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The graphite mineralization in the Aracoiába-Baturité District (CE): geotectonic and metallogenetic implications

As mineralizações de grafita do Distrito de Aracoiába-Baturité (CE): implicações geotectônicas e metalogenéticas

Paulo Roberto Pizarro Fragomeni[1], Ronaldo Mello Pereira[2]*

ABSTRACT: In the Aracoiába-Baturité region, the Baturité Subunit (Ceará Group) was divided into Baturité I and II domains. The Baturité I Domain comprises a supracrustal sequence, formed in an environment corresponding to a continental slope, overlying Paleoproterozoic rocks of the Gneissic-Migmatitic Complex. The graphite bearing aluminous gneisses associated with the Baturité I Domain were compared with those found in Khondalite belts from different parts of the world. The Baturité II Domain was formed in the foot of a slope-abyssal plain facies of a deep sea, and is associated with ortho-amphibolites and metaturbidites. Occurrences of graphite are distributed from Aracoiába to Canindé region, following the Baturité Subunit, defining an important regional metallotect. Graphite deposits are of two types: graphite gneiss (disseminated graphite) and veins (massive graphite) and have different genetic origins (epigenetic and syngenetic). $\delta^{13}C$ values between -30 and -20% indicate that graphite is derived from organic matter. The epigenetic mineralization is found in the vicinity of Pedra Aguda plutonic body (Pedra Aguda Gabbro-Diorite Complex) within a maximum distance of 2.5 km. The graphitic belt of the Aracoiába-Baturité District was regarded as a remnant of a subduction zone/suture zone derived from the process of closing of an ancient ocean with the consequent gluing of two continental micro-cratons (Baturité Block in the north and Caio Prado Block in the south) during the Brazilian orogeny.

KEYWORDS: epigenetic and syngenetic graphite; suture zone; Aracoiába-Baturité District.

RESUMO: *Na região de Aracoiába-Baturité, a subunidade Baturité (Grupo Ceará) foi dividida em domínios Baturité I e II. O Domínio Baturité I compreende uma sequência supracrustal paraderivada, formada em ambiente correspondente à zona de talude continental, sobreposta a rochas ortoderivadas paleoproterozoicas do Complexo Gnáissico-Migmatítico. Os gnaisses aluminosos portadores de grafita associados ao Domínio Baturité I foram comparados aos tipos encontrados nos cinturões khondalíticos de diversas partes do mundo. O Domínio II apresenta ortoanfibolitos e metaturbiditos, tendo estas rochas sido formadas em zona de sopé de talude-planície abissal em fácies de mar profundo. As ocorrências de grafita dispõem-se desde Aracoiába até a região de Canindé, acompanhando a Subunidade Baturité, que representa um importante metalotecto regional. Os depósitos de grafita são do tipo grafita disseminada e maciça, as quais estão, respectivamente, associadas a gnaisse grafitoso (tipo disseminado) e a veios (tipo maciço) e apresentam diferentes origens genéticas (singenética e epigenética). Valores de δ13C entre -30 e -20% indicam que a grafita é derivada de matéria orgânica. As mineralizações epigenéticas são encontradas no entorno do plúton de Pedra Aguda (Complexo Gabro-Diorítico Anelar de Pedra Aguda) a uma distância máxima do corpo de 2,5 km. A faixa grafitosa do Distrito de Aracoiába-Baturité foi considerada como um remanescente de uma zona de subducção/zona de sutura derivada do processo de fechamento de um antigo oceano com a consequente colagem continental de dois microcrátons (bloco Baturité a norte e bloco Caio Prado a sul) durante a orogenia Brasiliana.*

PALAVRAS-CHAVE: *grafita epigenética e singenética; zona de sutura; Distrito de Aracoiába-Baturité.*

[1]Programa de Pós-Graduação em Análise de Bacias e Faixas Móveis, Faculdade de Geologia, Universidade do Estado do Rio de Janeiro - UERJ, Rio de Janeiro (RJ); Santa Fé Mineração Ltda., Rio de Janeiro (RJ), Brazil. *E-mail: fragomeni@santafeminer.com.br*

[2]Faculdade de Geologia, Universidade do Estado do Rio de Janeiro - UERJ, Rio de Janeiro (RJ), Brasil. *E-mail: rmellouerj@hotmail.com; ronaldo.mello@pq.cnpq.br*

*Corresponding author

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INTRODUCTION

The occurrences of graphite in the Aracoiába-Baturité District are known since the late forties, the period of the Second World War, when there was an intense demand for this mineral to supply the allied war industry for use primarily as a lubricant for treadmills (caterpillars) of war tanks and combat cars. In Fazenda da Laje, near the village of Pedra Branca, Ceará State, there are still traces of excavations in deposits consisting of massive veins of graphite and a rudimentary ore processing plant, built by British researchers. After the Second World War (1939 – 1945), these occurrences did not arise the interests of mining companies until 2004, when large ore deposits of disseminated graphite were identified through systematic surveys conducted by mining companies. The mineral exploration allowed the blocking of reserves in excess of 1.8 million tons of graphite ore in this graphitic district.

The importance of graphite in the current industry worldwide relates to the enormous growth of its use in batteries for cell phones and other portable electronics, besides production of hybrid cars and fuel cells for the revolutionary use of hydrogen as fuel.

This work results from the study of the occurrences of graphite in the Northeastern part of the State of Ceará, Brazil, especially those found in the municipalities of Aracoiába and Baturité. The main objective was to present the geological characteristics of mineralization and to suggest a geotectonic-metallogenetic model regarding its formation.

Regional geologic context

The Aracoiába-Baturité District is inserted in the northern portion of the Borborema Neoproterozoic Tectonic province, more specifically in the Central Ceará Domain (Arthaud 2007, Fetter *et al.* 2003). The term "Borborema Province" (Almeida *et al.* 1977) comprises the Eastern South American Platform formed by a complex mosaic of independent Domains in fold belts separated by extensive crustal shear zones. This province suffered a complex polycyclic geological evolution, which represents the cumulative result of a series of continental orogenies, initiated in the Archean and finished in the Neoproterozoic Era. This region has been extensively studied — Braga *et al*. (1977), Gomes *et al*. (1981), Cavalcante *et al*. (1983), Alves (1984), Brandão (1995), Bizzi *et al*. (2001), Cavalcante *et al*. (2003) —, being the work of Torres *et al*. (2005, 2006), Arthaud (2007) and Fetter *et al*. (2003), just to mention some of the more recent papers.

