

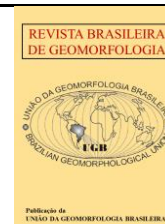


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Technical Note

Geomorphological control of quartzites in the Borborema Province: The case of the reliefs of Ceará, Brazil

O controle geomorfológico dos quartzitos da Província Borborema: O caso dos relevos do Ceará, Brasil

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Abstract: The state of Ceará presents a complex morphostructural context due to the diversity of lithotypes and the structural framework that make up its territory. In a geomorphological evolution context of a transform margin under a semi-arid climate, the differential resistance of rocks to weathering plays a fundamental role in shaping the relief. Within this scenario, the present study aims to analyze quartzites from different geological units outcropping in Ceará, seeking to assess their physical and mechanical properties through laboratory tests, and to discuss how these characteristics influence the preservation of landforms. A total of 24 quartzite samples, belonging to 13 distinct geological units, were analyzed, providing data on uniaxial compressive strength, physical indices, abrasion resistance, wave propagation velocity, and petrographic characteristics, in addition to analyses of the state's geomorphological context using a DEM. Understanding aspects such as low solubility, mechanical strength, degree of microfracturing, structure, and mineralogical composition of the different quartzites was essential for interpreting their important role in the preservation of ridges and massifs throughout the state territory as a result of differential erosion.

Keywords: Rock Mechanics; Differential Erosion; Parametamorphic Rocks; Structural Geomorphology.

Resumo: O estado do Ceará apresenta um complexo contexto morfoestrutural em função da diversidade de litotipos e da trama estrutural que compõem seu território. Em um contexto de evolução geomorfológica em margem transformante sob clima semiárido, a resistência diferencial das rochas ao intemperismo desempenha um papel fundamental na modelagem do relevo. Nesse cenário, o presente estudo tem como objetivo analisar quartzitos provenientes de diferentes unidades geológicas aflorantes no território cearense, buscando analisar suas propriedades físico-mecânicas por meio de ensaios laboratoriais, e discutir como essas características influenciam a preservação das formas de relevo. Foram analisadas 24 amostras de quartzito, pertencentes a 13 unidades geológicas distintas, obtendo-se dados de resistência à compressão uniaxial, índices físicos, resistência ao desgaste, velocidade de propagação de ondas e características petrográficas, além de análises do contexto geomorfológico estadual através de MDE. A compreensão de aspectos como a baixa solubilidade, a resistência mecânica, grau de microfraturamento, estrutura e composição mineralógica dos diferentes quartzitos, foram fundamentais para interpretar o seu importante papel na manutenção de cristas e maciços ao longo do território estadual em função da erosão diferencial.

Palavras-chave: Mecânica das Rochas; Erosão Diferencial; Rochas Paraderivadas; Geomorfologia Estrutural.

1. Introduction

Terrestrial landforms are shaped through the interaction of endogenous and exogenous processes acting over time, sculpting surface morphology (Penck, 1953). Denudational activity, in any climatic context, is influenced by the nature and arrangement of rocks, as well as by the overall tectonic evolution of the region (Tricart, 1974). The Earth's crust exhibits differential resistance, in which the behavior of rocks within the environment depends on their resistance to weathering agents (Büdel, 1982), which varies according to their physical and chemical properties under different climatic conditions (Pech, 2005).

Certain lithostructural contexts play a major role in the preservation of structural landforms, defined as those developed by erosion under the direct control of geological structure (Cotton, 1968). Saadi (1991) emphasizes that the term *morphostructural* should be associated with morphological compartments whose main characteristics demonstrate a clear control exerted by the lithological and/or structural framework.

The evolution of relief in passive margins depends largely on the action of morphoclimatic systems and geomorphological properties at the regional scale, given the reduced importance of tectonics in terms of regional uplift (Ott, 2020). Accordingly, the physical–mechanical behavior of rocks is one of the primary factors in the geomorphological interpretation of relief (Goudie, 2016).

Rock constitutes the main interface of interaction between endogenous and exogenous factors, being simultaneously deformed, fractured, uplifted, and downthrown, while also undergoing weathering and erosion. Gerrard (1988) argues that the physical properties governing the geomorphological behavior of rocks can be subdivided into three classes: first, properties related to hardness and toughness; second, properties controlling the interaction between rock material and water; and finally, properties related to the mechanical strength of rocks. Knowledge of the physical–mechanical characteristics of rocks is essential for geomorphological research (Yatsu, 1962). Thus, attributes such as porosity, permeability, solubility, cohesion, softness, and heterogeneity directly influence surface runoff, mechanical disaggregation, and chemical decomposition of rocks, constituting fundamental elements in landform interpretation (Penteadó, 1983; Casetti, 2005). Recent experimental studies reinforce this perspective by demonstrating that erodibility is strongly controlled by internal rock properties and may vary by several orders of magnitude even within a single lithotype (Turowski et al., 2023; 2024).

The Borborema Province (BP) constitutes a geological domain characterized by a complex lithostructural mosaic of metamorphic and plutonic rocks of Archean–Proterozoic ages (Van Schmus et al., 1998; Brito Neves et al., 2000), forming part of a Cretaceous passive margin (Matos, 2000). Its regional morphology is directly related to planation cycles, which were responsible for the current geomorphological compartmentalization of the region, marked by extensive planation surfaces interspersed with elevated residual landforms of varying dimensions and diverse morphological and lithostructural contexts (Peulvast; Claudino Sales, 2004). Differential erosion is a key element in the geomorphological interpretation of the BP, particularly with respect to lithologies such as quartzites, granites, orthogneisses, and sandstones, which play an important role in maintaining topographic highs of different forms and scales (Bastos; Cordeiro, 2021). However, the degree of fracturing can significantly reduce this resistance, as demonstrated in tectonically active environments of eastern Tibet, where fault zones can increase erosion coefficients by up to twofold and exert strong control over landscape evolution (Kirkpatrick et al., 2020).

The adoption of methodologies that characterize rocks by considering their physical parameters has the potential to contribute to discussions on geomorphological evolution across different spatial scales. Initiatives in this direction were encouraged by Yatsu (1966), Whalley (1976), Suzuki (2002), and others within the field of geomorphological research. Goudie (2016) reviewed the techniques currently available and commonly used for quantifying the physical parameters of rocks, in agreement with Gerrard (1988), who advocates the applicability of various quantitative tests, provided they are suitable for simulating natural environmental conditions.

The use of empirical data, rather than undermining theoretical interpretations of landscape evolution, can provide a robust foundation for arguments in complex geomorphological scenarios. Data derived from petrographic thin-section analyses—such as the orientation and intensity of microfracturing, the presence of inclusions or microstructures, quartz content, and related features—can contribute to regional geomorphological interpretations. By integrating these data with field observations and interpretations, it is possible to assess the extent to which the studied rocks exhibit fragile or resistant characteristics, even though such tests are not specifically designed for geomorphological studies, as they are performed on fresh, unweathered rock material.

Quartzites are siliceous rocks with low solubility (Wray; Sauro, 2017), containing more than 98% quartz in their composition (Tripathi; Rajamani, 2003), and occupy the upper end of erosional resistance relative to other

common surface lithologies. Accordingly, the present study aimed to determine the physical–mechanical behavior, wear resistance, and porosity of 24 quartzite samples distributed across the northern sector of the Borborema Province, specifically within the state of Ceará (Figure 1). To this end, tests were conducted to determine physical indices, uniaxial compressive strength, resistance to abrasive wear, and seismic wave propagation velocity. Data acquisition followed ABNT standards, and the final results were compared with the geomorphological behavior of these lithotypes.

2. Study Area

The analyzed rocks are located in the northern sector of the Borborema Province (BP), situated in the northeastern portion of the South American Platform, bounded to the south by the São Francisco Craton and to the west by the Parnaíba Basin and the São Luís Craton (Almeida et al., 1981). Despite its wide lithological diversity, the Borborema Province is predominantly composed of granitic and metamorphic basement blocks (Almeida et al., 1977; Van Schmus et al., 1995; Brito Neves et al., 2000), with ages ranging from the Archean to the Neoproterozoic, separated by extensive mobile belts that were structured during the late Neoproterozoic (Arthaud et al., 2014). The BP was formed through the convergence of the São Luís–West African and São Francisco–Congo cratons, resulting in the assembly of the West Gondwana supercontinent (Brito Neves; Cordani, 1991; Trompette, 1994).

Geologically, the BP represents the western portion of the Brasiliano/Pan-African orogenic belt, which extended from the South American Platform to the African continent (Almeida et al., 1977). This province is subdivided into three main subprovinces: Northern, Central, and Southern (Van Schmus et al., 1995). Each of these subprovinces comprises distinct geological domains: the Northern Subprovince includes the Médio Coreaú, Ceará Central, Jaguaribe–Orós, and Rio Grande do Norte domains; the Central Subprovince encompasses the São Pedro, Piancó–Alto Brígida, Alto Pajeú, Alto Moxotó, and Rio Capibaribe terrains; and the Southern Subprovince is formed by the Pernambuco–Alagoas, Sergipano, Riacho do Pontal, and Rio Preto domains (Santos, 1996; Brito Neves et al., 2000).

