ATELIÊ GEOGRÁFICO
ISSN: 1982-1956
http://www.revistas.ufg.br/index.php/atelie

The cycle of supercontinents and morpho-structural impacts on northwestern Ceará/Brazil

Ciclo dos supercontinentes e reflexos morfoestruturais no Noroeste do Ceará/Brasil

Ciclo de los supercontinentes y reflejos morfoestructurales en el Noroeste de Ceará/Brasil

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Abstract
Geological history records the occurrence of four supercontinents (Columbia, Rodínia, Panotia/Gondwana and Pangea). Traces of these events are recognized in the Northwest of Ceará through the following episodes: (1) Transamazonian/Atlantida Orogenesis (continental Columbia masses), generating the Granja Complex (2.0 Ga); (2) Columbia division generating klippe (1.7 Ga); (3) rifting of Rodinia (800-750 Ma), with deposition of neoproterozoic supracrustal sequences; (4) agglutination of Panotia/Gondwana (Orogenesis Brasiliana, 665-590 Ma), creating the Brasiliana Chain; (5) collapse of orogens and formation of the Jaibaras and Parnaíba basins, from the division of Panotia (530-515 Ma); (6) deposition of the Serra Grande Group in the Parnaíba Basin (440 Ma), associated with the drift of Gondwana; (7) intracontinental rifting (145-120 Ma) generating uplifting of the Parnaiba Basin and exhumation of granites, followed by the opening of the Atlantic, from the fission of Pangea/Gondwana (120-100 Ma); 8) flexural uplifting of the interior of the continent (from 65 Ma), with exhumation of massifs, crustal reactivation in the Meruoca Massif and denuding in the Parnaíba Basin, generating the Ibiapaba Glint.
Keywords: supercontinents; plate tectonics; megageomorphology.

Resumo
A história geológica registra a ocorrência de quatro supercontinentes (Columbia, Rodínia, Panotia/Gondwana e Pangea). Vestígios desses eventos são reconhecidos no Noroeste do Ceará através dos seguintes episódios: (1) Orogênese Transamazônica/Atlântida (massas continentais do Columbia), gerando o Complexo Granja (2,0 Ga); (2) divisão do Columbia, gerando klippe (1,7 Ga); (3) rifteamento do Rodínia (800-750 Ma), com a deposição de sequências supracrustais neoproterozoicas; (4) aglutinação do Panotia/Gondwana (Orogênese Brasiliana, 665-590 Ma), criando a Cadeia Brasiliana; (5) colapso de orógenos e formação das bacias do Jaibaras e Parnaíba, a partir da divisão do Panotia (530-515 Ma); (6) deposição do Grupo Serra Grande na Bacia do Parnaíba (440 Ma), associado com a deriva do Gondwana; (7) rifteamento intracontinental (145-120 Ma) gerando soerguimento da Bacia do Parnaiba e exumação de granitos, seguido da abertura do Atlântico, a partir da fissão do Pangea/Gondwana (120-100 Ma); 8) soerguimento flexural do interior do continente (a partir de 65 Ma), reativação crustal no Maciço da Meruoca e circunsdenudação na Bacia do Parnaíba, gerando o Glint da Ibiapaba.
Palavras-chave: supercontinentes; tectônica de placas; megageomorfologia.

Resumen
La historia geológica registra la ocurrencia de cuatro supercontinentes (Columbia, Rodínia, Panotia / Gondwana y Pangea). Los vestigios de estos eventos se reconocen en el Noroeste de Ceará a través de los siguientes episodios: (1) Orogénesis Transamazônica/Atlantis (masas continentales de Columbia), generando el Complejo Granja (2.0 Ga); (2) división de Columbia, generando klippe (1.7 Ga); (3) Rodínia rifting (800-750 Ma), con el depósito de secuencias supracrustales neoproterozoicas; (4) aglutinación de Panotia / Gondwana (Orogénesis Brasiliana, 665-590 Ma), creando la Cadena Brasiliana; (5) colapso de orógenos y formación de las cuencas Jaibaras y Parnaíba, de la división Panotia (530-515 Ma); (6) deposición del Grupo Serra Grande en la cuenca de Parnaíba (440 Ma), asociada con la deriva de Gondwana; (7) ruptura intracontinental (145-120 Ma) que genera elevación de la cuenca de Parnaiba y exhumación de granitos, seguida de la apertura del Atlántico, desde la fisión de Pangea / Gondwana (120-100 Ma); 8) elevación flexural del interior del continente (a partir de 65 Ma), reactivación de la corteza en el Macizo de Meruoca y circunsdeudación en la Cuenca de Parnaíba, generando el *Glint* de Ibiapaba.
Palabras clave: supercontinentes; placas tectónicas; megageomorfología.

Introduction

The advent of the plate tectonics during the second half of the 20th century represents a significant milestone in the interdisciplinary context of geosciences, enabling a paradigm shift in the evolutionary interpretation of the planet. This theory indicates that the movement of rigid blocks of the crust occurs with the Earth's internal heat as the source of primordial energy. In the last two decades, data from different sources understand that several supercontinents have punctuated Earth's history (MURPHY & NANCE, 2003, 2013; SANTOSH & ZHAO, 2009; CONDITION, 2011; YOSHIDA & SANTOSH, 2011; HUSTON, 2012; MITCHELL, 2012; NANCE, 2018; PASTOR-GALAN, 2018; LIU, 2019). A relevant contribution to the understanding of this process was the work of Wilson (1966). He proposed a cycle (Wilson Cycle) to the continental fragmentation, the opening/closing of oceanic basins, and the agglutination of continents.

According to the Wilson Cycle, heat builds up under a supercontinent because the rocks in the continental crust are bad heat conductors. A dome rises under the supercontinent soon after the high temperatures cause the base of the lithosphere to disappear. Thus, the basaltic magma rises from the bottom filling the fractures, which results in the dispersion of the continental masses from the opening of a new ocean (WICANDER & MONROE 2009).

The continents and seas are in constant changes, which modify the characteristics and shape of the Earth's surface. The opening-up of oceans forms ridges, the subduction occurs consuming the oceanic crusts, the magmatism subjects oceans, the accretion, fragmentation, and agglutination generate mountain ranges. These processes, which result from plate tectonics, condition the evolution of supercontinents (HASUI, 2012a).

This manuscript aims to present the stages associated with the supercontinents cycle in northeastern Brazil, explaining the most significant events and their structural impacts in an understandable and useful perspective. In particular, it details the morpho-structural situation resulting from these processes in northwestern Ceará.

Material and Methods

This manuscript is the result of scientific research carried out through desk work – involving a thorough literature review of the geological evolution of northeastern Brazil – laboratory and fieldwork. The data compilation was a form of promoting the paleogeographic reconstruction of the continents. It also assisted in measuring both geological and geomorphological impacts of the supercontinents cycle on the northeastern region.

