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Potential for kaolin and bauxite in the near-littoral sediments of the State of Amapá, Eastern Guiana Shield, northern Brazil

Wilson Scarpelli[1]

[1]Independent Consultant, Rua da Paz 119, Cotia-SP, Brazil, CEP: 06710-507.

Abstract

In Amapá, northern Brazil, there is potential for large and not yet identified economical deposits of kaolin and bauxite in the Cenozoic belt of sediments that cover the margins of the Eastern Guiana Shield next to the Atlantic Ocean and the Amazon River. During geological exploration of these mineral resources, it seems adequate to consider the geological characteristics of the kaolin deposit of Morro do Felipe, at the southwest of Amapá, and the deposits of bauxite replacing Cenozoic kaolin-rich sediments at the coast of Guyana and Suriname. While the Brazilian deposits of bauxite of the Trombetas and Jari rivers occur in topographically stable plateaus, the corresponding plateaus containing bauxite in Guyana and Suriname were lowered to below seawater, and covered by younger sediments. In the southeast of Amapá, sediments similar to some that in Guyana and Suriname are guide to bauxite deposits, as the white sands, appear widespread over a large area. A few but significant exposures of high-grade kaolin suggest high tonnages of the mineral. The presence of these layers of kaolin, the mother-rock of the bauxite of the belt, and the presence of actual paleoduricrust improve the possibility of existence of hidden deposits of bauxite.

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*Corresponding author
Wilson Scarpelli
E-mail address: wiscar@terra.com.br

1. Introduction

This manuscript intends to call the attention to the possible presence of large economic deposits of high-quality coating-paper kaolinite and bauxite in a vast and unexplored area in the southeast of the state of Amapá, Brazil, on the edge of the Precambrian Guiana Shield. This shield is exposed in the northeast of South America (Figure 1), with margins with the Atlantic Ocean by the east and with the Amazon River by the south. In these two margins, it is partially covered by marine and continental clastic sediments of Paleogene to Holocene ages. In Guyana and Suriname, pollen studies done during oil exploration demonstrated that, on several occasions, the terrain has been elevated above sea level and then lowered down (Monsels 2016).

During the periods of low sea level, the sediments were exposed in flat plateaus, which were traversed by fluvial systems. During these events, the sediments occurring in the upper parts of the plateaus were submitted to weathering, with dissolution of some of their mineral constituents. Easy-soluble elements like potassium, calcium, and magnesium were drained away. A large part of the dissolved iron, aluminum, manganese, and other elements recrystallized as supergene oxides, hydroxides, and phosphates and remained in the weathered zone, together with weather-resistant minerals like quartz and sericite. These minerals accumulated in the soil profile, in the form of a layer conformable to the surface of the terrain.

The size, composition, structure, and textures of the resulting soil are quite variable, depending on the mineralogy, chemistry, and permeability of the affected rocks, the pH and composition of the surface water, the temperature, the climate, the influence of organisms in the reactions, the efficiency of the drainage system to remove the leached elements, the local geomorphology, and the time available for the weathering. From place to place, the created soils vary from a loose distribution of weathered rock fragments to secondary mineral grains of fine to large sizes, including oolites, pisoliths, and concretions, forming a lateritic soil dominantly constituted by secondary minerals of iron, aluminum, manganese, silicon, other metals, and phosphates. When this soil is aggregated into a duricrust, that is, when they are compact and massive, they are called canga, when rich in iron, or bauxite, when rich in aluminum (Neuendorf et al. 2011).

Iron, aluminum, and silicon are the dominant metals of these soil horizons. The richer in iron constitute iron laterites, easily