In the current configuration, the province consists of a bundle of subvertical regional lineaments, occurring in metasedimentary supracrustal rocks and in the basement, and a continent-wide network of ductile transcurrent zones. This configuration was formed at the end of the Brazilian/Pan-African orogeny (between 660 and 570 Ma), within a continental plate to accommodate the strain imposed by the collision of São Luis-East Africa and São Francisco cratons in the context of amalgamation of Western Gondwana (Arthaud 2007).

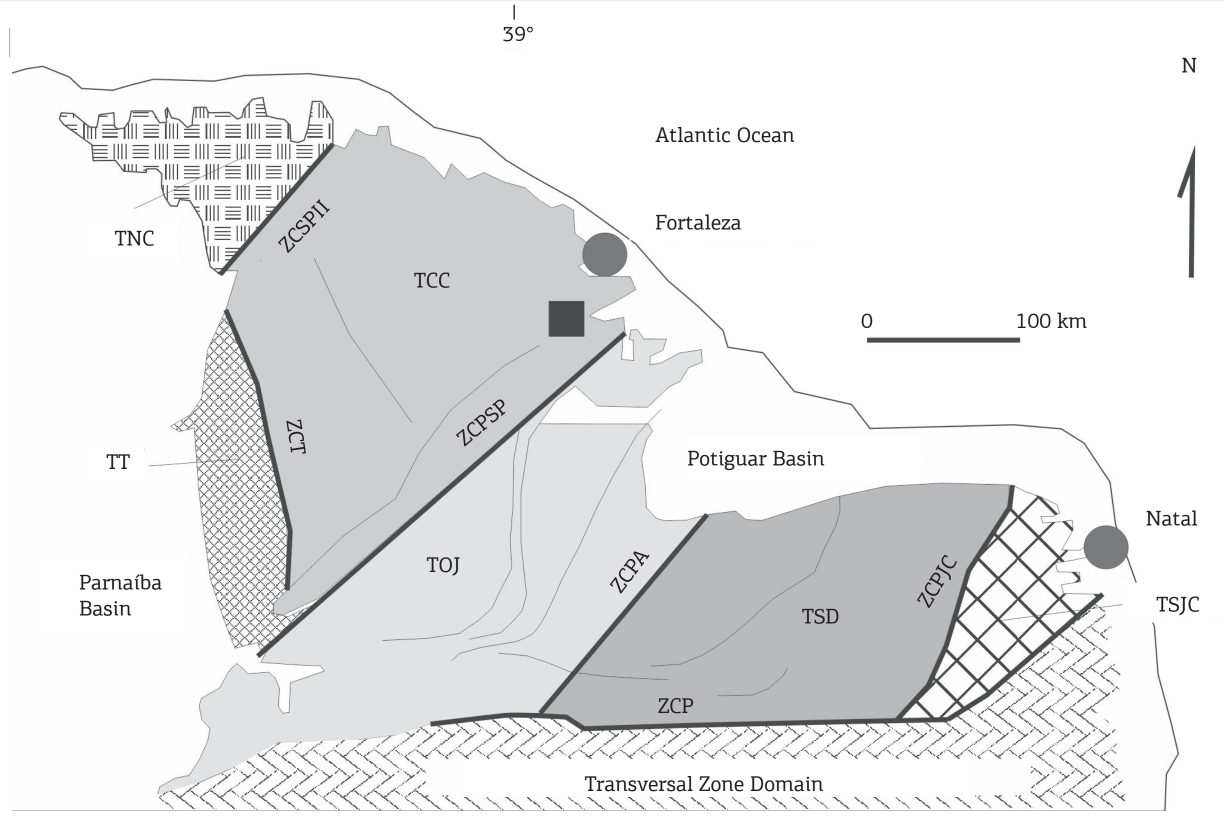
Campelo (1999), based on geological and gravimetric data integration, adopted the concept of "terranes", rather than "Domains", as proposed by Brito Neves *et al.* (2000), for the division of the limits of tectonostratigraphic terranes belonged to the Northern Borborema Subprovince. The subdivision proposed by Campelo (1999) for this Subprovince points out the possible limits of tectonostratigraphic terranes as being provided by shear zones like Patos (ZCP), Sobral-Pedro II (ZCSPII), Picuí-João Câmara (ZCPJ), Remígio-Pocinhos (ZCRP), Senador Pompeu (ZCSP), Tauá (ZCT) and Portalegre (ZCPA). The author recognizes — from West to East — the following terranes: North-West of Ceará, Central Ceará, Tauá, Orós-Jaguaribe, Seridó and São José do Campestre (Fig. 1).

The Aracoiába-Baturité Graphitic District is part of the Northern Borborema Subprovince of Central Ceará Terrane (TCC) according to Campelo (1999). The Central Ceará Terrane (TCC) consists mainly of a Paleoproterozoic basement with an Archean core (Tróia-Pedra Branca Massif) and an extensive Neoproterozoic coverage. The predominant tectonics is tangential, materialized by a complex stack of nappes of varying ages, followed by an intense transcurrent tectonic, whose structural records are represented by four large shear zones: Sobral-Pedro II, Senador Pompeu, Tauá and Rio Groaíras.

Fetter (1999), based on a geochronological study using the whole rock Sm-Nd methods and U-Pb in zircon, subdivided the TCC in four tectonic groups that correspond to an Archean core, Paleoproterozoic accretionary terranes, the Neoproterozoic supracrustal sequence of the Ceará Group and the Tamboril-Santa Quitéria Complex, besides a series of granitic plutons related to the Brazilian orogeny.

The Paleoproterozoic accretionary terranes are represented by four large assemblies of rocks called Gneissic-Migmatitic Complex, Madalena Suite, Algodões Unit (Martins *et al*. 1998) and Orós-Jaguaribe Belt (Arthaud 2007).

In the Neoproterozoic Supracrustal Sequence (Ceará Group), in which the TCC tectonically covers the Paleoproterozoic deformed and metamorphosed rocks, there is metapelite predominance, with narrow layers of quartzite, marbles and calcsilicate rocks. In the NE sector of the TCC, the supracrustal sequence is represented



TNC: Northwest Terrane of Ceará; TCC: Central Ceará Terrane; TOJ: Orós-Jaguaribe Terrane; TSD: Seridó Terrane; TSJC: São João Campestre Terrane; TT: Tauá Terrane; ZC: shear zone; ZCSPII: Sobral-Pedro II; ZCSP: Senador Pompeu; ZCP: Patos; ZCT: Tauá; ZCPJC: Picuí-João Câmara; ZCPA: Portalegre.