The laboratory stage involved a GIS environment, which was useful to develop the hypsometric, location, and geological maps. The hypsometric/localization map is an outcome of QGIS 3.4 from the SRTM radar raster database (SHUTTLE RADAR TOPOGRAPHY MISSION) with 30 m spatial resolution. The image superimposed on the cartographic base – developed in 2003 by the Brazilian Research and Mineral Resources Company (CPRM) – was useful to extract shear zones (Trans-Brazilian Lineament and Café-Ipueiras Fault). QGIS 3.4 carried out the thematic mapping on the work scale 1/100,000.

The geological map had the CPRM (2003) cartographic base as the starting point on a scale of 1/100,000 using QGIS 3.4. The grouping of chrono-correlated geological units, linked in an analogous way to events of a tectonic-structural-depositional nature, helped to produce a simplified geology map. The SRTM image with a spatial resolution of 30 m contributed to generate a relief shading superimposed on the geological units of northwestern Ceará.

The fieldwork (between 2018 and 2019) supported the recognition of the area reality, allowing a better interpretation of the morpho-structural conditioning. It contributed in a fundamental way to the understanding of the processes apprehended during the literature review stage.

The supercontinents cycle and the splitting of Gondwana/Pangaea

Rogers (1996) suggests that the first episodes of continental agglutination occurred around three continents: 1) Ur, formed by random accretion of small cratons and continental blocks around 3.0 Ga, gathering nuclei from South Africa, India, Australia, and Antarctica; 2) Arctica, whose origin would be associated with orogens and subductions occurred about 2.5 Ga, being constituted by sectors of North America, Siberia and Greenland, Northern Australia and China; 3) Atlantida, formed around 2.25-2.05 Ga, covering portions of South America and Africa (Figure 01).

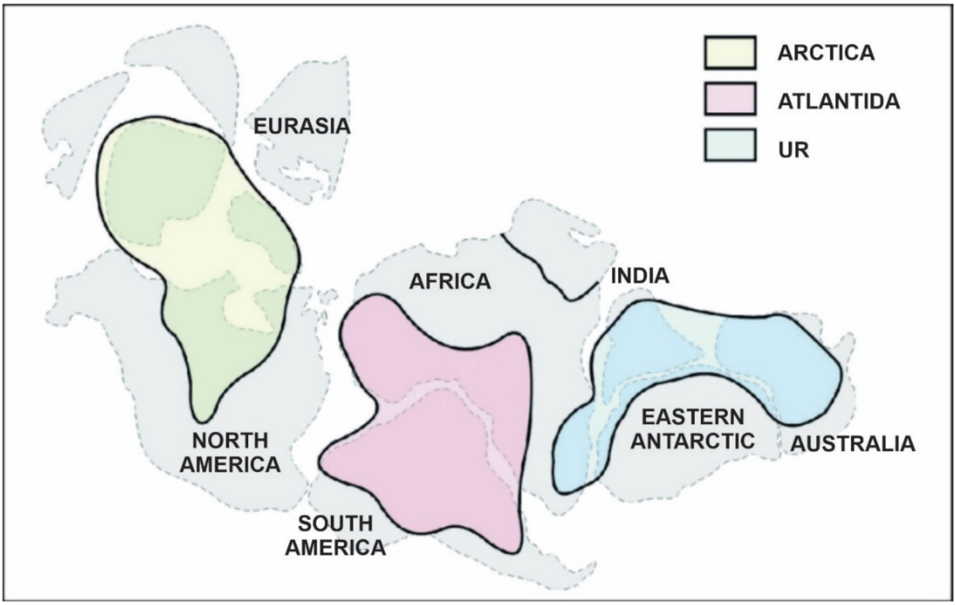

Figure 01: Spatial distribution of Ur, Atlantida, and Arctica.
Source: Schobbenhaus & Brito Neves (2003). Adapted from Rogers (1996).

These collisions took place at the beginning of the Proterozoic Eon as part of the Transamazonian Orogeny (Atlantida) in South America and Eburnean Orogeny in West Africa, which correspond to the Atlantida, which 54% of the land is Proterozoic, whereas 35% are Archaean (SATO & SIGA JR; 2000, TEXEIRA, 2007; CLAUDINO-SALES, 2016). The amalgamation of the Atlantida continent occurred about 2.2 Ga. This orogenetic cycle corresponds to a series of colisions between continent (PASTOR-GALAN et al. 2018).

Rogers & Santosh (2002) argue a continental collision among Ur, Atlantida and Arctica between the end of the Paleoproterozoic Era and the beginning of the Mesoproterozoic Era (around 1.9 Ga). The agglutination of continental mass promoted the formation of Columbia, whose outlines are rifts and mountain ranges. Besides, the rupture of India developed cracks that ended up in general clustering and extension of continental blocks from 1.6 to 1.4 Ga (NANCE & MURPHY, 2018). Figure 02 shows the Columbia continental mass.

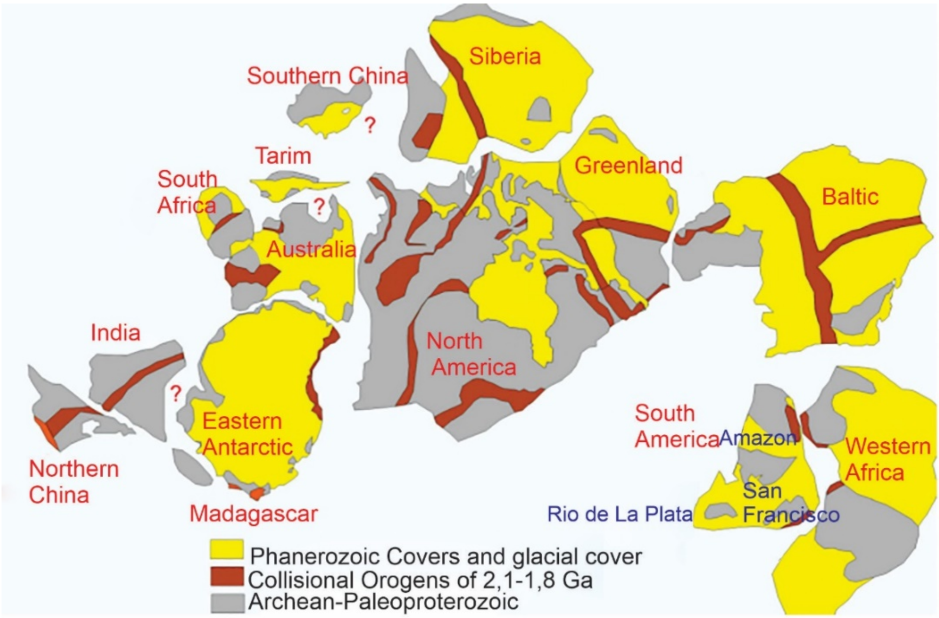

Figure 02: Columbia.
Source: Hasui (2012a). Adapted by Zhao (2004).