The BP experienced several ancient and relatively recent uplift episodes (Alves et al., 2022), associated with the rifting that led to the opening of the Atlantic Ocean, as well as subsidence related to the development of the Potiguar Rift and other local rifts. These events were followed by renewed uplift phases, the latter being more localized and associated with volcanic processes (Matos, 2000; Peulvast & Claudino Sales, 2000; Peulvast & Bétard, 2013), as well as Cenozoic to Miocene tectonic readjustments (Bezerra et al., 2020; Oliveira et al., 2023). As a consequence of these events, regional geomorphological evolution became predominantly controlled by the differential resistance of lithotypes to denudational processes.

The state of Ceará encompasses terrains belonging to the Médio Coreaú, Ceará Central, Jaguaribe–Orós, and a small portion of the Rio Grande do Norte domains. The regional semi-arid climate, predominant since the Miocene (Harris & Mix, 2002), has played a fundamental role in shaping the present-day relief through morphodynamics preferentially linked to mechanical processes, thereby controlling differential rock erosion. In this context, highly resistant lithologies—such as well-cemented sandstones, granites, and quartzites—play a key role in resisting denudational processes, accounting for topographic highs of varying forms and dimensions (Bastos; Cordeiro, 2021). This interpretation is consistent with the proposal of Turowski et al. (2023; 2024), who advocate the applicability of laboratory-based erodibility measurements at the landscape scale, reinforcing the relevance of the results obtained for the quartzites of Ceará.

Quartzites are rocks derived from the metamorphism of sandstones, whose abundance in the state of Ceará is closely linked to the formation history of the Borborema Province, characterized by multiple collisional belts. In general, the protoliths of these quartzites were generated within sedimentary basins located between crustal blocks that later amalgamated during cratonic convergence (Almeida et al., 1981; Brito Neves et al., 2000; Neves et al., 2008). Owing to the intense deformation associated with these processes, the sedimentary successions within these basins were subjected to metamorphism, giving rise to Quartzite–Pelite–Carbonate sequences (Arthaud et al., 2008; Pinéo, 2020). As a result, these lithotypes are highly deformed and widely distributed across the state territory (Figure 1).

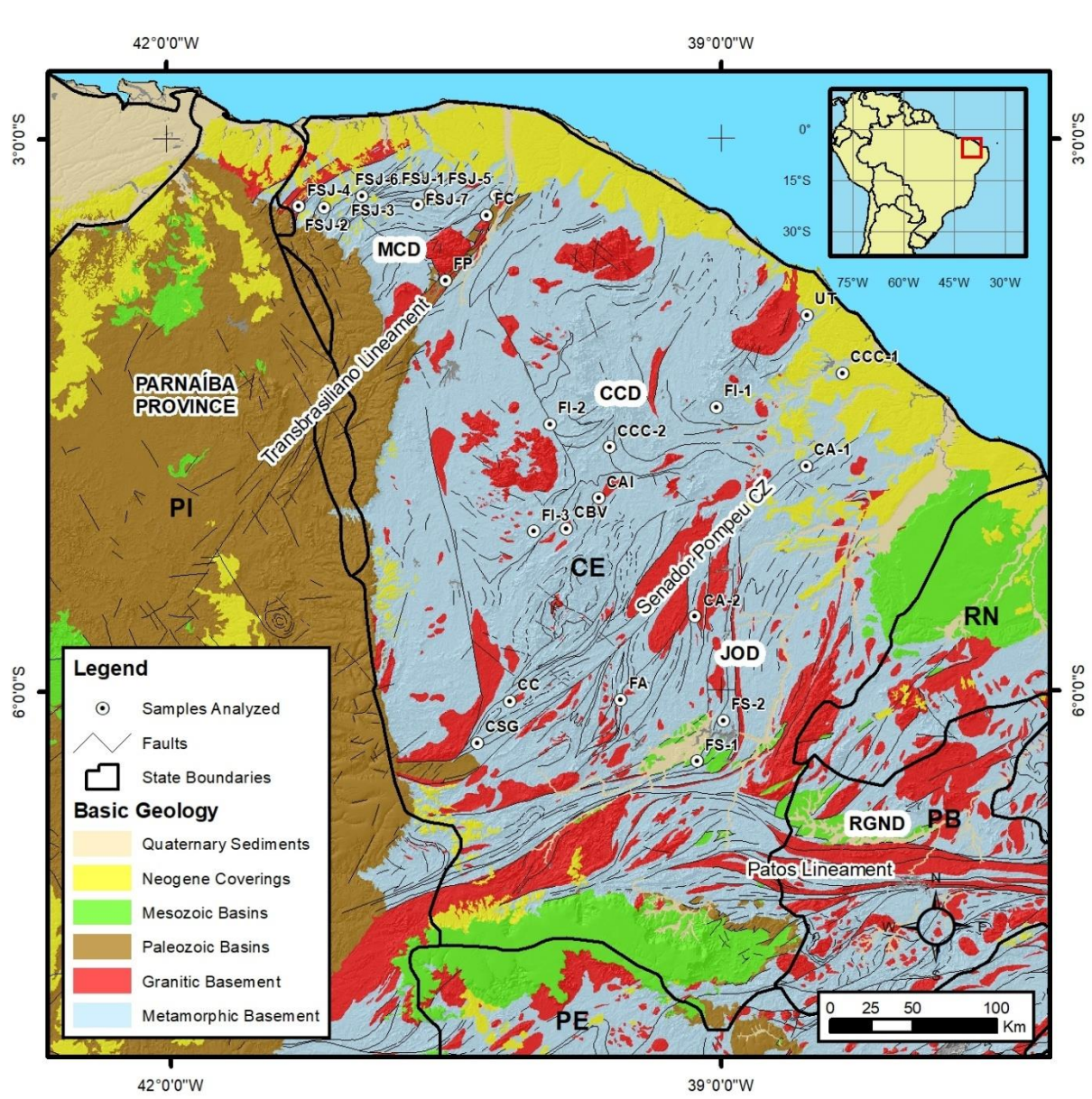


Figure 1. Simplified geological map of the state of Ceará showing the sampled quartzite points. Source: CPRM, 2006. Abbreviations: Domains – MCD: Médio Coreau Domain; CCD: Ceará Central Domain; JOD: Jaguaribe-Orós Domain; RGND: Rio Grande do Norte Domain; Analyzed Geological Units – FSJ: São Joaquim Formation; FC: Covão Formation; FP: Pacujá Formation; FI: Independência Formation; CCC: Canindé do Ceará Complex; UT: Tamboril Unit; CSG: São Gonçalo Complex; CC: Cruzeta Complex; FA: Arneiroz Formation; FS: Santarém Formation; CA: Acopiara Complex; CBV: Boa Viagem Complex; CAI: Algodões Complex.

3. Materials and Methods

The acquisition of data on abrasive wear resistance, determination of physical indices, compressive strength, and seismic wave propagation velocity was primarily motivated by the possibility of correlating these values with geomorphology, based on the subdivisions proposed by Gerrard (1988). In this framework, the first three tests correspond, respectively, to the classes defined by the author, while the last test serves the purpose of correlating these mechanical characteristics.

The development of this study was structured in several stages, with the aim of providing a comprehensive analysis of the geomorphological relationships of quartzites and their physical–mechanical characteristics. Initially, an extensive literature review was carried out, including the analysis of scientific articles, books, and other relevant publications, in order to understand contemporary discussions on the formation, evolution, and resistance of quartzitic rocks in different geological and geomorphological contexts.

Based on the literature review, 24 quartzite samples distributed throughout the state of Ceará were analyzed and tested (Figure 1). These samples were selected for their representativeness and importance within the geomorphological context of the state. The dataset provides broad regional coverage, encompassing the Cruzeta, Acopiara, São Gonçalo, Algodões, and Boa Viagem complexes, as well as the Tamboril and Canindé do Ceará units, and the Independência, São Joaquim, Santarém, Arneiroz, Pacujá, and Covão formations. Sample collection was carried out between March and December 2023.

To ensure the acquisition of accurate and reproducible data, rigorous procedures for sample collection and preparation were adopted in accordance with established technical standards. For the determination of physical indices, ten cubic specimens from each rock type ($5 \times 5 \times 5$ cm) were dried, water-saturated, and subsequently weighed, allowing the calculation of bulk density, porosity, and water absorption. Uniaxial compressive strength was determined using ten cubic specimens per rock ($7 \times 7 \times 7$ cm), which were compressed to failure in a hydraulic press with a capacity of 200 tonnes, recording the maximum stress sustained. Abrasive wear resistance was evaluated using the Amsler method, in which two specimens from each rock type were subjected to friction against a steel disk with standardized sand, and surface lowering after the test was measured. Finally, seismic wave propagation velocity was determined by ultrasonic testing on dry specimens, with three measurements per sample to reduce uncertainty. All tests were conducted in accordance with the standards of the Brazilian Association of Technical Standards (ABNT), including NBR 15845-2 (physical properties of rocks), NBR 15845-5 (uniaxial compressive strength), and NBR 12042 (abrasive wear of rocks).