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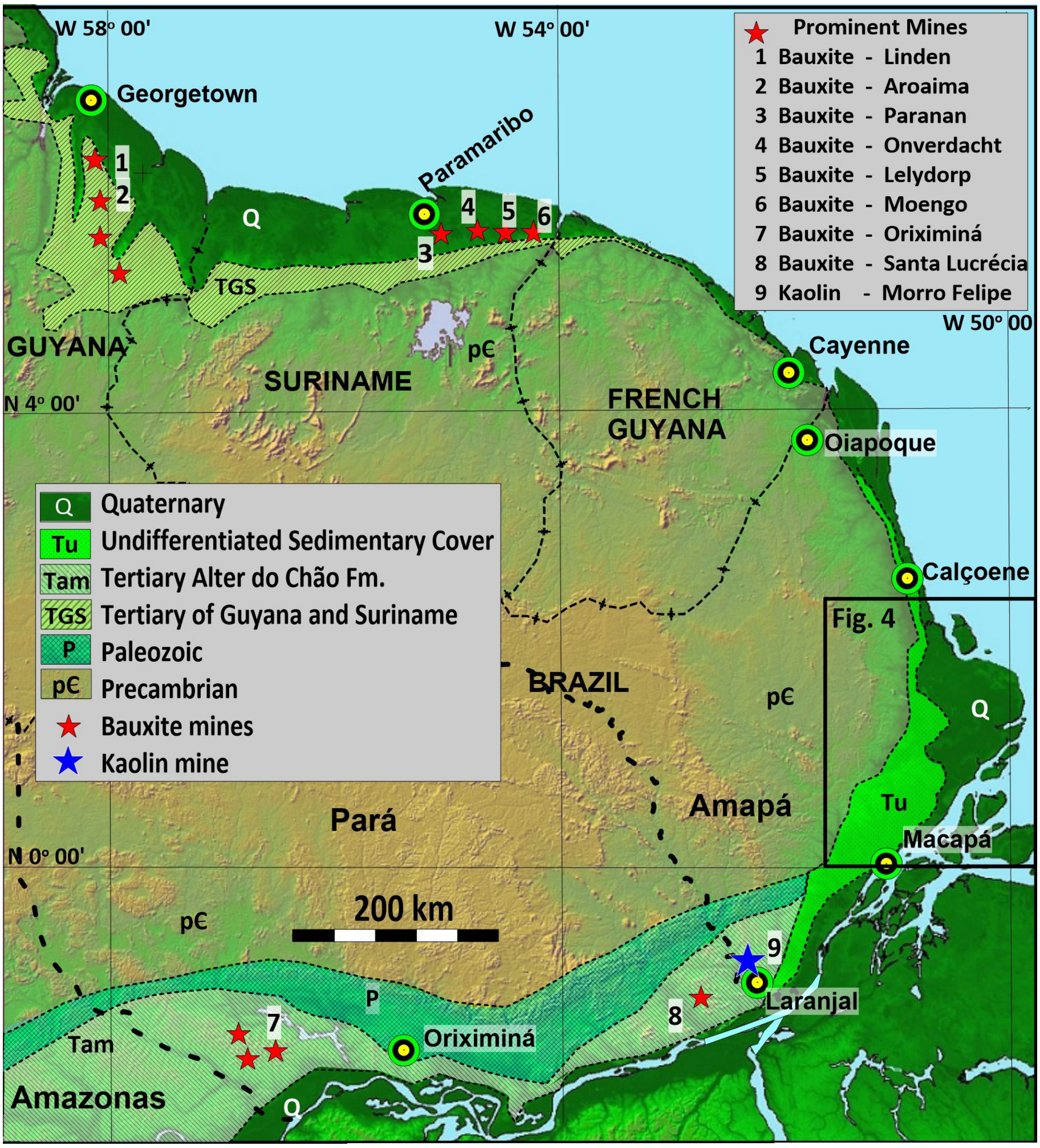


Figure 1. Large bauxite and kaolin mines occur in the Cenozoic sediments that covers the littoral zone of Guyana and Suriname, and in the margins of the Amazon River in the Brazilian States of Pará and Amazonas. At the southeast, detailed in Figure 4, there is a vast area with a similar sedimentary cover and without exploration workings for these commodities.

identified due to their reddish-brown color and the dominance of limonite and/or goethite. The more aluminous, the bauxites, appear with near-white to reddish colors, depending on the amount of contained iron, and present variable quantities of gibbsite, boehmite, diaspore, aluminum-bearing silicate clays, and quartz (Neuendorf et al. 2011).

Large deposits of bauxite were identified in the mentioned Paleogene to Holocene marine and littoral sediments deposited in two areas of the Guiana Shield. One in the South, in the northern margin of the Amazon River, with the deposits of Santa Lucrécia, in Pará, and Trombetas, in Amazonas. The other in the North, with the deposits of Pommerene, Linden, and Aroaima, in Guyana (Figure 2), and Lelydorp, Paranan, and Moengo, in Suriname. The bauxite of all of these deposits formed during the weathering of aluminous and clay-rich layers present in the sedimentary column (Aleva 1965; Aleva et al. 1969; Dennen and Norton 1977; Boulangé and Carvalho 1997; Monsels 2016). Some authors consider that the bauxite was formed by the superposition of several phases of alteration under variable environmental conditions (Dardenne and Schobbenhaus 2003), accompanied by silicification (Valeton 1974).