However, during the collage of Columbia, Atlantida was already undergoing a splitting process between 1.8 and 1.6 Ga into new continental blocks and oceans. Going on with the Wilson Cycle, there was the division of Columbia. After its fission, the geological history indicates the occurrence of a second continental mega-agglutination responsible for the formation of supercontinent Rodinia between 1.1 and 1.0 Ga. Thus, Rodinia (Figure 03) would have been born because of the addition of Atlantida as a result of the two phases of convergence and the expansion of Ur during the Grenville event (TOLLO, 2005; RIVERS, 2009; HASUI, 2012; NANCE & MURPHY, 2018).

Figure 03: Rodinia. Source: Hasui (2012a). Adapted from Li (2008).

Rodinia remained intact until about 850 Ma when it began to fragment, with maximum dispersion taking place around 750-700 Ma. The fragmentation of Rodinia resulted in continental blocks called East Gondwana, West Gondwana, Laurentia (LI, 2008; ERNST, 2009; LIU, 2019). The continental masses of Brazil from the fragmentation of Rodinia are the ones: Amazonian Cratons and San Luís (connected with West Africa), San Francisco (connection with the Congolese Craton) and Paraná–Rio da Prata–Paranapanema (HASUI, 2010, 2012a).

In the sequence, the fusion of Gondwana demarcates the events of the Brasilian Orogeny in the Brazilian Northeast. The Brasilian Orogeny corresponds to the 3rd episode of continental agglutination of the Wilson Cycle, having been responsible for the structuring of the geological-tectonic framework of the Borborema Province, which represents the large part of the Brazilian Northeast region. (BRITO NEVES & CORDANI, 1991; BRITO NEVES, 1999; CORDANI, 2013).

According to Arthaud (2015), the Brasiliana Orogeny resulted from the collision between the San Luís/West Africa and San Francisco/Congo cratons, where the apex of the deformation and metamorphization processes occurred around 600 Ma. This Neoproterozoic collage implied the formation of a mountain range within the Borborema Province – the so-called Brasiliana Mountain Range (BRITO NEVES, 1999).

The Brasiliana Collision Zone has its outlines at the base of the South American Platform and Borborema Province through an expressive SW-NE direction shear zone. The Transbrasiliano Lineament corresponds to one of the main suture zones that registers the amalgamation process of West Gondwana. It is in the Northwest of the Borborema Province, and its extension of continental margin go on in the crust of West Africa through the Kandi shear zones between the Dahomey Belt and the Transaharan Craton (BRITO NEVES & CORDANI, 1991; BRITO NEVES, 1999; CORDANI, 2013).

The existence of a tectonic strip formed by parallel ductile shear zones suggests that the Brasiliana faults came from a continental orogeny as a result of deformation at the margins of the ancient cratons. This fact indicates that the Transbrasiliano Lineament began to form when the first continental masses had already collided during the Brasiliana Orogeny (FUCK, 2013).

The eastern and western segments of Gondwana agglutinated with Laurentia and Baltic in a continental collision in the southern hemisphere to form the Pannotia mega continent (Figure 04) around 545 Ma (STUMP, 1987; POWELL., 1995; BRITO NEVES, 1999; TEXEIRA, 2007). This collision is still the subject of much controversy, but many authors consider the existence of a mega continent in this geological period (NANCE & MURPHY, 2018).

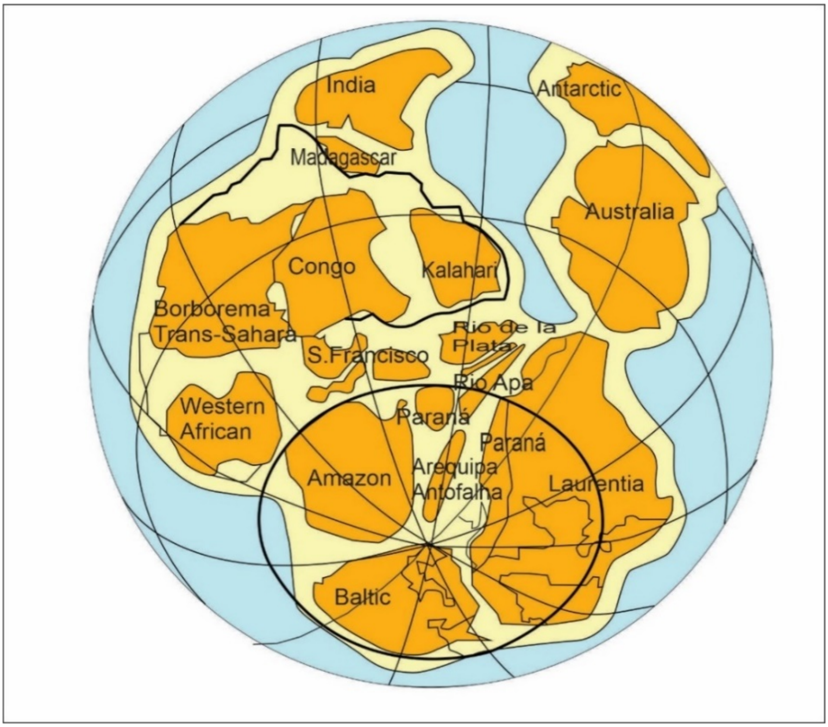

Figure 04: Pannotia.
Source: Hasui (2010). Modified by Cordani (2009).

The Pannotia mega-continent remained amalgamated for a short time (lasting around 30 Ma), fragmenting approximately 515 Ma into four continental masses, namely Laurentia, Baltic, Siberia, Southeast Asia, and Gondwana. Gondwana remains individualized as a supercontinent apart, corroborating for the Borborema Province long period of geological stability (BRITO NEVES, 1999; HASUI, 2010; CLAUDINO SALES, 2016).

During the Paleozoic Era, Gondwana wandered into agglutination with the Laurasia, at the same time as the collision between North America and Northwest Africa occurred (NANCE, 2014). The sequence of these events originated the supercontinent Pangea, which, surrounded by the Panthalassa, appeared in the Carboniferous around 320 Ma (ROGERS & SANTOSH, 2004; HASUI, 2012) (Figure 05). The Pangea last little time so that it undergoes the division process at the end of the Triassic and the beginning of the Jurassic.