In total, 528 specimens were prepared and tested following the aforementioned guidelines. Of these, 48 specimens were used in the abrasive wear resistance tests, 240 in the characterization of physical indices, and 240 in the uniaxial compressive strength tests. The number of specimens, in compliance with all quantitative requirements and quality standards established by the regulatory norms, ensured the statistical representativeness of the results, enabling detailed and robust analyses of the physical–mechanical behavior of the quartzites. In addition, the obtained data were correlated with the morphological characteristics of the source formations, allowing an integrated analysis that considered both the physical and geomorphological aspects of the samples.

For technical interpretation purposes, uniaxial compressive strength values were classified according to the international rock material strength classification proposed by Barton (1978). This classification defines seven categories based on stress intervals: extremely weak (<1 MPa), very weak (1–5 MPa), weak (5–25 MPa), moderately strong (25–50 MPa), strong (50–100 MPa), very strong (100–250 MPa), and extremely strong (>250 MPa). In addition to the physical–mechanical tests, petrographic analyses of thin sections were conducted. Two thin sections were prepared for each rock type and analyzed by optical microscopy under transmitted light. Mineralogical characterization followed the point-counting method, with approximately 300 points per thin section, allowing the estimation of mineral proportions and the assessment of the degree of microfracturing. This procedure provided quantitative data on composition and texture, which were subsequently correlated with the physical–mechanical results.

Finally, the results were discussed in light of current theories on geomorphological evolution and the resistance of quartzitic rocks to denudation. This discussion aimed not only to improve understanding of the formation and alteration processes of quartzites, but also to contribute to the advancement of knowledge in the field by offering new perspectives on the durability and stability of these rocks in different geological environments.

4. Results

4.1. Physical Parameters of the Quartzites

In order to organize the results obtained from the petrographic and physical–mechanical tests, the samples were grouped according to their respective structural domains: the Médio Coreau Domain (MCD), the Ceará Central Domain (CCD), and the Jaguaribe–Orós Domain (JOD) (Figure 1). As can be observed from the analytical data, the Ceará quartzites exhibit average values of bulk density of 2,638.94 kg/m³, porosity of 0.73%, water absorption of 0.29%, abrasive wear resistance of 0.31 mm, and uniaxial compressive strength of 122.62 MPa.

Rocks cropping out in the MCD present respective mean values of 2,653.56 kg/m³ for bulk density, 0.55% porosity, 0.22% water absorption, 0.21 mm abrasive wear, and 113.5 MPa uniaxial compressive strength. In the CCD, the corresponding averages are 2,601.69 kg/m³, 1.03%, 0.41%, 0.29 mm, and 135.36 MPa. Finally, rocks from

the JOD show mean values of 2,637.80 kg/m³, 0.36%, 0.13%, 0.49 mm, and 81.75 MPa. Mineralogical data by unit further indicate considerable variations in quartz content and degree of microfracturing (Table 1).

Table 1. Petrographic and Microstructural Characteristics of Quartzites from the State of Ceará.

Geological U.	Mineralogy (%)							Microfracturing (Total/mm ²)		Structure
	QTZ	MSC	SER	PL	SIL	ZIR	OP	Intergranular	Intragranular	
Tamboril Unit	81	6	3	7	-	1	2	2.24	1.68	Banding
Independência Formation	92 - 89	15 - 4	15 - 6	-	-	1 - 0	2 - 1	1.49	1.13	Massive
Canindé do Ceará Unit	95 - 70	25 - 0	-	2	-	2 - 0	3	2.79	1.24	Massive
Cruzeta Complex	65	26	3	-	4,5	0,5	1	0.88	0.67	Banding
São Gonçalo Complex	95	-	4	-	-	-	1	3.62	2.38	Banding
Algodões Complex	42	30	-	26	-	-	2	1.36	0.84	Massive
São Joaquim Formation	94	8 - 0	3	15 - 2	-	-	1	1.84	0.53	Massive
Pacujá Formation	55	24	3	18	-	-	-	1.27	0.47	Massive
Covão Formation	79,5	11	2	6,5	-	1	-	4.25	2.13	Massive
Santarém Formation	92	3	1	2	-	-	2	2.97	1.75	Banding
Acopiara Complex	75 - 67	9 - 5	2 - 1	17 - 14	3	0,5	1,5	3.73	1.46	Banding
Arneiroz Formation	79	9	-	6	4	1	1	1.06	0.38	Massive

Source: Prepared by the authors (2025). Legend: QTZ: Quartz; MSC: Muscovite; SER: Sericite; PL: Plagioclase; SIL: Sillimanite; ZIR: Zircon; OP: Opaques.

4.1.1. Médio Coreaú Domain

The Médio Coreaú Domain (MCD) is located in the northwestern portion of the state of Ceará, bounded to the east by the Sobral–Pedro II shear zone, to the west by the margins of the São Luís Craton, to the southwest by the Parnaíba Basin, and to the north by coastal deposits (Brandão, 2014; Brito Neves et al., 2000). This domain represents an orogenic belt that encompasses a wide variety of lithotypes of different ages, formed within a single tectonic unit (Brito Neves, 1975; Torquato, 1996).

Santos (2004) argues that the evolution of the MCD involved four deformational events, with the first stage of Transamazonian age and the subsequent three directly influenced by the Brasiliano Orogeny. The basement of this domain is composed of high-grade rocks such as gneisses, migmatites, and granulites of Paleoproterozoic age, overlain by Paleoproterozoic to Neoproterozoic supracrustal sequences (Nascimento et al., 1979). This basement comprises three main sequences: (i) orthogneisses of tonalite–trondhjemite–granodiorite (TTG) affinity; (ii) sequences of granulites, khondalites, and kinzigites; and (iii) ortho- and paragneisses and migmatites (Santos et al., 2004; 2007).

According to Siqueira et al. (2014) and Santos et al. (2007), two Tonian-age mobile belts can be identified within the MCD. The first is formed by metavolcanosedimentary rocks of the Martinópole Group, while the second comprises metapelitic–carbonate rocks of the Ubajara Group. Within this geological framework, the characteristics of quartzites belonging to the Pacujá, Covão, and São Joaquim formations were analyzed (Table 2).

Tabela 2. Physical-mechanical parameters of the quartzite rocks from the MCD.

Médio Coreaú Domain						
Code	Physical Indices			Compressive Strength (MPa)	Wear (mm)	Wave Velocity (m/s)
	Density (kg/m ³)	Porosity (%)	Water absorption (%)			
FJS-1	2670.16	0.27	0.1	75.9	0.15	6256.46
FSJ-2	2594.39	0.28	0.11	125.2	0.21	6276.28
FSJ-3	2630.84	1.1	0.42	161.5	0.25	6597.63
FSJ-4	2656.62	0.28	0.11	63.9	0.24	6084.42
FSJ-5	2641.43	0.56	0.21	77.4	0.21	6243.75
FSJ-6	2637.8	0.24	0.14	100.9	0.15	6239.05
FSJ-7	2642.6	0.45	0.26	208.7	0.15	6684.84
FP	2734.11	0.7	0.26	102	0.24	6143.98
FC	2690.7	0.8	0.3	68.4	0.29	5368.53

Source: Prepared by the authors (2025). Legend: FSJ: São Joaquim Formation; FP: Pacujá Formation; FC: Covão Formation.

The Pacujá Formation belongs to the metasedimentary sequences of the Jaibaras Group, together with the Massapê, Parapuí, and Aprazível formations (Costa et al., 1973). It is composed of sandstones to arkosic metasandstones, typically brown and beige in color (Pinéo, 2021). The Covão and São Joaquim formations, in turn, belong to the Martinópolis Group (Cavalcante et al., 2003). The former is composed of quartzites, chlorite–quartz schists, chlorite–talc schists, biotite–muscovite schists, phyllites, and iron formations, whereas the latter consists essentially of pure quartzites and micaceous quartzites (Prado et al., 1981; Pinéo, 2021) (Figure 2).