Situated between these two centers of deposits of bauxite, the southeastern part of the State of Amapá presents a large coastal area covered by the same sequence of Neogene sediments and constitutes a good target area for bauxite and high-grade kaolin. The area presents geological characteristics that might be used during such exploration, as it will be described.

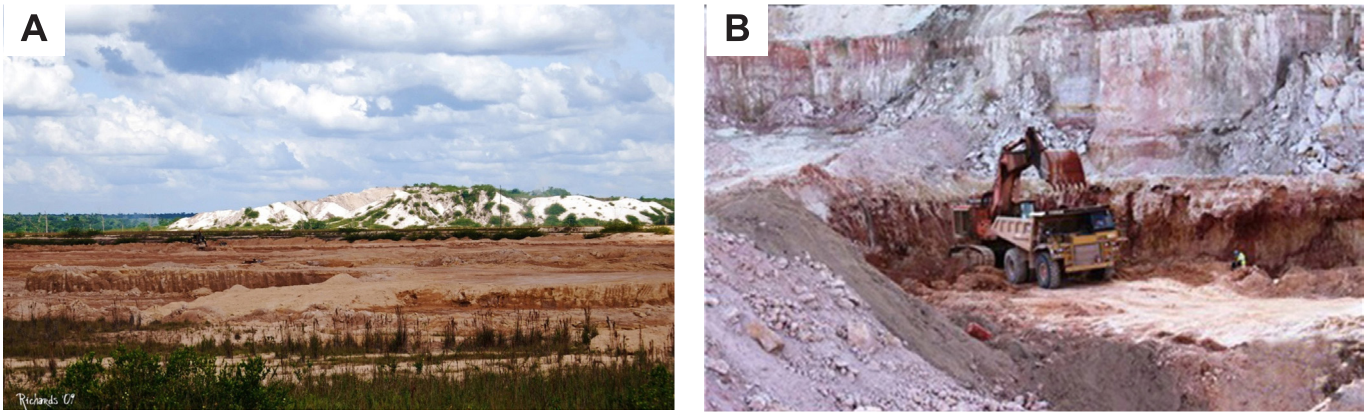


Figure 2. (A) A view of the Linden bauxite mine, in Guyana. The hard bauxite horizon appears stripped of its overburden of white sand, and ready for mining. In the distance, the pile of the removed sands. (Photo by Amanda Richards, available at the Google Earth). (B) Exploitation of bauxite, at the Aroaima mine, also in Guyana. An 8-meter-thick bed of well layered white sand covers the horizontal level of bauxite, which is extracted by shovel and truck.

2. Bauxite and kaolin ore deposits of the Guiana Shield

2.1. Bauxite and kaolin deposits at the northern margin of the Amazon River

Accompanying the northern margin of the Amazon River for about 1,100 kilometers, between the longitudes of -52º and -62º W, the Guiana Shield appears covered by the Amazon Sedimentary Basin, which is oriented East-West, and dips with a shallow angle to the South. Most of the base of the basin is formed by sandstones, shales, and limestones of Paleozoic age, which, close to the river channel, are covered by the Alter do Chão Formation (Mendes et al. 2012), a sequence of fluvial conglomerates, sandstones, and shales of Late Cretaceous to Early Neogene ages. This formation appears in plateaus that reach 100 to more than 170 meters above sea level. Lowlands between the plateaus are covered by Neogene and Quaternary fluvial sediments.

The Alter do Chão Formation occurs on both sides of the Amazon River and hosts deposits of bauxite and kaolin. The larger deposit of bauxite on the north was found in Porto Trombetas, Amazonas State, where the bauxite horizon reaches 6 to 10 meters of thickness (Boulangé and Carvalho 1997). At its base, the bauxite horizon grades into kaolin and, at its upper part, presents a few meters thick level of lateritic iron-rich concretions, above which the bauxite is nodular.