Figure 1. Location of Aracoiába-Baturité region and the division in tectonostratigraphic terranes of the Northern Borborema Subprovince, based on geological and geophysical data integration (Campelo 1999).

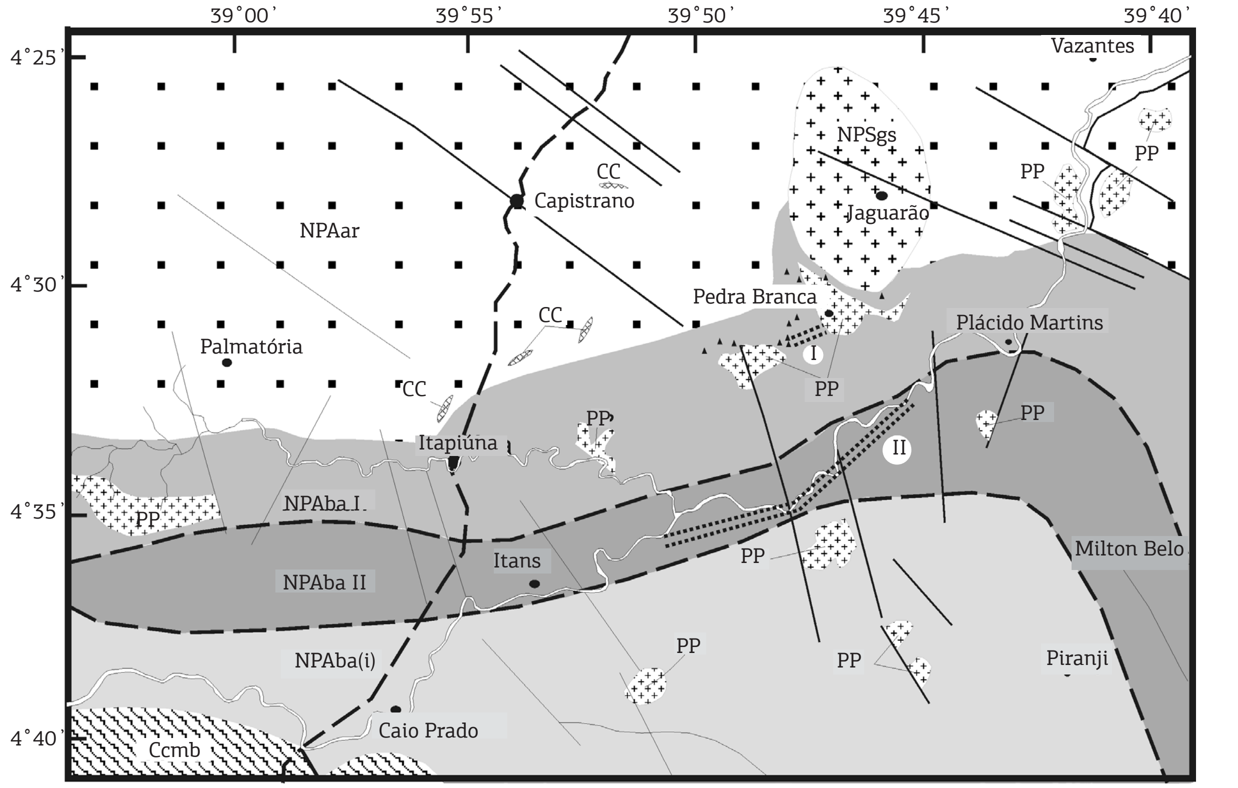
by metasedimentary rocks, with some inter-layered occurrences of metavolcanic rocks, mainly amphibolites, which were named by Torres *et al.* (2006) as the Acarápe Sequence. Two subunits were individualized (Aracoiába and Baturité), which, for that authors, are not considered as two distinct lithostratigraphic sequences; therefore, they present no significant erosive or tectono-metamorphic divergence.

For Torres *et al.* (2006), the Aracoiába Subunit paragneiss contains lenticular intercalations of marbles and quartzites, besides metapelite, calcsilicate, metadacitic and meta-trachyandesite rocks and represents lithotypes generated in shallow marine shelf environment. The Baturité Subunit, consisting of metasedimentary rocks (metapelites with centimetric alternances of metapsammites and metarhythmites, with beds of quartzite, amphibolites, metagabbros and metapyroxenites), corresponds — in the paleogeography of the Acarápe sequence — to the deepest ocean facies.

Geochronological studies carried out in metasedimentary rocks of Acarápe, whose Sm-Nd model ages (T_{DM}) range between 0.94 and 2.21 Ga, point to sources with distinct origins, Paleoproterozoic and Neoproterozoic (Torres *et al.* 2006). A metarhyolite interstratified into metapelite, with U-Pb zircon age of 0.77 ± 0.03 Ga, was considered by Fetter (1999) as a possible representative of the earliest rift formed before the opening of the oceanic basin and subsequently closed during the Brazilian orogeny.

Geologic context of the Aracoiába-Baturité District

The mapped area has about 1,000 km^2 (Fig. 2), at the scale of 1:250,000. It was made in the Seventies by the Fortaleza Project Team (Braga *et al.* 1977). This area is located in the Northeastern portion of the Central Ceará Terrane and is basically composed by five lithostratigraphic units: Mombaça Unit of the Cruzeta Complex, Paleoproterozoic Basement, Metavolcanic-Sedimentary Supracrustal Sequence, grey granitic rocks of the Late to Post-Orogenic Granitic Supersuite (late Neoproterozoic) and the Gabbro-Diorite Complex of the Post-Orogenic Gabbroid Suite.



NPSgs: Gabbroid Suite; NPAar: Acarápe Sequence, Aracoiába Subunit; NPAba I: Acarápe Sequence, Baturité Subunit, Domain I; NPAba II: Acarápe Sequence, Baturité Subunit, Domain II; NPAba(i): Acarápe Sequence, undivided Baturité Subunit I; PP: Paleoproterozoic basement; CC: marble; Ccmb: Mombaça Unit of Cruzeta Complex; Graphite gneiss belt: I – with subordinate calcsilicate rocks; II – interstratified with ortho-amphibolites.

Figure 2. Geological map of the Aracoiába-Baturité District (Fragomeni 2011).