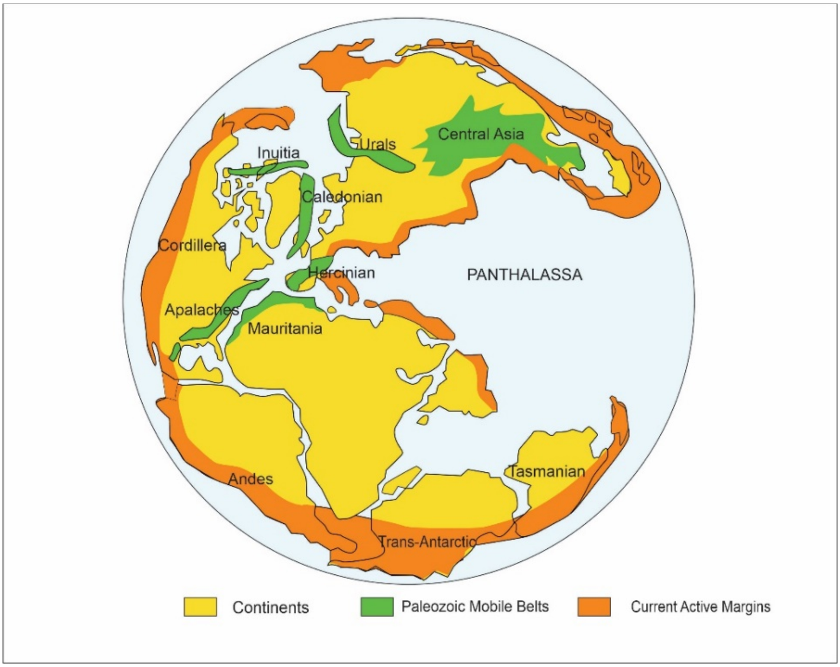

Figure 05: Pangea.
Source: Modified by Hasui (2010).

According to Carneiro (2012), the separation of Pangea occurs from the succession of three rifting stages, each one acting in different areas: 1) The first stage (Neo-Triassic-Cretaceous) affected mostly northern South America with the opening of the North Atlantic (making South America and Africa far from North America); 2) The second stage (Cretaceous-Pre-Aptian) occurred predominantly in southern South America and represents the opening of the South Atlantic (beginning of the separation of South America from Africa); 3) The third stage (Neo-Aptian-Cenomanian) marks the complete separation between South America and Africa (around 100 Ma) on the equatorial margin, whose boundaries are Patos and Pernambuco Lineaments.

Figures 6, 7 and 8 show a paleogeographic reconstruction of the different stages of division of the continent Pangea during the Mesozoic based on the work of Scotese and Golonka (1997), adapted in a 3D model through the program "Ancient Earth (2015): Breakup of Pangea", developed by Ian Webster:

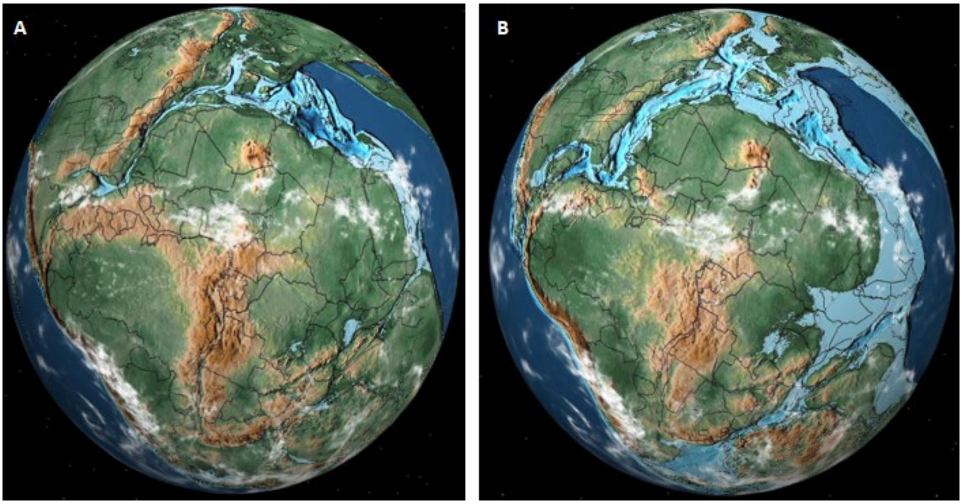

Figure 06: A) Opening of the North Atlantic between the end of the Triassic and the beginning of the Jurassic. B) Opening of the North Atlantic during the Middle Jurassic.
Source: Ancient Earth (2015), adapted from Scotese and Golonka (1997).

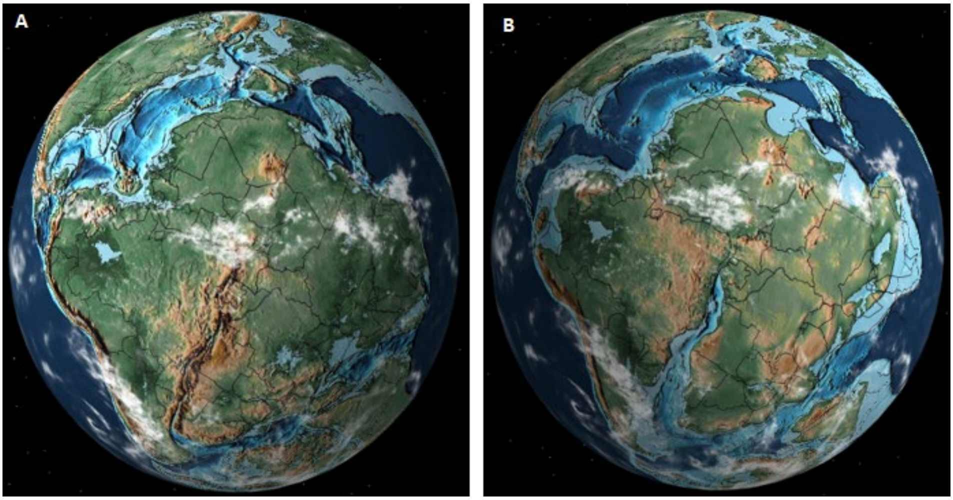

Figure 07: A) Individualization of the continents Laurasia to the North and Gondwana to the South in the Upper Jurassic. B) Opening of the South Atlantic during the Aptian.
Source: Ancient Earth (2015), adapted from Scotese and Golonka (1997).