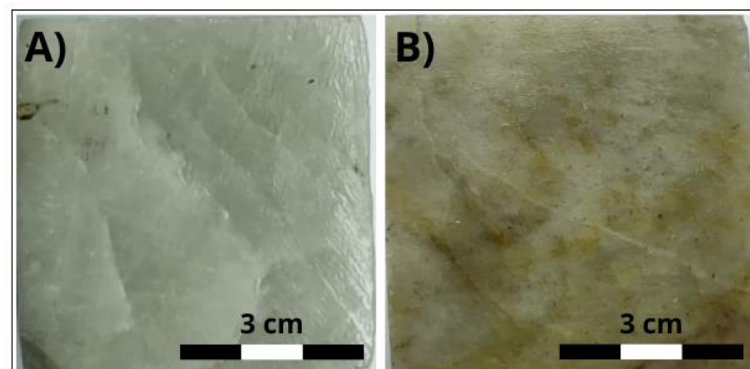


Figure 2. Facies variations of the São Joaquim Formation quartzites: A) Pure quartzite and B) Mica-rich quartzite. Source: Prepared by the authors (2025).

4.1.2. Ceará Central Domain

The Ceará Central Domain (CCD) is the largest tectonic block within the Borborema Province (BP), bounded to the north by the Sobral/Pedro II shear zone (Transbrasiliano Lineament) and the coastal plain, to the west by the Parnaíba Sedimentary Basin, and to the east and south by the Senador Pompeu Shear Zone (Arthaud, 2007). This domain occupies approximately 40% of the territorial area of Ceará (Brandão, 2014).

Fetter et al. (2000) subdivide the CCD into four lithostructural units: (i) Archean nucleus; (ii) juvenile Paleoproterozoic gneissic basement; (iii) metavolcanosedimentary supracrustal sequence; and (iv) Santa Quitéria magmatic arc. This domain contains the oldest rocks in Ceará, dated at 2.85 billion years (Fetter, 1999). These ancient rocks form the Archean nucleus of the province, consisting of tonalite–trondhjemite–granodiorite (TTG) rocks, ultramafic complexes, and metavolcanosedimentary units (Brito Neves et al., 1999; Costa et al., 2012).

The juvenile gneissic basement is composed of medium- to high-grade metamorphic rocks from the Cruzeta Complex, the Algodões, Acopiara, and Choró units, as well as Paleoproterozoic intrusive bodies (Castro, 2004; Arthaud, 2007). The metavolcanosedimentary supracrustal sequence is represented by the Ceará Complex, composed of metapelitic and metapsammitic rocks intruded by post-collisional Neoproterozoic granitic bodies (Amaral et al., 2012; Santos et al., 2015; Castro et al., 2012). This sequence includes lithotypes such as ortho- and para-gneisses, migmatites, marbles, metacarbonates, micaceous schists, quartzites, metagabbros, meta-ultramafics, and amphibolites.

Finally, the Santa Quitéria Magmatic Arc is formed by plutonic rocks with a magmatic arc isotopic signature, representing a suite of approximately 40,000 km², referred to as the Tamboril–Santa Quitéria Unit (Fetter et al., 2003). The domain is characterized by low-angle tangential tectonics, with the occurrence of several nappes and ductile strike-slip shear zones (Garcia & Arthaud, 2004; Arthaud et al., 2008).

Within this geological framework, rocks from the Canindé do Ceará and Tamboril–Santa Quitéria units, the Independência Formation, and the Algodões, São Gonçalo, Cruzeta, and Boa Viagem complexes were analyzed, covering nearly all units subdivided by Fetter et al. (2000). Table 3 presents the physical–mechanical parameters obtained from the analysis of rocks from the CCD.

Table 3. Physical-mechanical parameters of the quartzite rocks from the CCD.

Ceará Central Domain						
Code	Physical Indices			Compressive Strength (MPa)	Wear (mm)	Wave Velocity (m/s)
	Density (kg/m ³)	Porosity (%)	Water absorption (%)			
UT	2621.59	0.28	0.11	155.35	0.18	6352.62
FI-1	2646.89	0.64	0.24	194.89	0.16	5527.94
FI-2	2638.62	0.46	0.17	117.4	0.16	5826.16
FI-3	2643.5	0.44	0.16	128	0.11	5737.04
CBV	2580.23	0.73	0.28	42.3	0.23	4798.35
CCC-1	2650.24	0.46	0.17	179.9	0.33	5824.46
CCC-2	2632.34	0.32	0.12	186.56	0.24	5870.33
CC	2392.53	5.69	2.4	86.2	0.48	4967.64
CSG	2581.32	1.02	0.4	128.4	0.54	5824.50
CAI	2629.66	0.34	0.13	134.6	0.47	5698.05

Source: Prepared by the authors (2025). Legend: UT: Tamboril Unit; FI: Independência Formation; CBV: Boa Viagem Complex; CCC: Canindé do Ceará Complex; CC: Cruzeta Complex; CSG: São Gonçalo Complex; CA: Algodões Complex.

Paraderived rocks, such as quartzites, are rare in the Cruzeta Complex (Pinéo, 2021), with ages between 2.85 and 2.68 Ga (Ganade et al., 2017), as this complex is primarily composed of orthogneisses, partially migmatized, with quartz-dioritic to tonalitic–granodioritic compositions, including lenses of amphibolites and meta-ultramafic rocks (Pinéo, 2021). In contrast, the Algodões Complex contains a greater abundance of metasedimentary units (Palheta, 2017), with quartzites dated at 2.07 Ga (Costa & Palheta, 2017).

Among the most sampled units, rocks from the Canindé do Ceará Complex (Araújo & Pinéo, 2011; Cavalcanti, 2011) have ages ranging from 2.14 to 2.04 Ga (Amaral, 2010; Castro, 2004). Quartzites within this complex are classified within the paragneiss–migmatite unit and are associated with schists, calc-silicate rocks, amphibolites, and marbles, forming a metamorphosed Quartzite–Pelite–Carbonate sequence dated at 613 Ma (Amaral, 2010). The Independência Formation is part of the Ceará Group (Arthaud, 2007), following the subdivisions proposed by Pinéo (2021) (Figure 3). This formation is composed primarily of aluminous schists and paragneisses, although it may locally include quartzite layers (Pinéo, 2021).

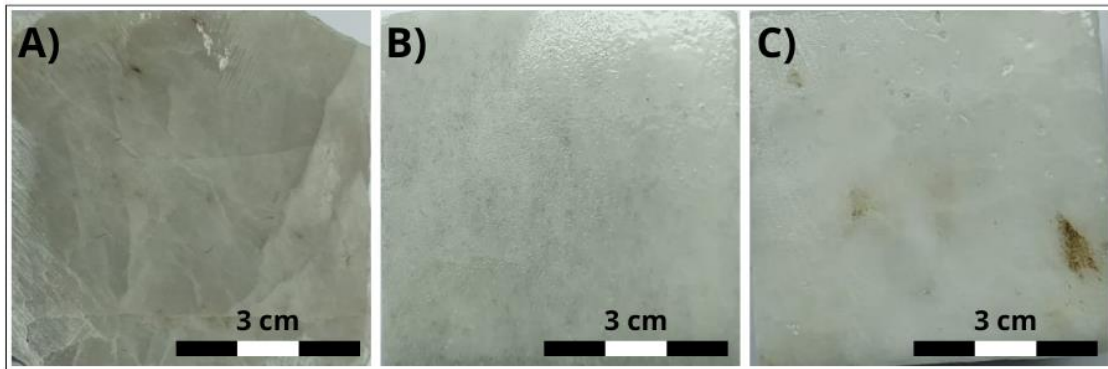


Figure 3. Quartzites of the Ceará Central Domain: A) Independência Formation, B) Canindé do Ceará Unit, and C) Tamboril-Santa Quitéria Unit. Source: Prepared by the authors (2025).

4.1.3. *Jaguaribe-Orós Domain (Jaguaribeano)*

The Jaguaribe–Orós Domain (JOD) corresponds to the northeastern to south-southeastern portion of Ceará, bounded to the northwest by the Senador Pompeu Shear Zone and to the south by the Patos Lineament (Brandão, 2014; Brito Neves et al., 2000). This domain also extends into the territory of Rio Grande do Norte and has a formation history linked to the convergence and amalgamation of migmatitic gneissic blocks, supracrustal sequences, and Archean terrains during the Brasiliano Orogeny (Hasui et al., 2012; Nascimento et al., 2015).

The basement of the JOD is predominantly composed of an Archean nucleus, represented by the Granjeiro Complex. The Granjeiro Complex mainly consists of tonalitic and granodioritic gneisses with an age of 2.54 Ga (Silva et al., 1995). Souza et al. (2007) and Hollanda et al. (2011) describe the Paleoproterozoic rocks of this domain as gneisses and migmatites metamorphosed under amphibolite facies conditions. For this region, quartzites from the Acopiara Complex, as well as the Santarém and Arneiroz formations, were analyzed (Table 4).

Table 4. Physical-mechanical parameters of quartzite rocks from the Jaguaribe-Orós Domain.