The Mombaça Unit (Cruzeta Complex) is represented by granite and granodiorite gneiss and migmatites, usually of gray color, and occupies a small portion of the area, in the Southwest corner. In the area, the Cruzeta Complex is bordered by metasedimentary rocks of the Ceará Complex, being interpreted as early Archean proto-craton, limited by a Neoproterozoic collisional belt formed by rocks of the Ceará Complex. Meta-calcareous and calcsilicate rocks, as the remains of paraderived rocks, were described in the Cruzeta Complex (Oliveira & Cavalcanti 1993); however, these were not found in the area.

The Paleoproterozoic Accretionary Terranes occur in erosive windows isolated in the Ceará Group and distributed preferentially in the ENE direction. This unit consists of migmatites, granulites (enderbite gneiss), metanorites, orthogneiss and schists derived from basic protoliths. Structurally positioned in antiform cores, it is usually associated with the thrusting fault zones and presents complex structure with dome-and-basin and boomerang-type interference figures.

The migmatites, prevalent in this unit, are homogeneous with a broad field of Neosome on the Paleosome, and are generally of metatexite facies, keeping as characteristic planar elements, and also displaying folded, flebitic, stromatic and dominant schollen structures. Outcrops of this unit are exposed in the Lajes de Pedras creek near Pedra Branca village dam. Leucocratic rocks are usually light grey, with fine to medium grain size and texture ranging from granular-oriented to thin gneissic. The Neosome has granitic to granodiorite composition, locally presents coarse grained texture, with pegmatites and more rarely aplites. The Paleosome are usually schists mostly composed of biotites or amphibolites or represented by amphibole-biotite gneiss, as it can be observed in the access road to the headquarters of the Fazenda da Laje, near the village of Pedra Branca.

Also in the Fazenda da Laje area and the surroundings of Pedra Branca village, the dominant terms of this unit were classified as enderbite gneiss and metanorites. The first features dark gray color, medium-grained, banded structure, being characterized by the alternation of clear and discontinuous bands (1 to 5 mm) composed of plagioclase and quartz, and also discontinuous dark bands formed by biotite, pyroxene and opaque minerals. Its texture pattern is granolepidoblastic, with plagioclase mega-crystals surrounded by bundles of biotites whose orientation gives the rock a well-defined schistosity. It is composed of oligoclase-andesine (54%), biotite (15%) with reddish color and it is rich in Ti, quartz (20%), often forming clusters of granules, pyroxenes (10%) in anhedral and subhedral crystals, in addition to zircon and iron and titanium oxides (ilmenite and magnetite) as accessory minerals (1%). The ortho-pyroxene is represented by hypersthene. The metanorite has dark brown color, finely grained, foliated, showing whitish to yellowish plagioclase crystals (55%), dark brown to black hornblende crystals (20%), ortho-pyroxenes (8%) and reddish brown traces of biotite (14%). Garnet (2%), opaque minerals (1%), as well as traces of apatite and quartz are also recognized.

The orthogneiss is medium grain sized, light grey in color, leucocratic and foliated due to the biotite orientation. It has remnants of planar structures of schlieren, nebulitic type, as well as cataclastic in shear zones. The texture is granolepidoblastic, where the potassium feldspar occurs as a percentage equivalent to the plagioclase (oligoclase), associated with the xenomorphic quartz, with biotite in small bits and hornblende. As accessory minerals there are muscovite, sericite, zircon, apatite, chlorite and titanite.

In the Aracoiába-Baturité District, there are rocks of the two subunits of the Acarápe Sequence of Torres *et al.* (2006). The Aracoiába Subunit stands out for the presence of marble, quartzites and banded biotite gneisses. The marbles are pure, white, fine medium grained and form lenses which cover tens of meters in length and metric thickness; dolomites also occur. The quartzites occur in the form of lenses, with variable decimetric thickness, light beige in color. They are pure and laminated, with rare muscovite crystals.

The gneisses are banded (bands with 1 to 5 cm) and made of clear quartz-feldspar beds intercalated with bands of dark material constituted by quartz, feldspar, biotite, garnet and sillimanite. On the outskirts of the town of Capistrano, these gneisses, with centimetric quartzite beds, are intensely deformed, with isoclinal folds on a subhorizontal axial plan, and were interpreted as related to fronts of nappes.

In this work, and regarding the Baturité Subunit from Torres *et al.* (2006), two domains were recognized, informally called Baturité I and II.

The Baturité I Domain was individualized, based on the identification of a belt with its own characteristics, in which typical facies of shallow sea (quartzite and carbonate rocks) were not recognized and neither typical facies of shallow sea and neither ortho-amphibolites and turbidites, which would represent the deep sea facies. This belt features an alignment of occurrences of orthogneiss of the Paleoproterozoic basement, rising in erosive windows beneath the sillimanite gneisses. The horizons of graphite gneiss of Cheréco-Eron ore belt are situated in this unit, more specifically on the border of the Aracoiába Subunit. The most common lithotypes found are: garnet-biotite-graphite gneiss, garnet-biotite gneiss, biotite-quartz gneiss and plagioclase-microcline-sillimanite-biotite gneiss.

The garnet-biotite gneiss, which predominates in the area, has features like: dark gray color, medium-grained, banded structure, alternating thin clear bands (5 to 10 mm), discontinuous, composed of plagioclase and quartz, and dark bands, also discontinuous, with biotite, garnet and opaque minerals. Microscopically, it shows a granolepidoblastic textural pattern, with plagioclase porfiroblasts surrounded by thin biotite blades whose direction marks the schistosity of the rock. Garnet porfiroblasts are associated with the plagioclase, quartz and biotite. The quartz crystals occupy, along with biotite, the interstitial spaces left by the plagioclase crystals. Potassium feldspar is rare, but present. The mineralogical composition is summarized as follows: plagioclase (40%), biotite (30%), garnet (15%), quartz with zircon (14%), iron and titanium oxides and graphite (1%).

The plagioclase-microcline-sillimanite-biotite gneiss is whitish to grey, medium to fine grained, foliated, formed by light bands composed of quartz (40%) and feldspar (microcline 15% plus plagioclase 5%) and dark bands with biotite (20%), fibrolite (17%) and graphite traces. The mineralogical composition also includes opaque minerals (3%), as well as traces of muscovite and zircon.