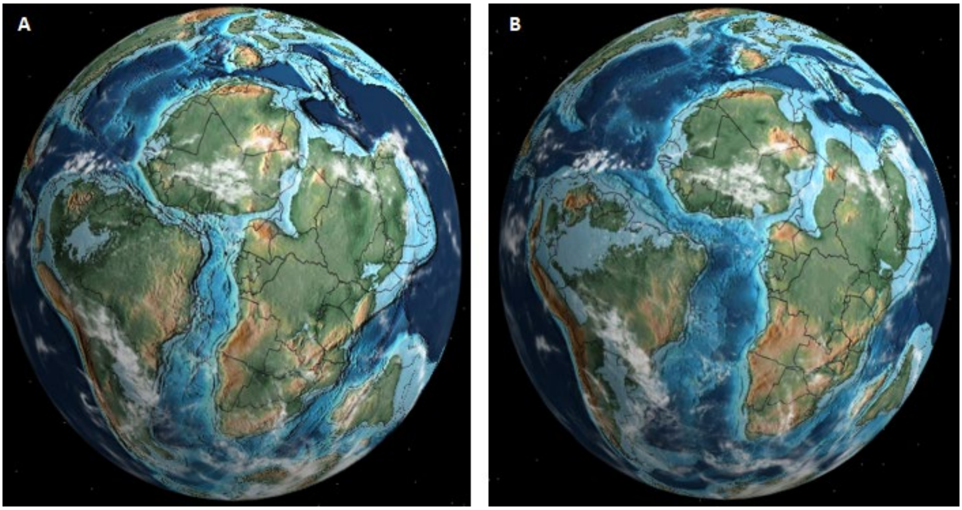

Figure 08: A) Opening of the Atlantic Equatorial Rim with the final separation between South America and Africa in the Albian/Cenomanian transition B) Individualization of the South American Platform from the Cenomanian. Source: Ancient Earth (2015), adapted from Scotese and Golonka (1997).

The splitting of Pangea in the Borborema Province: the formation of the Atlantic Equatorial Rim

The Brazilian equatorial margin includes the entire northern continental plataform of Brazil and its adjacent submerged portion, extending for about 1900 km. It covers the following basins: Potiguar, Ceará, San Luis/Bragança-Vizeu/Ilha Nova, Barreirinhas, Pará-Maranhão, Marajó and Caciporé/Foz do Amazonas. It comprises a segment of approximate WNW direction, which can be subdivided into smaller E-W and NW-SE sectors (ANTUNES, 2004) (Figure 09).

The Atlantic Equatorial Rim is a transforming tectonic margin that developed over a multi-phase, breaking, and distension process that involved the creation of multicyclic basins. It goes from classic rifts (orthogonal distension) preceded by basic magmatism (Jurassic, Cretaceous) to non-magmatic basins followed by the activation of transforming faults in the transtension state (Aptian-Albanian, in the Cretaceous) (ZALAN 2012).

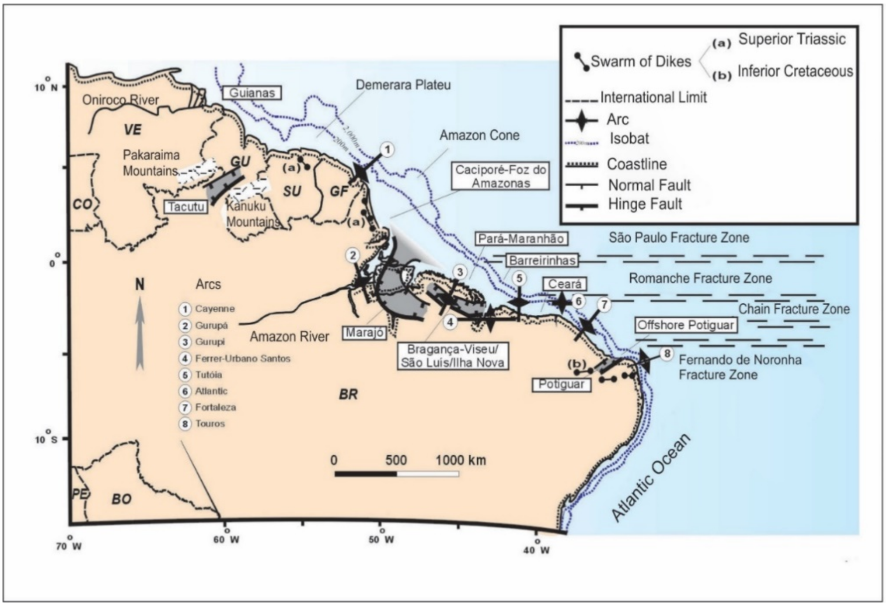

Figure 09: Atlantic Equatorial Rim.
Source: Moriak (2003), modified by Milani and Thomaz Filho (2000).

In the northeastern segment, the Atlantic Equatorial Rim is part of the Borborema Province (PEULVAST & CLAUDINO-SALES, 2004). The opening of intracontinental rifts, which formed the Cariri-Potiguar structural axis, and as documented by Matos (2000), occurred in 145-120 Ma, following the structure of the Brasiliana NE-SW and E-W shear zones.

The rift faillures occurred in the Barremian age between 120-115 Ma with the formation of the basins Potiguar, Araripe, Iguatu, Icó/Lima Campos, and Rio do Peixe. The depocenters for Mesozoic sedimentation have origins under transtension conditions from the reactivation of the shear zones, namely Senador Pompeu, Orós/Jaguaribe, Portalegre, and Patos (SHOBBENHAUS & BRITO NEVES, 2003).

The shear zones Patos and Senador Pompeu have continuity in Africa through the shear zones Garoua and Ile Ife, respectively. Besides, there is a connection between Northwest Borborema Province (CE) and West Africa through the Transbrasiliano/Kandi Lineament. (Figure 10) (CASTRO, 2012).