Jaguaribe-Orós Domain						
Code	Physical Indices			Compressive Strength (MPa)	Wear (mm)	Wave Velocity (m/s)
	Density (kg/m ³)	Porosity (%)	Water absorption (%)			
FS-1	2601.91	0.56	0.22	147.1	0.19	6498.72
FS-2	2591.59	0.61	0.21	138.47	0.14	6537.56
CA-1	2971.85	0.37	0.12	79.6	2.01	5695.27
CA-2	2637.57	0.28	0.1	43.6	0.14	5340.89
FA	2647.4	0.2	0.08	150.0	0.09	6789.24

Source: Prepared by the authors (2025). Legend: FS: Santarém Formation; CA: Acopiara Complex; FA: Arneiroz Formation.

The Acopiara Complex represents a package of paraderived rocks, cropping out between the Senador Pompeu and Orós shear zones (Gomes & Vasconcelos, 2000; Ferreira & Santos, 2000). Lithologically, it is composed of migmatites, paragneisses, aluminous schists, graphitic schists, quartzites, marbles, calc-silicate rocks, amphibolites, and orthogneisses (Pinéo, 2021). Although no geochronological datings are yet available for this complex, its age can be inferred by correlation with similar units, such as the São Gonçalo Complex, dated at 2.15 Ga (Palheta et al., 2019).

The Arneiroz Formation, like the Independência Formation, is part of the Ceará Group (Arthaud, 2007). However, it is predominantly composed of quartzites, with limited layers of schists and marbles (Pinéo, 2021), and has been dated between 772 Ma and 620 Ma (Fetter, 1999; Arthaud, 2007) (Figure 4). The Santarém Formation belongs to the Orós Group (Palheta et al., 2019), with an age ranging from 1.70 to 1.79 Ga (Costa & Palheta, 2017;

Sá, 1991). It is composed of phyllites and mylonitic schists, metagraywackes, with intercalations of quartzites, calc-silicate rocks, marbles, and amphibolites (Pinéo, 2021). These rocks occur near the Senador Pompeu Shear Zone, exhibiting high deformation rates and ridge-like morphologies aligned with the regional deformation trend.

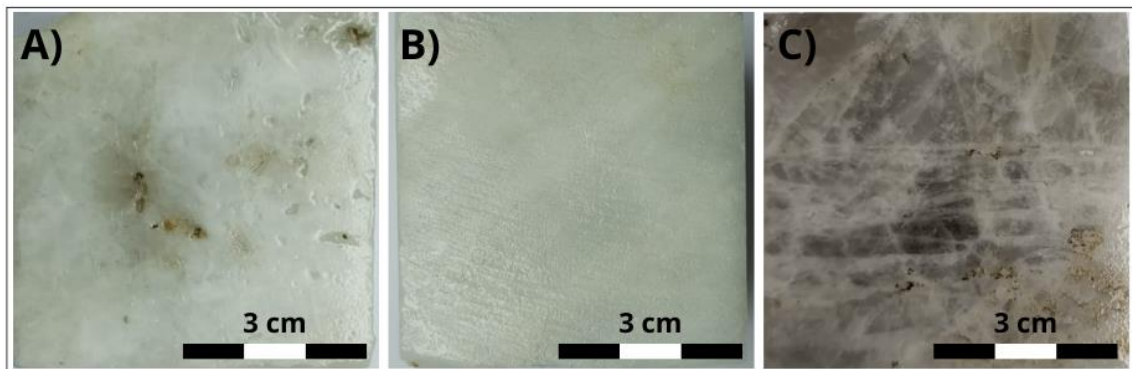


Figure 4. Quartzites of the Jaguaribe-Orós Domain: A) Santarém Formation, B) Arneiroz Formation, and C) Acopiara Complex. Source: Prepared by the authors (2025).

4.2. Deformational History of the Analyzed Lithologies

Throughout its geological evolution, the Borborema Province (BP) underwent several deformational events, with a geological history recorded as early as the Paleoproterozoic, as exemplified by the São José do Campestre terrains dated at approximately 3.4 Ga. However, records of quartzites in the state of Ceará begin with the Cruzeta Complex, of Neoproterozoic age. Bizzi (2003) indicates that intense tectonic activity affected these embryonic nuclei during the Archean, promoting either crustal growth or the reworking of pre-existing terrains. In this context, the rocks composing the Cruzeta Complex exhibit characteristics of juvenile crust, later involved in Paleoproterozoic accretionary processes.

Beyond the Archean accretionary events, the sequence of deformational episodes most relevant to Ceará began during the Paleoproterozoic. Initially, during the Rhyacian orogenic cycle (2.25–2.05 Ga), crustal blocks corresponding to the Jaguaribe–Orós, Médio Coreau, and Ceará Central domains were amalgamated into a single continental mass (Santos, 1999; Ferreira & Santos, 2000). This event contributed significantly to the metamorphism of the lithotypes that constitute the Canindé do Ceará Unit (Fetter, 1999). Toward the end of the Paleoproterozoic, this continental mass was fragmented by intense rifting processes associated with the Statherian taphrogenesis (1.8–1.7 Ga), giving rise to structures such as the Jaguaribe rift (Brito Neves, 1995a).

With the onset of the Mesoproterozoic, the BP experienced the Cariris Velhos orogenic event (1.08–0.95 Ga) (Brito Neves et al., 1995b), which was responsible for the deformation of several crustal segments along a belt at least 800 km long and with a variable width ranging from 300 to 50 km (Santos, 1996). During the Neoproterozoic, the most extensive event affecting the BP took place: the Brasiliano Orogeny (0.75–0.5 Ga), which was responsible for the final structuring of the province and acted intensely through the amalgamation of continental blocks, the formation of rift-margin basins, and the emplacement of granitic plutons (Brito Neves et al., 2000; 2014; Santos et al., 2001).

Following the end of the Brasiliano Orogeny, the BP remained in relative tectonic stability of its crustal blocks until the onset of processes related to the opening of the Atlantic Ocean, which involved the reactivation of several structures as well as uplift caused by flexural processes (Matos, 2000; Saadi et al., 2005; Peulvast et al., 2006). Finally, the influence of neotectonic activity must be considered, as it may lead to significant deformation at smaller spatial scales. Because deformational processes affected the entire pre-existing rock assemblage, quartzitic rocks record an intense deformational history, often comprising more than one tectonic event (Figure 5).

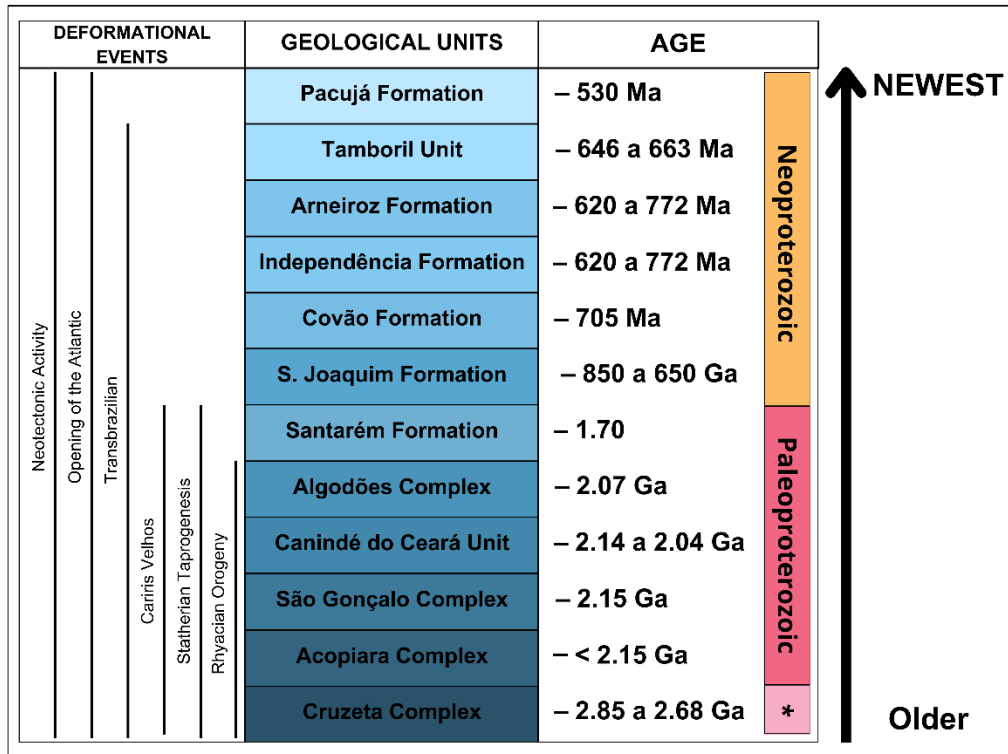


Figure 5. Correlation between the age and deformational events that affected geological units containing quartzites. Source: Prepared by the authors (2025).

5. Discussion

The general characterization of the quartzites provided relevant data (Tables 1, 2, 3, and 4), showing considerable variation in physical parameters. Porosity ranges from 0.2% to 5.62%, water absorption varies from 0.09% to 2.4%, and uniaxial compressive strength ranges from 42.3 MPa to 208.7 MPa. Using the strength limits proposed by the classification *Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses* (Barton, 1978), it is observed that 62.5% of the analyzed rocks fall into the “very strong” category, while 37.5% are classified as “strong” (Figure 6).