The Baturité II Domain occurs along an E-W belt, about four-kilometer wide, located in the Southern part of the town of Jaguarão. The dominant rocks in the Baturité subunit facies are biotite-garnet gneiss, biotite-garnet-graphite gneisses, in addition to centimetric to decimetric bands of ortho-amphibolites, which are considered as derived from basalts and metaturbidites. These last two lithotypes outcrop in the Choró River, near the village of Itans. Some of the amphibolite rocks found in the vicinity of the Fazenda Alvorada, near the village of Lagoinha, are metagabbros, with nematoblastic texture, that display iso-oriented hornblende crystal, with plagioclase crystals in the interstitial spaces. The mineralogical composition is represented by hornblende (80%), plagioclase (15%) and ortho-pyroxene (5%). Titanium-biotite, rutile and opaque minerals complete the mineralogy.

In the Southeast part of the area, near the town of Milton Belo, there is a single N-S elongated body with approximately 1 x 3.5 km and considered as belonging to the Granite Supersuite. The rock can be classified as biotite granite which shows light grey in color, medium to fine grained and composed of microcline, quartz, plagioclase and biotite.

Rocks of the Gabbro-Diorite Complex of Pedra Aguda are situated in the Northern part of the area, and form a body of ellipsoidal shape, with the major axis measuring about 10 km, along the N-S direction. Contact with the host rocks is sharp and vertical with milky quartz veins present. There are large migmatite xenoliths, probably related to the Paleoproterozoic Unit, in the Southern part of the complex, near the village of Pedra Branca.

In its border zone, there are lithotypes of basic to intermediate composition (gabbros and diorite), while the central part is dominantly of granitic composition. In the central part of the complex, there is biotite granite of clear gray color, with medium-size phanerites, composed of microcline, quartz, plagioclase and biotite plus opaque minerals like epidote and rutile as accessories.

The contact between the Ceará Group and the Paleoproterozoic basement is considered tectonic, due to the mylonite occurrences and the metamorphic grade contrast between its rocks. The contact is by low-angle thrusting (nappes) developed during the Brazilian Cycle (Caby & Arthaud 1986). However, near the dam located at Fazenda da Laje, the banded sub-horizontal gneiss of the Baturité Subunit (Acarápe Sequence) lies in a nonconformity contact with the orthogneiss (N75°W/subvertical) of the Paleoproterozoic Basement.

Geologic-structural context

In this study, the geological evolution of the area was considered to be related to two cratonic platforms, one to the North and the other to the South, separated by a complex fold belt of general ENE direction.

The domains of rigid behavior with relatively simple structure are basically covered by the Acarápe Sequence (Aracoiába Subunit). In the Southwest portion of the South Domain, the Archean basement also outcrops (Cruzeta Complex).

The Cruzeta Complex (in Southwest cratonic domain) consists mainly of ortho-derived banded gneisses, with intercalated boudins of basic rocks. Its rocks are intensely deformed, with gneissic banding and fracture cleavage, with directions ranging from N80°W to N60°E and dip about 40°S.

In areas of the Acarápe Sequence, within the cratonic domain, paragneisses are predominant, with intercalations of marble and quartzite and structures generated in progressive deformation of ductile nature, with intrafolial folds and mesofolds tight and open, with a slightly sloping. In both domains, the foliation is generally parallel to the lithological contacts, and their directions follow the edge limits of the rigid zone where the dips vary from 30 to 45° towards South.

The central belt area, located between the cratonic areas, expresses compressional tectonics, being cut by extensive nappes that resulted in overlapping of Neoproterozoic metasedimentary rocks on the Paleoproterozoic basement orthogneiss. The amphibolites and gneisses have intrafolial folds, tight to recumbent and centimetric to milimetric S/Z structures, marked mainly in the gneisses and amphibolites. The dominant style is isoclinal folding, with kilometric-scale folds, with axial plans showing low dip to ENE, in association with the main phase of nappes transport. In the area of folds, transcurrent faults are also frequent, perpendicular to the direction of the nappes, where the two main directions are N20-30°W and N15-25°E.

In the Northeastern portion of the area, there are two extensive subvertical fractures of directions N45 and N55°W, respectively, with the second one extending over 30 km and cutting the Pedra Aguda Gabbro-Diorite Complex.

In the South of Baturité II Domain, there is a zone of high deformation, characterized by the presence of quartz rods and mullions, stacks of nappes and thrust faulting verging from South to North. The tectonics resulted from a regime of compressive stress in the Southeast-Northwest axial direction is certainly responsible for the closing of the Acarápe's Neoproterozoic sedimentary basin.

The graphite mineralizations

Graphite deposits in the Aracoiába-Baturité region are associated with graphitic gneiss (disseminated graphite) and veins (massive graphite). They present distinct characteristics and geological environments, which are reflected in their syngenetic and epigenetic origins, respectively (Fragomeni 2011).

Disseminated ore

Disseminated ore (graphitic gneiss) shows 1.5 to 7% carbon content and is located according two main belts that stretch for kilometers in the general ENE direction, called Chereco-Erom and Fazenda Alvorada-Itans, which are associated to Baturité I and II subunits, respectively.

The Chereco-Erom ore belt presents 50 meter-wide and extends toward the Southwest for more than 8 km, starting in the outskirts of the Pedra Branca village in the East and extending westward. It consists of different bodies of graphitic gneiss that can be individualized and classified as graphite gneiss, garnet-biotite graphite gneiss and biotite-graphite gneiss. These rock types are hosted in a quartz-biotite gneiss, which can also contain a little bit of graphite, and constitutes anti-formal isoclinal structures, with axial plans slightly inclined to the South (>70°), in the direction of strains.

The ore belt of the Fazenda Alvorada-Itans is very similar to Chercéo-Erom ore belt, and it is also related to the Baturité Subunit, although associated with deeper facies of the paleogeography of the Acarápe sequence (Baturité II Domain). This registers the occurrence of biotite graphitic gneiss bodies, interspersed in a sequence of ortho-amphibolites and biotite gneisses, about 50 meter-wide, extending WSW direction for more than 10 km. This belt starts at Fazenda Alvorada on the outskirts of Lagoinha, and extends Southwest to the village of Itans.

In both belts, the graphite ore forms extensive lenticular-shaped bodies with hundreds of meters long and dozens of meters of width.