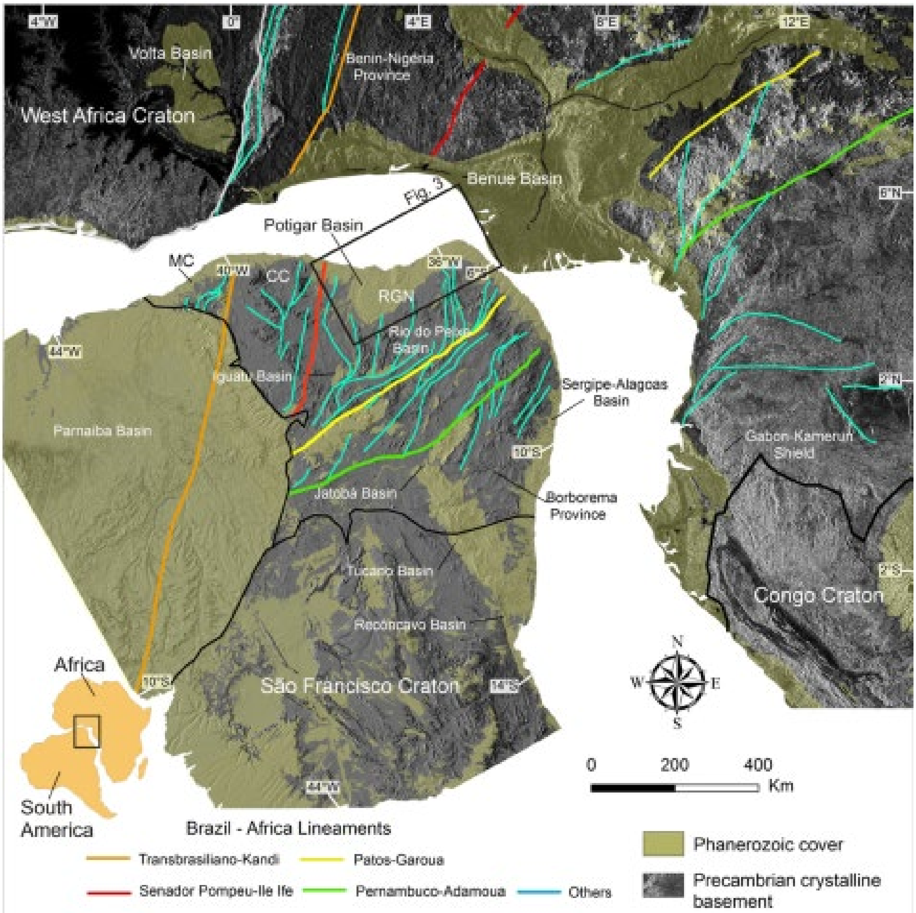

Figure 10: Continuity of the Brasiliana shear zones of Borborema Province in West Africa.
Source: Castro (2012).

The opening of the intracontinental rifts of the Potiguar-Cariri structural axis formed rift shoulders to the East (Borborema Massif) and the West (Ceará Central from the Structural Massifs Domain). It justifies the absence of rift shoulders and the inexistence of coastal mountains in the northeastern Brazil (CLAUDINO SALES, 2016).

In the Albian age, 20 million years after intracontinental rifting, the pole of the rotation from South America to Africa moved West to near the Oiapoque, so that rifting spread in a backstepping pattern, resulting in the opening of the Equatorial Atlantic (SZATMAR, 1987; MATOS, 2000; TRODSTORF JUNIOR, 2007). The continuity existing between the North-East and West Africa – the last segment of Gondwana – was responsible for stopping the drifting (CLAUDINO SALES, 2016).

Around 100 Ma, the transforming faults – with NE-SW distension and E-W shear – completed the separation (MATOS, 2000). In other words, with the rupture of Gondwana, the Atlantic Ocean was formed from a dextral lateral shear with E-W direction, evolving the region of the Borborema Province deformed by this division later to a passive tectonic margin (SZATMAR, 1987; MATOS, 2000; CASTRO, 2012; BASILE, 2015).

Morpho-structural factors of supercontinent cycles in northwestern Ceará

The northwestern Ceará – object of detailed analysis of this research (Figure 11) – presents high geological and morpho-structural complexity. The geological units in the area consist of Paleoproterozoic basis (Granja Complex and Saquinho Volcanic Unit), Neoproterozoic supra-crustal sequences (Martinópole and Ubajara Groups, Ceará Complex), Tamboril-Santa Quitéria Granitic Unit, Post-Orogenic Granitic Unit (Plúton Anil, Mucambo and Meruoca Unit). Paleozoic Jaibaras and Parnaíba Basins and Cenozoic sedimentary deposits (Figure 12).

In morpho-structural terms, eight outstanding events have acted on the evolution of the relief in the area, between the eastern edge of the Parnaíba sedimentary basin and the Ceará Central and Middle Coreaú domains (Northwest of Borborema Province):

1) The Transamazonian Orogeny (Atlantida) with the formation of the Granja Complex – constituted by gneiss, migmatite, granulite, and amphibolite. The (2.0 Ga) zircons obtained through the U-Pb method (SANTOS, 2001) suggest that the evolution of the primary granulite assembly results from pre-Brasiliano metamorphism. The Paleoproterozoic base is cut by the NE-SW and NW shear zones, in addition to the lateral positioning of rocks of different ages and metamorphic degrees expressed in the SE direction (VAUCHEZ, 1995);

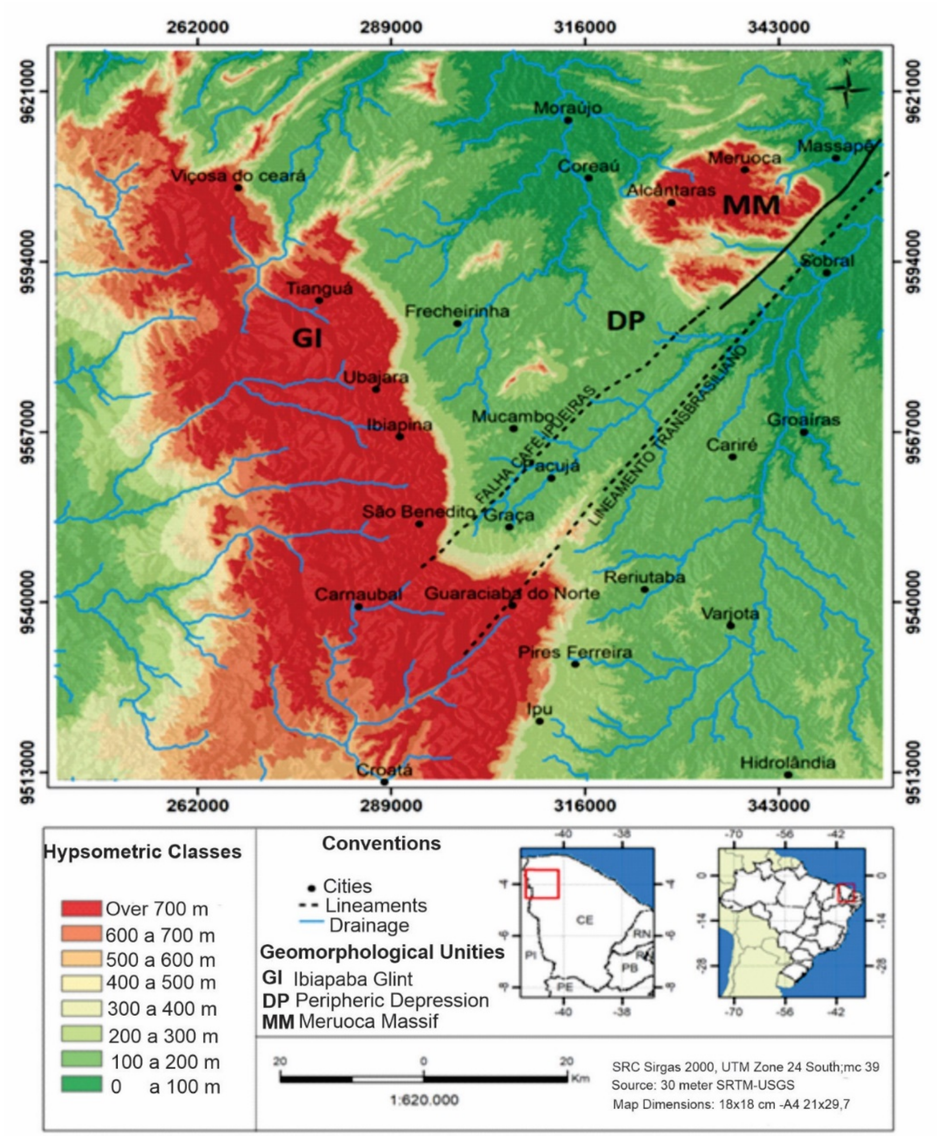

Figure 11: Relief and Hypsometry of the area. organized by the authors.