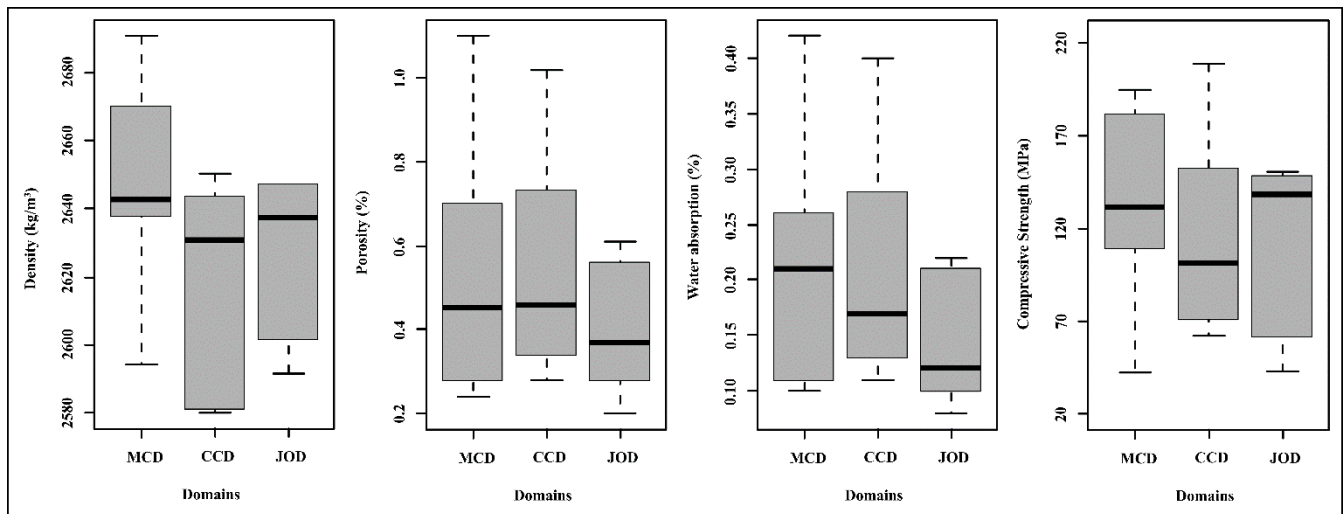


Figure 6. Box-plot graphs showing the differences in mechanical parameters of the rocks by domain. MCD: Médio Coreáú Domain, CCD: Ceará Central Domain, and JOD: Jaguaribe-Orós Domain. Source: Prepared by the authors (2025).

When the obtained strength results are compared with the average physical–mechanical behavior of different rock types, such as granites, marbles, and sedimentary rocks, it becomes evident that quartzites exhibit superior mechanical performance (Table 5). Quartzites are among the most resistant metamorphic rocks to both mechanical and chemical weathering processes (Gerrard, 1988). Considering the deformational history to which the Borborema Province quartzites have been subjected, most of them are organized in folded structures, which results in a very distinctive geomorphological behavior. This is reflected both in the drainage network, showing rectangular and trellis patterns as observed in the MCD, and in sharp residual features such as ridges and hogbacks, which stand out topographically relative to the surrounding planation surfaces.

Table 5. Comparison of the physical-mechanical behavior patterns of different rocks. Source: Prepared by the authors (2025).

Rock type	Density (kg/m ³)	Water absorption (%)	Compressive Strength (MPa)	Reference
Calcite Marble	>2.595	≤ 0.20	≥52	ASTM C 503 (ASTM, 2022)
Quartz Sandstone	>2.400	≤ 3.0	≥ 68.9	ASTM C 616 (ASTM, 2024)
Granites	≥ 2.550	≤ 0.40	≥ 100	NBR 15844 (ABNT, 2015)
Quartzites (Database ROCK/10/4025)	2.548	-	159.09	Ferentinou & Muzamhindo (2025)
Quartzites (PB)	2.638	0.29	122.65	Author

By correlating the ages of the analyzed geological formations with physical–mechanical parameters such as uniaxial compressive strength, an inverse relationship between age and strength values can be observed (Figure 7). In other words, the older, and consequently more deformed, rocks exhibit lower strength values than younger and less deformed rocks. From a geomorphological perspective, the oldest quartzites show the weakest correlation with preserved topographic highs, particularly the rocks deformed during the Riacian, which tend to form smaller ridges compared to other quartzites. An exception is observed in the quartzites of the Pacujá Formation, located within the Jaibaras Graben context. These correspond to sandstones locally metamorphosed into quartzites and are associated with a morphology related to planation surfaces.

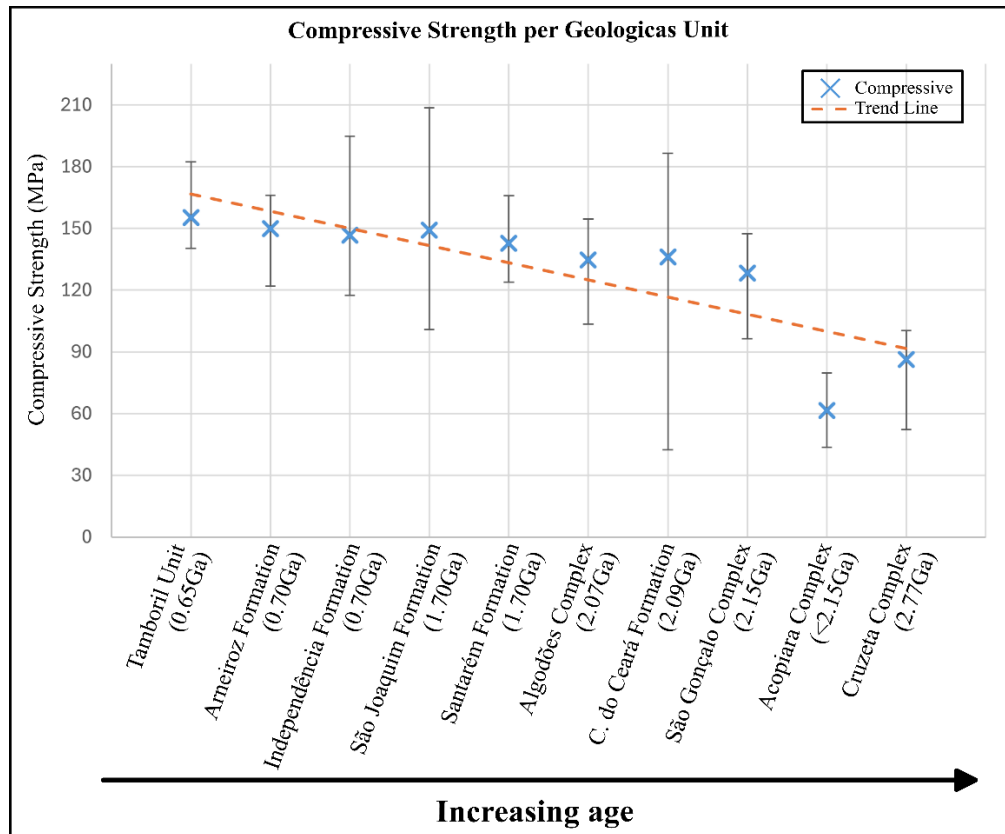


Figure 7. Correlation between the age of lithologies and uniaxial compressive strength results. Source: Prepared by the authors (2025).

Thus, the deformational events exhibit a dual influence on the morphology of quartzites. On one hand, thrust or strike-slip movements are highly significant due to their ability to metamorphose sandstones and induce mild to pronounced tilting and/or folding of rock layers. On the other hand, the overprinting of these deformational events can lead to the weakening of lithotypes and their subsequent denudation.

Considering that these are lithological units with a scattered distribution across the studied area, it can be stated that the fluvial controls on quartzites occur at a very local scale, with first-order parallel drainage along ridge slopes. However, structural control becomes evident in sectors where quartzites are associated with shear zones, showing rectangular drainage patterns and fluvial superimpositions along quartzite ridges. In some cases, the exhumation of folded Precambrian structures conditioned the development of Apalachian-type relief, with trellis drainage patterns, whose morphological expression was later erased by modern planation cycles, leaving preserved features only in epigenic gorges that cut through the ridges (Ab’Sáber, 1957) (Figure 8).



Figure 8. Examples of fluvial superimpositions over quartzite ridges. A – Boqueirão de Arneiroz formed by the Jaguaribe River over a ridge developed in quartzites of the Arneiroz Formation (dry season); B – Boqueirão de Lavras da Mangabeira formed by the Salgado River over a ridge developed in quartzites of the Lavras da Mangabeira Unit (rainy season). Source: Authors' collection (2024).