Overlaying the ore, there is a more than 10-meters thick structureless brownish and aluminous clay, the Belterra Clay (Boulangé and Carvalho 1997). These authors found evidence that the unit was affected by a pedoturbation that destroyed and silicified aluminum oxides and hydroxides. Comparing the concentrations of zircon in the fresh sediment and in the Belterra Clay, they found that leaching of 90 meters of the sediment would be required to produce 1 meter of the Belterra Clay. Other authors consider that this clay horizon results from the weathering of fine-grained sediments deposited over the bauxite (Truckenbrodt and Kotschoubey 1981), in a river (Aleva 1981) or in a lake (Sombroek 1966) environment.

At about 500 kilometers to the East, at Almeirim and Mazagão, another group of bauxite deposits occur in plateaus reaching elevations of 150 to 250 meters above sea level. They were also formed by the weathering of layers of kaolin of the Alter do Chão Formation. At Santa Lucrécia, in the Pará State, the mineable horizon of bauxite has 4 to 7 meters of thickness and is ferruginous in its upper portion. It is overlain by an 8-meter-thick unit of the Belterra Clay. Bauxite of chemical grade was once produced by a now-closed mine and used to produce refractory materials (Braga and Alves 1988). Large deposits of kaolin of the Alter do Chão Formation occur in Morro do Felipe, in the southwest of the Amapá State, at the eastern margin of the Rio Jari. They occur high in plateaus of 170 meters of elevation above sea level. The layer of kaolin reaches about 60 meters of thickness (Montes et al. 2002), being covered by a 1 to 5 meters thick zone of lateritic iron concretions, 2 meters of nodular bauxite and up to 10 meters of Belterra Clay (Wilson et al. 1998; Kotschoubey et al. 1999). A few residual layers of quartzose sands indicate a stratification and a sedimentary origin for the kaolin, that "should be considered as having originated from kaolinitic clay sediments that were submitted to intensive lateritic weathering processes" (Montes et al. 2002), which lead to the removal of iron and the bleaching of the clays. The exploited ore is treated to remove impurities, and is sold as a high-grade, coating-paper quality kaolin (Kotschoubey et al. 1999).

2.2. Bauxite ore deposits in the coastal area of Guyana and Suriname

Fluvial, littoral, and marine sediments of Cretaceous to Quaternary ages occur in the coastal area of Guyana and Suriname. They are oriented parallel to the coast line, dip towards the ocean with a low angle, and extend over the continental shelf for variable distances. On land, the sequence reaches about 70 meters of thickness. The deposition of these sediments was initiated with the opening of the Atlantic Ocean and continues until now. The portion above the continent is represented by superposed layers and lenses of variable extension and thickness of gravels, sands, silts, and clays. Their ages are well known due to pollen studies done during the exploration for oil in the sea. Their stratigraphy is shown in Table 1, based on Wong (1984), Gibbs and Barron (1993), Aleva and Wong (1998), Hammond (2005), and Monsels (2016).

During the years, the area was affected by fluctuations of the sea level, with deposition of sediments during periods of high sea level, and erosion, lateritization and bauxitization during periods of low sea level. Erosive contacts mark the ends

TABLE 1. Stratigraphy of the Coastal Area of Guyana and Suriname.

	GUYANA	SURINAME		
AGE	FORMATION	FORMATION	ENVIRONMENT OF DEPOSITION	LITHOLOGY
Holocene	Demerara	Demerara	Close to the shore line	Sands, clays
				Clays
Pleistocene	Coropina	Coropina	Close to the shore line	Sands, clays
				Shales, clays
Pliocene	(White Sands)	(Zanderij)	Littoral sands	Very clean white sands
	Berbice	Coesewijne	Fluvial, littoral	Sands, clays
Miocene	Courentyne	Courentyne	Inner neritic	Clays, sandy clays
Oligocene	(Bauxite Hiatus)	(Bauxite Hiatus)	Erosional, fluvial	Bauxite fluvial sands
Eocene	Pomeroon	Upper Onverdacht	Inner neritic, fluvial, deltaic,	Kaolin, clays, sandy clays
Paleocene	Georgetown	Lower Onverdacht	Fluvial, deltaic, neritic	Sands, clays, occasional carbonates
Late Cretaceous	Nickerie	Nickerie	Fluvial to shallow marine	Gravels, sands, kaolinitic clays
Precambrian	Basement			Metamorphic and igneous rocks

Based on Wong (1984)

of the cycles of deposition (Monsels 2016). The longer period of low sea level, accompanied by erosion and weathering on the continental side, occurred during the Oligocene, and is referred to as the Bauxite Hiatus (Monsels 2016). During this period, extensive formation of bauxite occurred in the kaolin and clay-rich units of the Onverdacht (in Suriname) and Pomeroon (in Guyana) Formations exposed in ridges and plateaus, and in favorable crystalline rocks in hills and mountains in the interior of the continent. During this period, the only deposited sediments were fluvial sands and clays.