Graphite, although widespread, most often occurs at richer levels of biotite, which may be intergrown with it. The graphite corresponds to between 8 and 14% of total samples. It displays tabular or lamellar texture (flakes). The lamellar structure is parallel to the overall rock schistosity, is folded and exhibits strong pleochroism reflection and crease, possibly as a result of folding. They are virtually free of inclusions, where it shows only a few minor inclusions of rutile (?), plus small lenses of quartz-feldspar in the foliation plans.

Massive ore

A total of 12 significant massive ore bodies associated with veins were registered in the area surrounding the Pedra Aguda Gabbro-Diorite Complex with the furthest body (Juamirim) situated 2.5 km from the pluton. They correspond to the following bodies: Cava Sul, Norte-Sul, Madalena-Seu Chico, Juamirim, Seu Chico, Cava Norte, Serrote Açude, Serrote Estrada, Tida, Chico Néri, Antonio Alves and Tô (Fig. 3).

The massive ores, with colors ranging from gray to black, present in variable amounts white millimetric inter-layers formed by aggregates of feldspar crystals (usually kaolinized). They occur in tabular or lenticular bodies of small dimensions, and have sharp contacts with the host rocks, which are represented by ortho and parade-rived gneisses. The composition of the ore is represented by graphite, quartz and feldspar as well as subordinate amounts of goethite, biotite, clay minerals, amphibole, aluminosilicates (sillimanite and/or kyanite), titanium oxides (rutile and leucoxene), hematite, magnetite and ilmenite. The carbon content in this type of ore ranged from 20.5 to 40.0%.

Two bodies exemplify very well this type of mineralization: the Cava Sul target, with ore formed by graphite veins (stockwork) and associated to pegmatite, which shows typical hydrothermal characteristics where it cuts gneissic rock consisting of feldspar, quartz and biotite and the N-S body, which fills in a vertical fault and consequently has a tabular form, with 2.0 m wide and over 120 m long.

Graphite genesis

The genesis of these graphite deposits was closely related to the regional tectonic-thermal evolution. The disseminated ore type (graphitic gneiss) comes from carbonaceous material of sedimentary origin. It is hosted in Acarápe Metavolcanic-Sedimentary Supracrustal Sequence and related to this metamorphic belt. The massive ore type (veins) relates to Pedra Aguda Gabbro-Diorite Complex and was presumably formed from the remobilization of disseminated graphite by hydrothermal solutions derived from an igneous body and deposited in fractures and faults.

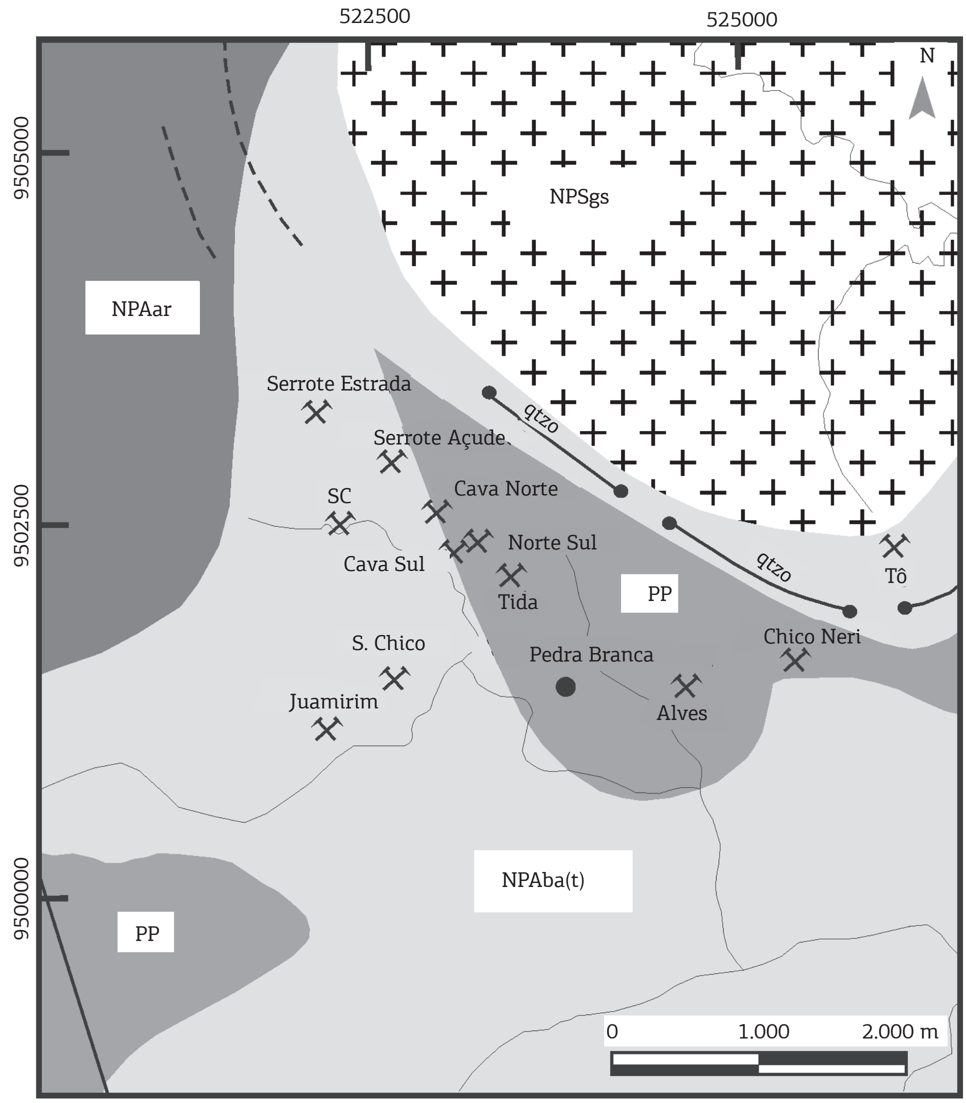
This is corroborated by analyses carried out on graphite samples taken from the main mineralized bodies found in the Aracoiába-Baturité area that were dosed for determination of stable carbon isotopes in the Organic Geochemistry laboratory of Faculdade de Geologia of Universidade do Estado do Rio de Janeiro (FGEL/UERJ). The analyses (Tab. 1) were obtained using the instruments of LECO Corporation (Model CHN-600), using ASTM-D5373.