Another highly relevant characteristic that can influence the physical–mechanical behavior of quartzites is their degree of purity and fracturing. Clear examples of this behavior were observed in the rocks of the São Joaquim and Independência formations. Torquato and Neto (1996) describe the São Joaquim Formation as subdivided into pure to micaceous quartzites. Based on the petrographic description of the rocks, it is possible to observe an increase of 8% in the content of micaceous minerals (muscovite and sericite) and 13% in K-feldspar when comparing the pure and impure facies of this quartzite. This mineralogical change led to a variation of at least 36.36% in the mechanical strength values of the quartzites (FSJ-3 and FSJ-4) (Figure 9).

The Independência Formation shows little mineralogical variation compared to the São Joaquim Formation. It has a purer facies composed of quartz (95%), muscovite (3%), sericite (1%), and zircon (1%), and a less pure facies composed of quartz (89%), muscovite (4%), K-feldspar (6%), and sericite (1%). However, when comparing the degree of microfracturing, the “impure” facies exhibits a significantly higher microfracturing than the pure facies. The combination of these mineralogical differences resulted in a 34.4% decrease in mechanical strength values.

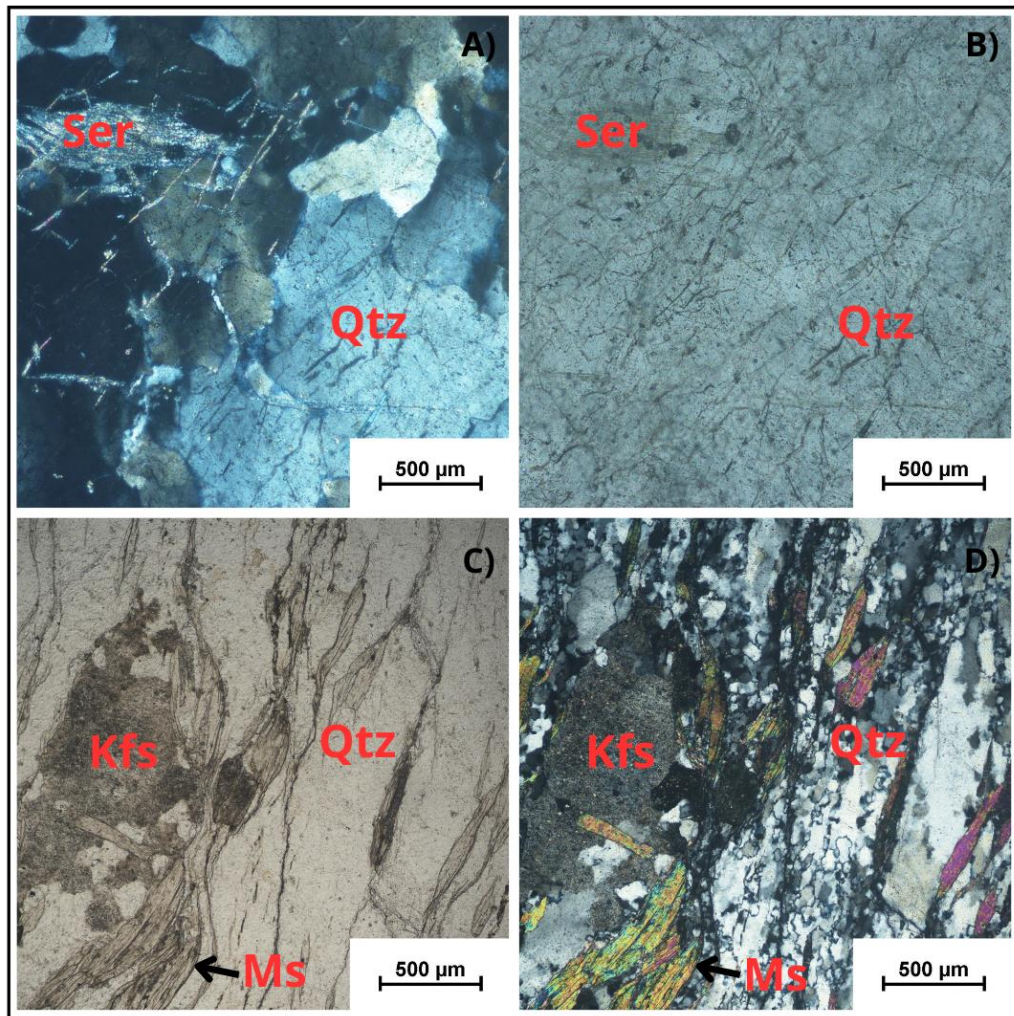


Figure 9. Photomicrograph of thin sections of quartzites from the São Joaquim Formation: A) and B) Pure quartzite, C) and D) Impure quartzite. Ser: Sericite, Qtz: Quartz, Kfs: K-feldspar, Ms: Muscovite. Source: Authors' elaboration (2025).

Within the analyzed sample set, the quartzites from the São Joaquim and Independência formations are those forming the highest reliefs. They are represented by the sigmoidal ridges of the São Joaquim and Ubatuba ranges (500–700 m) and by the elongated ridges in the western and southern sectors of the Baturité Massif (900–1,100 m), respectively. In the Baturité Massif, the quartzites of the Independência Formation play a crucial role in preserving the elevated surfaces of the massif's plateau, acting as a large natural “retaining wall” that protects the high sectors of the massif from surrounding regressive denudation (Bétard et al., 2007; Bastos, 2011). These quartzites also maintain the massif's highest point at 1,115 m (Pico Alto – Figure 10). Samples FI-1 and FI-3, collected from quartzite ridges of the Independência Formation, present strength values of 194.89 MPa and porosity of 0.46% (Table 2).

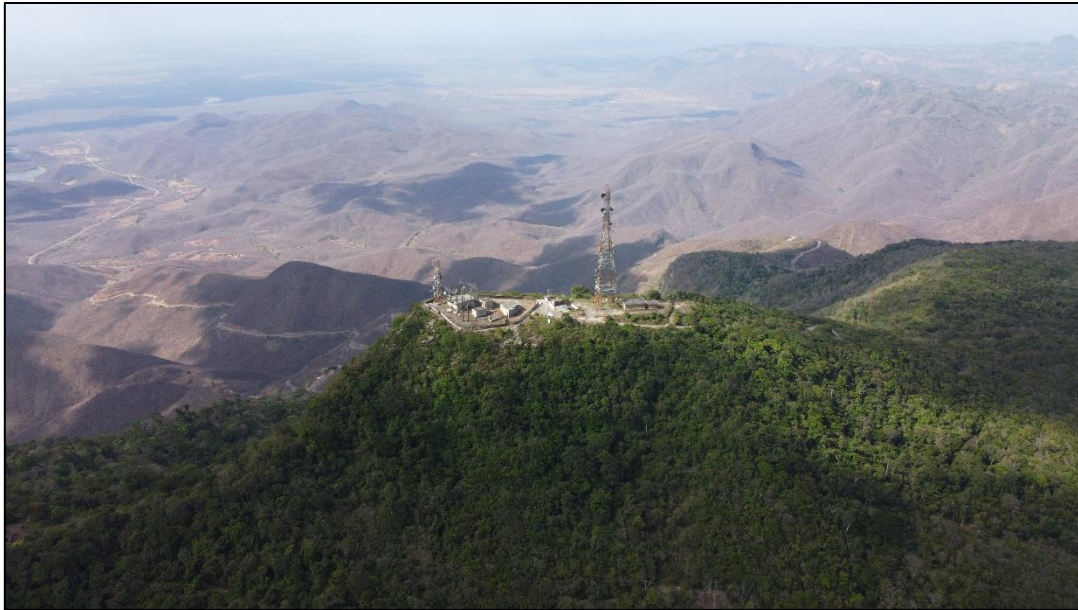


Figure 10. Ridge in the summit sector of the Baturité massif (Pico Alto), supported by quartzites of the FI. Source: Authors' collection (2024).

Due to their uniqueness, several studies have addressed the morphology of the quartzites that make up the MCD. Cordeiro et al. (2021) argue that in the MCD area, erosional processes planed the reliefs supported by more fragile lithologies, resulting in the prominence of more resistant morphologies composed of quartzites. The São Joaquim Formation quartzites in the MCD are responsible for maintaining elevated ridges (São Joaquim and Ubatuba ranges) as well as rocky coastal morphologies, such as those observed at Jericoacoara (Figure 11).

Claudino-Sales (2016) indicates that the ridges formed by the São Joaquim Formation quartzites represent remnants of a pre-Silurian or post-Brasilian fossilized surface, now exposed due to the removal of the Serra Grande Group sandstones. The dynamic association between the retreat of the Parnaíba Basin and the morphology of the exhumed quartzite ridges led to the formation of two embayments over the lowered erosive surface, namely the Sobradinho and Quatiguaba embayments, named after the rivers to which they are associated (Moura-Fé, 2017). In this context, the data obtained from mechanical characterization tests support Cordeiro et al.'s (2021) argument that quartzitic rocks, especially those of higher purity, were capable of resisting denudation due to their physical-mechanical properties (Table 2).