After the formation of the bauxite, most of the terrain was once again lowered to below sea level and covered by the marine Miocene Courentyne Formation and, next, by the Pliocene littoral Coesewijne and Berbice Formations. In areas away from the sea side, the Coesewijne and the Berbice Formations, which are locally covered by the remarkable Zanderij and the White Sands units, both constituted by meters thick clean and bright white fluvio-littoral sands, made by well classified grains of quartz, and nearly free of clay minerals. Towards the sea, the Coesewijne and the Berbice Formations become poor of the covers of these sand units, showing more clay and silt (Wong 1984).

In Guyana, shallow deposits of bauxite, occurring closer to basement rocks, appear directly under the White Sands Unit of the Pomeroon Formation (Figs. 2 and 3), with the clayey

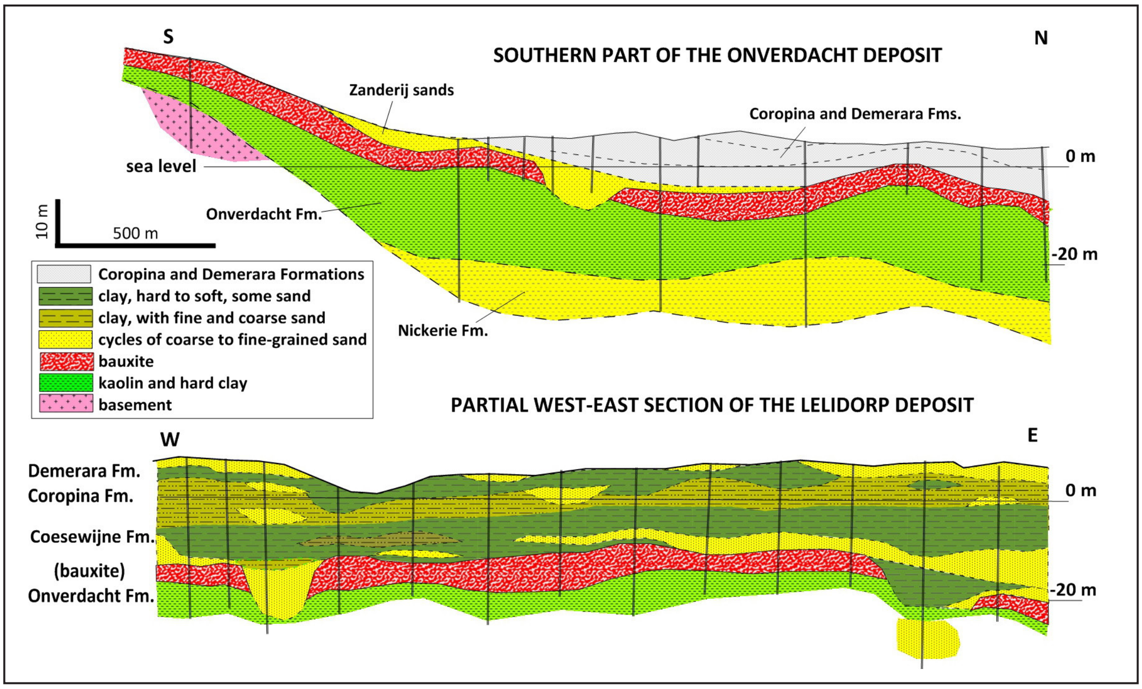


Figure 3. Partial sections of the Onverdacht and Lelydorp deposits, in Suriname (Aleva et al. 1969). See Figure 1 for the location of these mines, near Paramaribo. Above, a south-north section of Onverdacht shows an outcrop of the bauxite at the south, progressively covered northwards by the Zanderij white sands and by the Quaternary Coropina and Demerara Formations. The bauxite occurs at the top of former plateaus made of a kaolin layer of the Onverdacth Formation. Old valleys crossing the plateaus formed gaps of the continuity of the bauxite. Below, an west-east section of the Lelydorp showing the bauxite below sea level and entirely covered by the Coesewijne, Coropine and Demerara Formations.

units of this formation becoming dominant towards the sea (Wong 1984). The sequence is completed by sands and clays of the Pleistocene Coropina and the Holocene Demerara Formations, some of which were deposited in swampy environments (Monsels 2016), as it is seen today.