2) During the post- Transamazonian Orogeny (Atlantida) period, extensional events associated with the division of Atlantida/Columbia occur on the Paleoproterozoic base of the Middle Coreau Domain as part of the Saquinho volcanism (1.79 Ga U-Pb), responsible for the occurrence of intense magmatism and rifting (SANTOS, 2002, 2008).

It is a small individual klippe amidst the Neoproterozoic supra-crustal sequences from the Ubajara Group, whose composition is rhyolite, volcanoclastites, sandstone, metariolite, and metabasalt (HASUI, 2012b; CPRM, 2003).

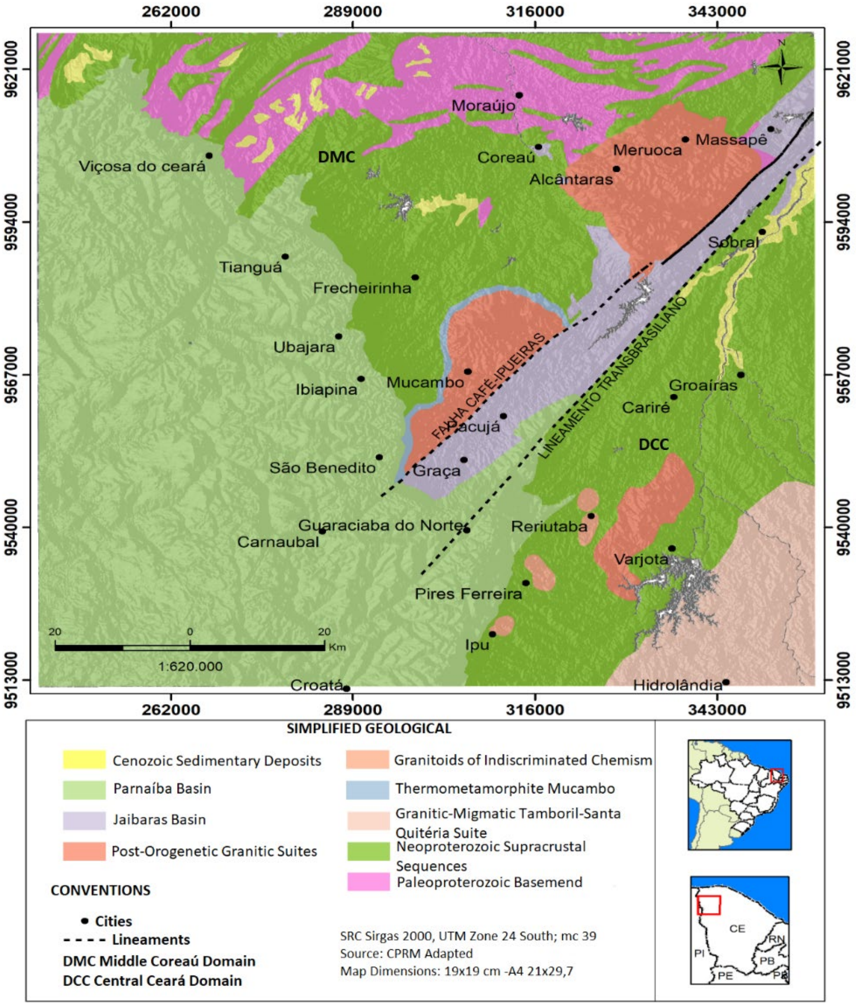

Figure 12: Simplified geological mapping units of Northwest Ceará. Cartographic base: CPRM (2003), organized by the authors.

3) West Africa-São Luis Craton division from the opening of an ocean basin between the Central and Middle Coreau domains. This event marks the rifting of the continent Rodinia in Borborema Province between 800-750 Ma. In the Central Ceará Domain occurred the deposition of Neoproterozoic supra-crustal sequences, belonging to

the Independência and Canindé units. They correspond to rocks metamorphized to a high degree. They are composed of gneiss, quartzite, schist, amphibolite, and meta-limestone. In the extreme Northwest of the Médio Coreau Domain were deposited the volcano-sedimentary back-arc sequences of the Martinópole Group under low energy environments. The formation composition is quartzite, schist, marble, and meta-rhyolite. (FETTER, 1997, 2003; CPRM, 2003; ARTHAUD, 2007; HASUI, 2012).

4) The Brasiliana orogeny (665-590). With the formation of the Tamboril-Santa Quitéria magmatic arc, the result was the crustal thickening by stacking thrust sheets resulting from a Himalayan orogeny, creating the Brasiliana Mountain Range due to the closure of small oceanic basins during the collage of West Gondwana. The stress fields suffered inversion to an oblique collision about 590 Ma ago, creating NNE-SSW direction dextral shear zones – like the Transbrasiliano Lineament, which demarcates the suture zone of this collision in the Borborema Province. The deposition of supra-crustal sequences of the Ubajara Group also occurs, presenting contractional and strike-slip structures with low metamorphic rocks, linked to the Brasiliana Orogeny (BRTTO NEVES, 1999; FUCK, 2013; ARTHAUD, 2015; SOUZA, 2018).

5) Post-Brasiliana Orogeny period. Simultaneous post-tectonic extensional episodes occurred in the Transbrasiliano-Kandi tectonic strip (CORDANI, 2013) with the intrusion of granite (570-530 Ma) from the tectonic collapse of the Brasiliana Mountain Range and the formation of Jaibaras Basin. The implementation of the Parnaíba Syneclise (Neoprotezoic-Paleozoic) occurs from the Paleozoic rifting (CASTRO, 2014) associated with the division of the Pannotia mega-continent (CLAUDINO-SALES, 2016), which produced ample subsidence in the Northern and Northern East (CLAUDINO-SALES, 2018). The intrusion of granitoid formed the Anil granitic suite, in the southeast of the Transbrasiliano Lineament (Ceará Central Domain), Meruoca and Mucambo (Médio Coreaú Domain). The last two suites are aligned to the Northeast by the Café-Ipueiras fault, demonstrating the control of the shear zones in the lodging of post-orogenic granitic magmas. These events represent the transition stage between the most significant tectonic phase and the subsequent stabilization of the continental crust (OLIVEIRA, 2001; SANTOS, 2008; PEDROSA JR, 2016).