According to Weis *et al.* 1981, $\delta^{13}C$ values with a range from -30 to -20% indicate that the source of the material is of biogenic origin derived from sedimentary organic matter. The $\delta^{13}C$ values between -7.0 and -5.0% indicate that this material is of magmatic origin; $\delta^{13}C$ values between 9.7 and 0% correspond to material derived from mineral carbonate reactions. The $\delta^{13}C$ values determined for the graphite samples (collected) in the area range from -26.72 to -23.52% (disseminated ore) and from -27.03 to -20.83% (massive ore). These values, all between -30 and -20%, show signs of biological activities (bio-signatures) which allows the assumption that the graphite samples were derived from organic matter.

Controls of graphite occurrence

The ore types (massive and disseminated) identified in the Aracoiába-Baturité District indicate distinct controls. The spatial association between the two types of ores was used in the Central Ceará Terrane to identify the metallotects common to both mineralizations.

The graphitic belt, which extends from the town of Aracoiába and continues West to the region of Canindé,



NPSgs: Gabbroid Suite; NPAar: Acarápe Sequence, Aracoiába Subunit; NPAba(t): Acarápe Sequence, Baturité Subunit; PP: Paleoproterozoic basement.

Figure 3. Geological map with the location of the main massive graphite bodies (vein-type).

Table 1. Carbon isotopic composition of graphite samples of the Aracoiába-Baturité District

Sample	Ore	$\delta^{13}C$	C (%)
10666	Massive ore (vein-type)	-27,036	25 a 30
10660	Massive ore (vein-type)	-21,162	50
10659	Massive ore (vein-type)	-20,827	35 a 40
10665	Graphite-biotite gneiss	-26,719	2 a 3
10664	Manganesiferous graphitic gneiss	-24,833	7
10663	Graphitic biotite gneiss	-25,397	5 a 6
10662	Garnet-biotite-graphite gneiss	-23,247	6
10661	Garnet-biotite-graphite gneiss	-23,520	6

follows exactly the Neoproterozoic supracrustal sequence of the Baturité Subunit (Acarápe Sequence), showing that this subunit is an important regional metallotect. In semi-regional scale, it is possible to observe that the two belts of syngenetic ore type occurrences are inserted into sets of rocks that have their environments well-defined in specific paleogeographic conditions considering this Sub-unit:

- Cheréco-Erom graphitic gneiss belonging to Baturité I Domain, regarded as situated in the continental slope, adjacent to shallow sea facies (Aracoiába Subunit of shelf type). This subunit corresponds to the paraderived rocks (aluminous gneisses) of the supracrustal sequence (Ceará Group) overlaid on ortho-derived rocks (migmatites, enderbite gneiss, metanorite) of the Paleoproterozoic accretionary terranes (Gneissic-Migmatitic Complex);
- Fazenda Alvorada-Itans graphitic gneiss, belonging to Baturité II Domain, is considered as being deposited at the foot of a slope-abyssal plain facies of deep sea, mainly associated with ortho-amphibolites and other sequences, herein interpreted as turbidites.

In the case of the epigenetic (vein-type) mineralization styles present in this district, it is quite obvious that the location of all these occurrences, in a radius of up to 2.5 km around the Pedra Aguda body (Pedra Aguda Gabbro-Diorite Complex), which cuts the Baturité I Domain, points to an epigenetic event. So far, no epigenetic graphite bodies have been found outside the area surrounding the pluton. Therefore, this granitic body relationship seems to define an area of thermal influence regarding a remobilization by hydrothermal fluids (syngenetic graphite) and its subsequent deposition in the faults and fractures.

In this mineralization, increasing the observation to a more detailed scale, there is a control on a local scale, characterized by relief structures (faults, fractures etc.) that allowed the percolation of mineralizing fluids. These fluids migrate preferentially to low pressure areas (contact zones, fold axis, fractures etc.) where graphite is re-deposited in conditions of lower temperature. The main local controls for the formation of epigenetic graphite of the Aracoiába-Baturité District correspond to fractures with directions ranging from 60° to 80°NW (Chico Neri – N75°W; Antônio Alves – N60°W/; Madalena – N80°W; Tô – N70°W). An exception is found for two ore bodies which are hosted along the foliation plans (Juamirim – N80°W/25°N and Cava Sul – N60°W/60°N bodies).

The stockwork type features are probably associated with hydraulic fracturing resulting from pressure exerted by hydrothermal fluids released during the post-magmatic stage by the Pedra Aguda pluton. These magmatic-hydrothermal fluids are presumably responsible for the graphite mobilization, transportation and deposition of the massive ore bodies.

RESULTS AND DISCUSSION

The performed study aimed at the identification of the graphite mineralization geological controls of the Aracoiába-Baturité District, Ceará.

It was adopted for the Northern Borborema Subprovince, where the studied area is situated, the division of tectonostratigraphic terranes proposed by Campelo (1999). This division resulted from the investigation of shear zones as likely limits of terranes, from the recent geological and gravimetric surveys, where large shear zones presented in the Central Ceará Domain (DCC) were interpreted as escape or side adjustment zones between blocks. However, according to Almeida & Nogueira Neto (1996), the shear zone of Senador Pompeu would represent a geosuture, and for such, they indicate as evidence the presence of glaucophane schist, found in the vicinity of Canindé and eclogite facies rocks located in the region of Chorozinho, particularly in Choró river bed. This idea, however, is not consistent with the present work, because it considers that the actual position of the geosuture — a result of the collision of microplates — would correspond to the sequence of turbidites and ortho-amphibolites that encompass the syngenetic graphite belt of Aracoiába-Baturité District. Geographically, Canindé and Choró river areas — where it was recorded the presence of glaucophane schists and eclogite mentioned by Almeida & Nogueira Neto (1996) — are located outside the shear zone of Senador Pompeu, following the amphibolite-graphite outlined herein (Fig. 2).

Based on the study of the major world occurrences of graphite, this paper intended to define the broader mineralization context in order to determine some sort of analogy with the geological framework of the area in question. This study shows the close association between the abundant organic matter that originated the graphite and sedimentary layers in Precambrian basins, in particular of Neoproterozoic age. The major graphite districts in the world, such as the Mashan group in Northeast China, Madagascar and Sri Lanka clearly represent sedimentary basins that were a repository of organic matter that, when closed, originated a large graphite mineralized belt of Pan-African age (Dissanayake & Chandrajith 1999). This disseminated graphite metasedimentary rocks has been considered and adopted as a useful geo-indicator of ancient sedimentary basins, as well as the geosutures resulting from the subsequent closings of these primitives oceans (Dissanayake *et al.* 2000).