Two partial sections of the Surinamese bauxite deposits of Onverdacht and Lelydorp, exploited by Billiton Maatschappij, are shown in Figure 3 (Aleva et al. 1969). The section of Onverdacht is oriented south to north, along the dip of the sediments, showing, at the south, a rare outcrop of the bauxite, partially covered by the Zanderij white sands. The Lelydorp deposit, localized further to the north, is represented by a west to east section, nearly parallel to the strike of the beds. Both sections show the bauxite occupying the upper part of former plateaus, now submerged below the level of the sea, and covered by sediments of the Coesewijne, Coropina and Demerara Formations.

2.3. Comparison between the bauxite deposits of Guyana and Suriname, with those of the margins of the Amazon River

An overview of the bauxite deposits of Guyana, Suriname, and on the northern margins of the Amazon River, was presented by Grubb (1979), and a summary of the information of the deposits in the States of Pará and Amazonas was prepared by Dennen and Norton (1977). Aleva (1981) describes the differences between Moengo, one of Suriname's major deposits, and the Trombetas deposit (Table 2). He points out the greater time lag available for the formation of bauxite at Trombetas, where the sediments have been weathered since the Pleistocene, without being covered by younger sediments as in Guyana and Suriname. He also wrote that the massive kaolinitic clay, the parent rock of the Trombetas deposits, is more favourable to the formation of bauxite than the sediments of Moengo, which are formed by the alternation of kaolinitic silts, clays, peaty clays and sands. Another important difference is the topography of the two areas. In the northern part of the Amazon, the deposits occur in elevated plateaus, with the bauxite on the higher surface and well exposed on the flanks of the valleys that cross the plateaus. The bauxite of Guyana and Suriname, on the other hand, occurs in lowland areas, usually covered by younger sediments, and outcrops are rare. In Suriname, many deposits occur below sea level and are mined behind dikes that protect them from the influx of river and sea water.

Regarding structures and textures, Aleva (1981) wrote that the upper part of the bauxite at Trombetas is pisolithic, and that the main bauxite horizon "has vertical columnar structures in the upper part and is blockier in the lower part", internally presenting a "simple crystalline-granular texture of fine grain size." For comparison, he describes the main horizon of the Onverdacht mine, at Suriname, as presenting a "concretionary texture, 5-15 millimeters in size," and that the lower horizons present "rounded cellular and polygonal chambered/box work texture," and that there are "crystalline-granular intercalated beds."

3. Sedimentary cover of the coastal area of Amapá, eastern Guiana Shield

The belt of the coastal sediments that host bauxite deposits in Guyana and Suriname extends southwards, appearing as narrow strips along the coast of French Guiana and northern Amapá, until about the city of Amapá, at latitude +2º N. Southwards from this latitude, it appears with a width of 50 to 100 kilometers and extends southwards for 250 kilometers until about longitude -51º 30' W, where it reaches the eastern limit of the Amazon sedimentary basin (Figure 4). This large area, with more than 30,000 square kilometers of land surface, still awaits geological work to define the stratigraphy of the sediments and the potential for kaolin and bauxite. Most of this area is covered by open savanna, grown on a dominantly flat surface which slopes southeastward, from the contact with the Precambrian Basement towards the coast and the Amazon River.