Figure 11. Landforms associated with the quartzites of the São Joaquim Formation. A – Rocky coast at the Jericoacoara shoreline; B – Serra de São Joaquim. Source: Authors' collection (2020).

In the CCD region, quartzites occur both as ridges and as flattened reliefs. Regarding the ridges, particular attention should be given to the Arneiroz and Independência formations, which form the ridges of the southern portion of the Baturité Range, the Machado Massif, and the Baratão, Salgado, and Ourego ranges, among others. Other formations form residual reliefs in the form of lower-altitude ridges or flattened surfaces. The rocks of the Arneiroz and Independência formations mainly outcrop in the central-northeastern portion of the domain, forming ridges exceeding 700 meters in elevation, such as in the aforementioned sector of the Baturité Massif and ridges located in the municipality of Independência.

The quartzite ridges of the Jaguaribe-Orós Domain are primarily formed by rocks from the Acopiara Complex and the Arneiroz and Santarém formations. These ridges exhibit strong structural control associated with the Senador Pompeu and Orós shear zones, with a preferential NE-SW and N-S orientation (Figures 12 and 13), particularly evident in the Serra do Félix, located in the municipality of Morada Nova. These elongated ridges act as watershed divides for the Banabuiú and Jaguaribe river basins, with some fluvial superimpositions that were historically used for the construction of two of the three largest reservoirs in the state of Ceará (Orós and Banabuiú).

When comparing the three geological units, the ridges of the Acopiara Complex reach the lowest altitudes, with gentler slopes on their flanks. In contrast, the Independência and Arneiroz formations reach the highest altitudes, with the former sometimes exceeding 540 meters of elevation difference and the latter typically ranging between 300 and 400 meters. Both geological units exhibit rocks with similar physical-mechanical parameters, and the topographic differences may be related to mineralogical, structural, or deformational characteristics.



Figure 12. North-oriented ridges supported by the quartzites of the Santarém Formation, in the vicinity of the city of Orós/CE. Source: Authors' collection (2024).



Figure 13. Northeast-oriented ridges supported by the quartzites of the Arneiroz Formation, in the vicinity of the city of Arneiroz/CE. Source: Authors' collection (2024).

At a mineralogical and compositional scale, studies such as those by Robb (1979), Brook (1978), Gibbons (1981), and Pye (1986) highlighted the importance of potassium-bearing minerals, such as orthoclase and microcline, in the composition of relatively weathering-resistant granitic lithotypes. However, when analyzing quartzitic rocks, this principle does not apply in the same way. This is because alkali-rich minerals, such as feldspars and plagioclases, are more susceptible to chemical alteration than quartz crystals, the main constituents of quartzites. Thus, a higher proportion of these minerals indicates a greater presence of zones potentially vulnerable to chemical weathering. In the mineralogical analyses of the quartzites studied, the most altered minerals were indeed feldspars and plagioclases, which showed varying degrees of sericitization. These results corroborate the findings of Zhu (2010) for sandstones in the Danxia region of China, where higher contents of alkali minerals reduced the rocks' resistance to chemical weathering.

Beyond mineralogical composition, microstructural characteristics—particularly the degree of microfracturing—were also critical for evaluating the durability and resistance of these rocks. According to the classification proposed by Meyer (2003), all analyzed samples exhibited a high degree of fracturing. When

correlating the degree of microfracturing with uniaxial compressive strength in quartzites containing more than 90% quartz, it was observed that more intensely microfractured samples tended to show more brittle mechanical behavior. Conversely, quartzites with less than 90% quartz generally exhibited a lower degree of microfracturing, though they also showed lower mechanical strength and lower resistance to alteration. Based on the discussions by Carbillet et al. (2025), the degree of microfracturing can also influence rock permeability and, consequently, its physico-chemical resistance.

The quartzites analyzed in this study exhibited high values of abrasion resistance, as determined by the Amsler method. From a geomorphological perspective, Krabbendam (2011), using alternative geotechnical tests, compared the fluvial and glacial abrasion resistance of substrates composed of sandstones and quartzites in northern Scotland. His results indicated that quartzites had approximately twice the abrasion resistance of sandstones in that region. Based on these data, he concluded that lithotypes highly resistant to abrasion, such as quartzites, are predominantly eroded by plucking processes. The results obtained in the present study, conducted in the semi-arid environment of Ceará, support this hypothesis of mechanical-erosive behavior, indicating that quartzites in this context are also less susceptible to direct abrasion and more influenced by plucking mechanisms. Considering that all quartzites exhibited a reduction in resistance values when tested in water-saturated conditions, wetter seasons and/or climatic conditions may intensify plucking processes.

Thus, by correlating the mineralogical characteristics of Ceará quartzites with their physical-mechanical behavior, it is possible to observe that units such as the São Joaquim Formation, Santarém Formation, Independência Formation, and Canindé do Ceará Unit exhibit high resistance to weathering (Figure 14). In contrast, units such as the Acopiara Complex, Cruzeta Complex, and Covão Formation show greater susceptibility to weathering disaggregation. From this, it is also possible to note that quartzites with lower quartz contents tend to experience greater denudation, representing the zones where most quartzites with low resistance to both physical and chemical weathering are concentrated (Figure 14).

Relationship between quartzites and resistance to weathering						
SiO ₂	Geological Units	M.R	D.M	PER	R.C.W	R.P.W
95%	São Gonçalo Complex	↑	↑	↑	↑	—
94%	São Joaquim Formation	—	—	—	↑	↑
92%	Santarém Formation	↑	↑	↑	↑	—
90.5%	Independência Formation	↑	↓	—	↑	↑
82.5%	Canindé do Ceará Unit	↑	↑	↑	↑	↓
81%	Tamboril Unit	↑	—	—	↑	↑
79.5%	Covão Formation	↓	↑	↑	↓	↓
79%	Arneiroz Formation	↑	↓	↓	↑	—
71%	Acopiara Complex	↓	↑	—	↓	↓
65%	Cruzeta Complex	↓	↓	↑	↓	↓
55%	Pacuja Formation	—	↓	—	↓	↓
42%	Algodões Complex	↑	↓	—	↑	↓

Legend;

- ↑ High
- Medium
- ↓ Low
- ▨ Banded Quartzite
- < 90% SiO₂

M.R: Mechanical Resistance
D.M: Degree of microfracture
PER: Permeability
R.C.W: Resistance to Chemical Weathering
R.P.W: Resistance to Physical Weathering

Figure 14. Correlation between the physical-mechanical and petrographic characteristics of the quartzites by geological unit. Source: Prepared by the authors (2025).

Studies such as those by Campos et al. (2023) and Marques et al. (2021) have demonstrated, in various locations across Brazilian states, a correlation between the high mechanical resistance of quartzites and the preservation of relief. Although these studies approach this relationship in a predominantly semi-quantitative manner, their conclusions reinforce the importance of physical-mechanical properties in geomorphological dynamics. In international contexts, and using different lithotypes other than quartzites, authors such as Barlow (2002), Korup (2009), Pellegrino (2007), Moumeni (2024), and Men (2024) have applied laboratory-obtained

physical–mechanical data to investigate geomorphological processes in regions such as Niagara (Canada), the Swiss Alps, Calabria (Italy), northwestern Iran, and Danxia (China). When compared to these studies, the resistance values obtained for Ceará quartzites are equivalent to the most resistant lithotypes analyzed by these authors, supporting the hypothesis that mechanical resistance plays a central role in landform development and preservation.

Regarding the development of weathering mantles over quartzites in the studied area, these are generally poorly developed, given the semi-arid climate and the strongly rugged topography, which together act as significant limiting factors for pedogenesis. As a result, shallow soils predominate, lacking a B horizon (Litholic Neosols). This pedogenetic behavior is very common in quartzites, whose regoliths show strong preservation of the original characteristics of the altered lithological material, including structural orientations (Gerrard, 1988).

6. Conclusions

This study analyzed 24 quartzite samples varying in structure, texture, and location. Such a robust sample set is highly relevant for understanding the overall characteristics of the study area. The purpose of this work is to foster discussions within the academic community regarding the preservation of topographic highs based on the physical and mechanical properties of the rocks. In this way, the study aims to reinforce empirical data-based approaches for comparing rock types to interpret landform genesis, while also contributing to the development of geomorphological evolution models that consider the physical–mechanical behavior of bedrock.

Beyond the physical–mechanical results, the study revealed the close relationship between quartzite ridges and the local deformational history, showing that nearly all of these landforms exhibit structural control. Additionally, it was observed that the superposition of deformational events can lead to the weakening of quartzites, consequently facilitating their denudation.

This work has the potential to contribute to discussions on the geomorphological evolution of quartzites and regions underlain by metamorphic rocks of varying resistance. The determination of rocks' physical–mechanical parameters through laboratory analyses serves as a highly valuable tool to support geomorphological interpretations.

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