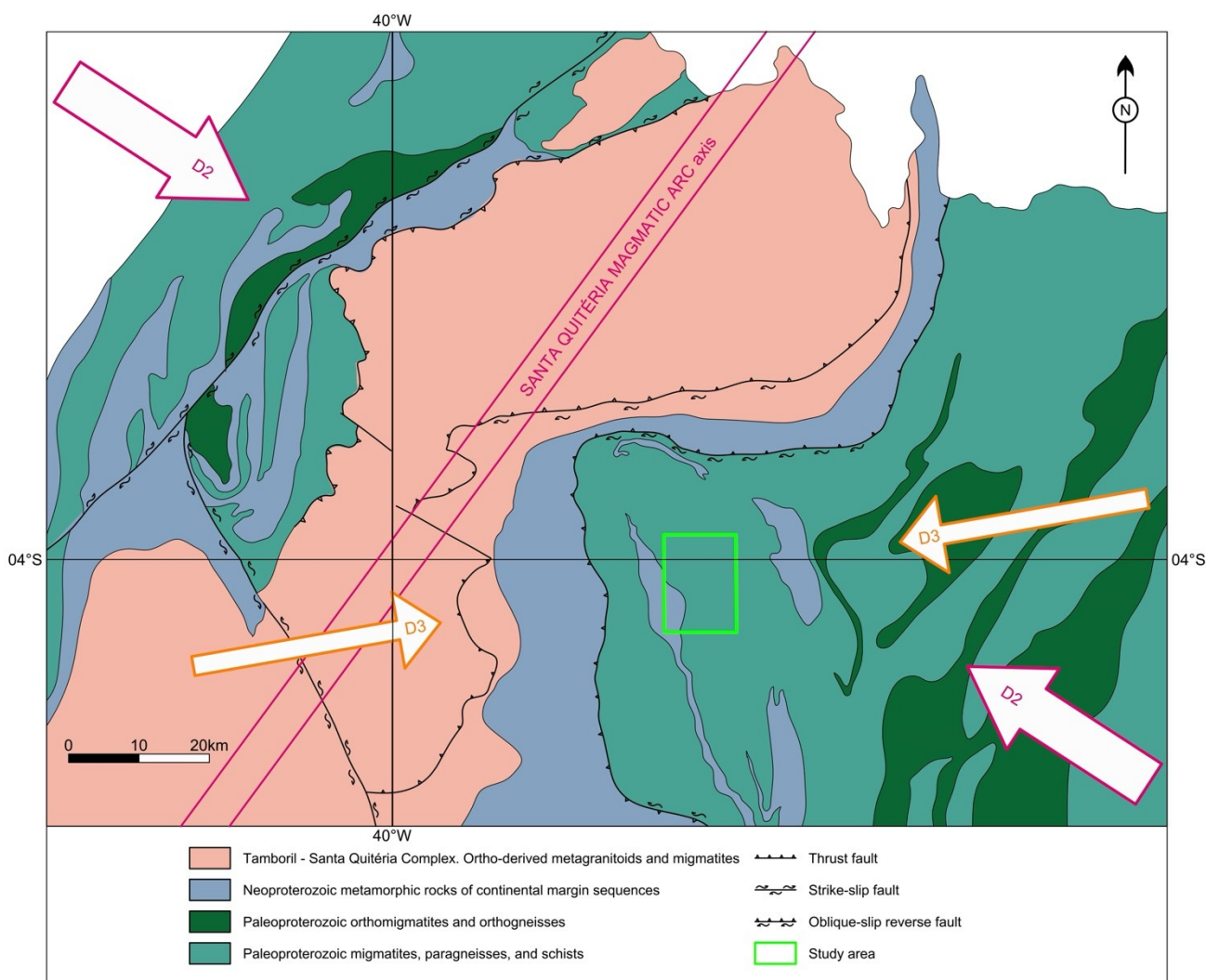


Figure 12 – Simplified cartographic schematic showing the distribution of the main precambrian units and structures within the regional context of the study area. The orientation of the SQMA axis and the interpreted compression directions for deformation phases D2 and D3 are indicated. Geodetic coordinates (WGS84).