There are two partially overlapping sedimentary belts. The younger, considered to be Quaternary, occurs along the coastline with the Atlantic Ocean and the left margin of the Amazon River, presents swamps and lakes, and consists of unconsolidated fluvial and marine sediments, essentially sands, silts and clays. These sediments appear to be correlatable with the Demerara Formation of Guyana and Suriname (this work).The older belt, taken as Tertiary, is exposed next to the crystalline Precambrian Basement, and dips southeastwards under the younger sequence. It is composed of consolidated fine to medium-sized clastic sediments. At the surface, their beds are weathered into partially lateritic light-brown to orange, and structureless soils. Outcrops along the few road and railway cuts expose lenses and layers of sand, silt, shale, kaolin, coarse grit, arkose and small-pebble conglomerate, usually with planar bedding presenting a near horizontal angle

TABLE 2. Some differences between the deposits of bauxite of Trombetas, at the northern margin of the Amazon River, and Onverdacht, at the coastal areas of Suriname.

DETAIL	TROMBETAS DEPOSIT, IN THE AMAZON VALLEY	ONVERDACHT DEPOSIT, IN SURINAME
Duration and age of bauxite genesis	2 my, during Pleistocene	20 my, during Eocene-Oligocene
Main iron minerals	Hematite only	Aluminium-bearing goethite, hematite
Textures	Vertical variation. Pisolithic and permeable above, to massive and granular-chrystalline and fine porous texture of main iron-rioch horizon	5-15 mm concretions in main horizon. Rounded cellular and polygonal box work in lower horizon. Frequent crystalline-granular beds. High porosity overall.
Topography	Bauxite formed on plateaus, now from 130 to 180 meters above present sea level	Bauxite formed on plateaus now from 5 to -40 meters of present sea level
Cover	8-10 meters thick Belterra clay	0 to 70 meters thick sequences of sediments
Parent rocks	Massive variegated kaolinitic clay, with grains of quartz and feldspar, grading into quartz sands	Pure, mostly white, locally violet, kaolinitic clay, heavy minerals and scales of muscovite
Export-grade ore	Crude ore requires washing and drying to reach export-grade quality	Crude ore used to require only drying to reach export-grade quality

Summary of a more detailed table of Aleva (1985). See the location of Trombetas and Onverdacht in Figure 1.