6) Stabilization of the South American Platform with the deposition of the Paleozoic Serra Grande Formation sandstones during the first marine incursion of the Parnaíba Basin. It corresponds to the wandering period of the supercontinent Gondwana, which did not split into the Pannotia division. The Serra Grande Group subdivides itself from its base by the Ipú, Tianguá, and Jaicós formations (VAZ, 2007). This event relates to the Hirnantian, a global episode of about 2 Ma, during the Ordovician-Silurian transition, well documented in other Gondwana basins in Africa (ASSIS, 2019). The Ipú Formation had its deposit process around 440 Ma under conditions of proximal glacial and glacial-fluvial nature and alluvial fans or deltas. The Tianguá Formation, in turn, had a deposit process in a shallow marine environment during the maximum extension phase of global glacial and eustatic transgression, followed by ice melting in North Africa. The Jaicós Formation underwent the deposit process by interlaced and deltaic systems in the continental, transitional, and shallow marine environment during the Neosilurian and

Eodevonian. In general, sandstone, conglomerate, shale, and sandy siltstone prevail (OLIVEIRA & MORIAK, 2003; GOES & FEIJÓ, 1994; VAZ, 2007).

7) Intracontinental rifting (Cariri-Potiguar Fold), followed by the opening of the Equatorial Atlantic in the Cretaceous, from the fission of Pangea/Gondwana under a transforming/transcurrent regime conditioning the reactivation of the Brazilian shear zones NE-SW (MATOS, 2000; CASTRO, 2012). The Transbrasiliano Lineament reactivation due to transpressive stresses uplifted the Eastern edge of the Parnaíba Basin, generating the Ibiapaba Plateau (PEULVAST & CLAUDINO-SALES, 2004). The drainage structure promoted the dissection of the basin front, modeling a glint due to the resistance of the rocks of the Serra Grande Group concerning the crystalline base. The minimum strength of the basement produced a significant removal of the pre-Cambrian rocks, leaving the Serra Grande Group in sharp relief (CLAUDINO-SALES, 2016, 2018). The reactivation of the Café-Ipueiras Fault and the exhumation of Mucambo and Meruoca suites formed the crystalline massifs Serra do Carnutin and Serra da Meruoca, respectively (PEULVAST & CLAUDINO SALES, 2006). The erosive resumption promoted the formation of triangular facets on cliffs inherited from faults of the Meruoca Massif.

8) Flexural uplifting inside the continent in response to sediment overload in the platform from the Upper Cretaceous to the Cenozoic. Climatic variations (Cenozoic), alternating between the humid and semiarid climates (CLAUDINO SALES, 2018). Intra-plate tectonism is responsible for the uplifting and exhumation of structural massifs (MAIA & BEZERRA, 2014). Neotectonics promoted pulses of crustal reactivation in the northern escarpments of the Meruoca Massif with transcurrent dextral rejects in the Café-Ipueiras Fault (PEULVAST & CLAUDINO SALES, 2006). The semiarid conditions promoted the elaboration of the Sertaneja planation surfaces from the dismantling and retreat of Ibiapaba Plateau, developing a subsequent peripheral depression (SOUZA 2000). The relief is a glint – Ibiapaba Glint – formed due to the weak resistance of the pre-Cambrian rocks, leaving the Paleozoic sedimentary rocks in the rebound. Subsequently, correlative colluvium (Neogene Quaternary) and alluvium (Quaternary) occurred (CLAUDINO SALES, 2016; CLAUDINO SALES & LIRA, 2011). The remontant erosion produced dissecation in the cliffs of the Ibiapaba plateau and inselbergs in the area of the peripheral depression since rivers section the opening of the valleys in the opposite direction of the sedimentary layers. The topographic rupture is above 700 m, favoring the occurrence of orographic rains with rainfall averages higher than the semiarid backcountry depressions, demonstrating the role of the plateau as the center of origin of the rivers that drain towards the Coreaú and Acaraú river basins, in northwest Ceará (SANTOS & NASCIMENTO, 2017). The topographic exposure of the quartzite in São Joaquim (Martinópole Group) and Trapiá (Ubajara Group) formations reflects the resistance of these lithologies to the selective work of differential erosion under predominantly semiarid conditions.

Nowadays, the whole analyzed area slowly evolves from the dominant action of physical morphogenesis controlled by the existence of the semiarid climate. Also worth mentioning are the social activities, which alter, above all, the highest regions of the Meruoca Massif and Ibiapaba Glint, resulting in a significant alteration of the superficial formations and considerable environmental modifications, in particular the flora and climate.

Final considerations

The analysis of the Wilson Cycle – performed to the Northwest region of the State of Ceará – indicates that practically all the tectonic events associated with the fusion and fission stages of the four mega-continents that the geological history records, impacted the Northwest of the State of Ceará.

Nevertheless, the most relevant morpho-structural constraints of the geomorphological landscape of the area of analysis are (1) the Atlantida orogeny (2.2 Ga), represented by the rocks of the Paleoproterozoic base; (2) the Brasiliana orogeny (Neoproterozoic), which defined the Transbrasiliano Lineament and the shear zones of NW-SE and E-W directions that control the drainage network and the installation of the Brasiliana granites that support part of the reliefs, and; (3) the Cretaceous division of Pangaea, which caused the uplifting of the regional surface and the exhumation of the Brasiliana granites.

The current morpho-structural organization seems to have changed little since the Cretaceous episodes of Gondwana's division. However, the morpho-structural devices have undergone relocation by tectonic (marginal flexure) and erosive (associated with climatic changes, sea level changes and accumulation of sediments on pre-Cambrian rocks) activities.

In the Cenozoic era, the differential erosion commanded by dry climates (PEULVAST & CLAUDINO-SALES, 2004) represents a relevant factor. Since it explored the elements of the pre-existing structural mesh, generating topographic bumps (such as the Ibiapaba Glint) and a denudation surface (the depression peripheral to the Glint). Nowadays, dry climates continue to act, resulting in a slow erosive process. The use and occupation of the area are promoting more relevant changes than the natural erosive process.

The literature on mega-geomorphology in northwestern Ceará State is scarce (CLAUDINO-SALES and LIRA, 2011) concerning the stages of plate tectonics and the cycle of supercontinents in the genesis and evolution of reliefs. In future researches, other sectors of the Borborema Province will be analyzed from continental mergers and fissions and resulting morpho-structural elements.

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Acknowledgment: *Thanks to the Graduate Program in Geography of UFC and to Capes for the granting of the Ph.D. scholarship for research funding.*

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Received for publication December 2020
Approved for publication April 2020