Source: Pinéo *et al.* (2020).

The D3 phase is related to the advanced collisional stage of the Brasiliano-Pan-African Orogeny, being a phase dominated by intense tectonic transport that allowed the spatial accommodation of rock masses in a highly compressional environment (BRITO NEVES *et al.*, 2000). This process occurred predominantly through the generation of regional-scale thrusts associated with internal deformation processes, which led to the reorientation of the foliation according to the attitude of the fault planes, accompanied by the generation of folds with sub-horizontal axes parallel to the foliation strike (CAXITO *et al.*, 2020; FERREIRA *et al.*, 2020).

Locally, the D3 phase affected the studied area through compressive stresses and tectonic transport in the ENE direction (Figure 12), resulting in the development of foliations (S3) with NNW-SSE strike and folds (F3) with axes and axial planes subparallel to this foliation. Concomitantly, NNW-SSE-directed extensional processes developed during this phase, evidenced by the mineral stretching (L3) observed in the rock fabric and by the goudite *boudin* train represented in the

mapping. Additionally, it is observed that the neoproterozoic rocks of the Ceará Group locally exhibit a longitudinal development perpendicular to the D3 compression direction, suggesting that they adopted this orientation as a result of the deformation produced by this phase.

The D4 deformation phase is related to the development of strike-slip tectonics (ARCHANJO *et al.*, 2021; ARTHAUD *et al.*, 2008), which represents a post-collisional stage of lateral terrane escape and manifests in the study area through the strike-slip shear zone identified in the northeastern portion, where the deformation obliterates pre-existing structures of the rocks, imparting a high-angle mylonitic foliation (S4) with a NW strike and sinistral kinematics (NALETO, 2018).

According to Souza Junior and Gomes (2024), the described lithotypes were initially metamorphosed under medium-grade conditions (low amphibolite facies) and subsequently underwent low-grade retrometamorphic processes (greenschist facies). The first metamorphic episode, attributed to the D2 deformation phase, was recorded by the presence of biotite, muscovite, plagioclase, microcline, and garnet in the paragenesis of the para-derived rocks, with hornblende and clinopyroxene also participating in the ortho-derived rocks.

The superimposed retrometamorphism is evidenced by the formation of epidote along the margins of biotite and the alteration of plagioclase to sericite in the paragneisses, as well as by the partial replacement of hornblende by epidote, biotite, or tremolite/actinolite in the ortho-derived rocks. The existence of myrmekitic and antiperthitic textures is also attributed by the aforementioned authors to retrograde metamorphic processes associated with mineral cooling and recrystallization phenomena. These transformations are estimated to have occurred during the D3 phase, under lower temperature conditions.

6. Conclusions

The produced geological map increases the level of detail of the study area, providing a source of lithostructural information at a 1:12,500 scale with potential to contribute to regional mapping projects. In total, 5 lithofacies of the Canindé do Ceará Complex (para-derived migmatites and gneisses, orthogneisses, amphibolites, calc-silicate rocks, and gondites) and 3 lithofacies of the Ceará Group (para-derived gneisses and micaschists, marbles, and quartzites) were mapped. To complement the cartographic product, a petrographic characterization of each identified lithological unit was presented.

Through the structural analysis conducted, four ductile deformation phases were identified, which can be correlated with four distinct episodes within the regional evolution: a pre-Brasiliano deformational event (D1), the initial collisional stage of the Brasiliano-Pan-African Orogeny (D2), the advanced collisional stage of the Brasiliano-Pan-African Orogeny (D3), and a post-collisional stage dominated by strike-slip shear tectonics (D4).

Additionally, we highlight that occurrences of manganese and iron were identified in the study area.

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