Some of these geosutures zones correspond to Khondalite belts and represent a significant component of granulite facies terranes with the gneiss that occurs associated with the belts derived from sedimentary rocks. In India (Kerala) and China (North China craton), these metasedimentary lithotypes are generally those found with graphite and characterized by aluminous gneisses. In Kerala's Khondalite Belt, gneisses are subdivided into two sets represented by garnet-biotite (± graphite) gneiss and garnet-biotite-sillimanite (± graphite) gneisses (Wilde *et al.* 1999, Chacko *et al.* 1988). Nevertheless, it must be considered that, in the Archean and lower Proterozoic belts of the North-Central part of China, the dominant Khondalite Suite rocks are sillimanite-garnet gneisses, garnet-quartz gneisses, and quartz-feldspar gneisses (Zhang *et al.* 2000, Condie *et al.* 1992). In Fennoscandia, Khondalite rocks are represented by sillimanite-garnet gneiss and garnet gneisses which include gneisses rich in quartz lenses, calcsilicate and mafic rocks (Barbey *et al.* 1982) and are derived from turbidite sediments (gray wacke shale/flysch sequence) (Barbey *et al.* 1982). In Brazil, the Khondalite belts identified in Rio de Janeiro (Santos 2008, Pereira & Guimarães 2012) were characterized as garnet gneiss related to mineralized belts in graphite, in the regions of São Fidélis and Santo Antônio de Pádua-Itaperuna.

Similarly, the aluminous gneisses with graphite of the Aracoiába-Baturité District, particularly those found in Baturité I Domain, can also be compared to the types found in Khondalite belts in various parts of the world. In this way, the Baturité I Domain was also considered as a Khondalite belt.

For Arthaud (2007), between 750 and 850 Ma, the crustal evolution of the Central region of Ceará developed after the rifting of a fragment of the continental Archean-Paleoproterozoic crust and, over this crust, there was, in the form of a shelf sequence, the deposition of sediments of Ceará Group.

Still according to the same author, the metamorphic evolution of the subunit (belonging to the Ceará Group and here correlated to Baturité II Domain) started in eclogite facies conditions, has undergone granulite facies conditions of high pressure and ended at amphibolite facies conditions of high temperature and low pressure along the subduction process of a passive margin. The existence of subduction zone means that the rifting process occurred between 750 and 850 Ma led to the opening of an oceanic domain closed later.

In line with Arthaud (2007), it is assumed that the graphitic belt of the Aracoiába-Baturité District would represent the remnant of a subduction zone and would correspond to a suture zone derived from the closing process of a former ocean with a consequent continental gluing of micro-cratons (Baturité block on the North and Caio Prado block on the South, informal designations) during the Pan African-Brazilian orogeny.

For Torres *et al.* (2006), the metasedimentary rocks of Acarápe Sequence presented different depositional systems: shallow sea (Aracoiába Subunit) and deep sea (Baturité Subunit). Arthaud (2007), in turn, also interprets the sedimentation of Ceará Group as a shelf of passive margin environment. In the studied area, the lithological sequence of Acarápe rocks clearly shows that sedimentation was consistent with a shelf of passive margin type. These sets are distributed according to parallel belts of approximate ENE direction, and interpreted as different facies in paleogeography. In summary, there is a change of paleo-environments, from North to South, beginning with the Aracoiába Subunit (NPAar), of shallow sea facies, passing through a zone of continental slope (NPAba-t) and then to a deep sea environment (NPAba- mp), the latter being regarded as the Baturité I and II domains.

In the Baturité I Domain, the studied lithotypes allowed the individualization of this belt and its interpretation as a domain, in which pelitic sedimentation prevailed in the area of the continental slope. In this context, the basement consisting of ortho-derived rocks (SIAL) represented a foothill in the compressional event closing the Acarápe basin. In this way, there would be the interaction between para- and ortho-derived rocks (respectively, aluminous gneisses with graphite and metatonalite) in close association. Whereas the Baturité II Domain, due to the presence of metaturbidites interspersed with ortho-derived amphibolites, probably corresponds to deep sea facies in the interaction between the foot of the continental slope and an abyssal plain. Pelagic sedimentation in anoxic zone would concentrate the carbon transforming it into graphite during metamorphism. In this context, the amphibolites could represent a remnant of oceanic crust.

CONCLUSIONS

The information obtained from the field work and laboratory data, interpreted in line with the current stage of knowledge of the main world graphite districts and geological context of the State of Ceará, allows the following conclusions.

Graphite deposits in the Aracoiába-Baturité District are hosted in graphitic gneiss (disseminated ore) and veins (massive ore).

Disseminated ore (graphitic gneiss) presents carbon levels ranging from 1.5 to 7%, forming extensive lenticular-shaped bodies of hundreds of meters long and dozens of meters wide, which resulted in large deposits. These bodies are distributed along two parallel ore belts, according to the general NNW direction, called Cheréco-Erom and Fazenda Alvorada-Itans, with extensions of 8 and 10 km, respectively.

The massive ore (vein-type) is epigenetic and presents grades between 20 and 40%. It occurs in tabular bodies and pods, controlled at a local-scale by lower pressure zones in structures such as faults, fractures, contact zones, folds etc. (metallotect structures), which enabled the percolation of mineralizing fluids. These mineralizations represent graphite remobilization of the syngenetic belt by magmatic/hydrothermal fluids related to Pedra Aguda plutonic body.

The $\delta^{13}C$ values determined on graphite samples of disseminated ore vary from -26.72 to 23.52% and in the massive ore from -27.03 to -20.83%. The carbon isotopic composition of the two types of ore reveals a biological activity signal (bio-signature), confirming that the graphite of the samples was derived from organic matter. The occurrences of syngenetic and epigenetic ore bodies are hosted in the Baturité Subunit, which constitutes an important regional stratigraphic metallotect.

The rocks of Baturité Subunit (paragneisses with graphite and graphite combined with metaturbidites and ortho-amphibolites) correspond, in paleogeographic terms, to the Acarápe Sequence of the slope facies (Baturité I Domain) and the foot of a slope-abyssal plain (Baturité II Domain). Thus, an important paleogeographic control is associated with the graphite mineralized zones.

The association of metamorphic graphite disseminated in aluminous paragneisses of the Acarápe Sequence, similar to those found in Khondalite belts of India and China, is a geo-indicator of ancient Neoproterozoic sedimentary basin and also can be considered as a geosuture zone resulting from the subsequent closing of a primitive ocean.

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