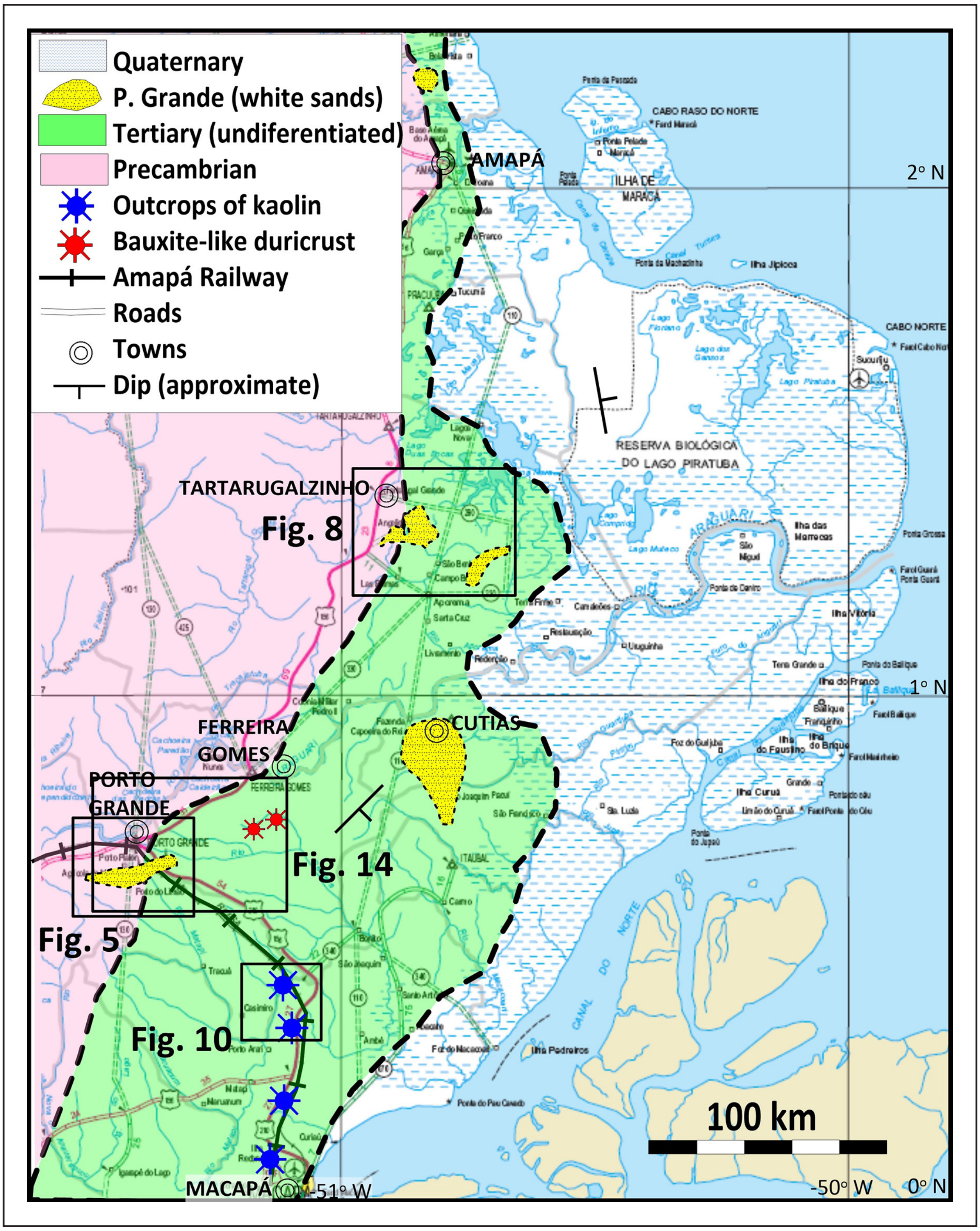


Figura 4. Map of part of the area containing the Tertiary sediments, in the southeast of the State of Amapá,Brazil, with the location of Figures 5, 8, 10, and 14.

of dip. In most geological maps, these sediments appear as the Barreiras Formation (DNPM 1974), which is the common name given in Brazil to sediments considered to be of Tertiary age. Barbosa and Chaves (2015) informed that only a small portion of these sediments was properly characterized, naming it as the Itaubal Formation (see below for a description), and choose to record the complete sequence as Undifferentiated Sedimentary Cover (USC), a name that calls the attention to the lack of knowledge about these sediments (Table 2).

Geologists of the State of Amapá mapped the surface geology and the geomorphology of an area of 40 to 60 kilometers of width, next to the northern margin of the Amazon River, from the Jari River at the west, to the edge of the Atlantic Ocean at the east (Santos et al. [2003]; IEPA 2003). They observed that, in the bottom of valleys, at lower elevation, there is a dominance of whitish to gray clay sediments, which are usually covered by clayey, siltic, and sandy sediments, occasionally with lenses of microconglomerates. The description seem to correspond to the Itaubal Formation. Near Cutias, they found white sands and conglomerates, with similarities to the white sands of Porto Grande (see below for a description).

TABELA 3. Stratigraphy of the Cenozoic Sediments of Amapá.

AGE	UNIT	ENVIRONMENT OF DEPOSITION	LITHOLOGY
Quaternary	USC (*)	Fluvial systems	Alluvial deposits
	USC (*)	Near sea floodplains	Sands, clays, arkoses
Pleistocene	Porto Grande Fm.	Braided streams	Clear white sands
	Itaubal Fm.	Fluvio-marine	Sands, clays, arkoses
	(Fe and Al-rich duricrusts)	Weathering	Plateaus
(Tertiary)	Pedreira Fm.	Marine	Kaolin, silts, sands
	USC (*)	Fluvio-marine	Sands, clays, arkoses
Precambrian	Basement		Metamorphic and igneous rocks

(*) USC: Undifferentiated Sedimentary Cover. Based on Bezerra et al. (2015).

Mapping road cuts near Tartarugalzinho, Bezerra et al. (2015) observed that the Itaubal Formation was made of two sequences, separated by an unconformity. They mentioned that the upper sequence is dominantly rich in sands and clean of clays, deposited in a littoral environment, while the lower is marine, arkosic and rich in shale components. Using OSL (Optical Stimulated Luminescence), they obtained an age of 0.023 Ma for the upper sequence, and 0.120 to 0.071 Ma for the lower. They correlated this older sediment with the Coropina Formation of Guyana and Suriname. Considering that the unconformity indicates two independent units, deposited in distinct environments, and with distinct range of ages, it is felt that they deserve individual names. In this article, the name Porto Grande Formation is used for the upper unit, maintaining the name Itaubal Formation to the lower one. With this information, the stratigraphy of this part of Amapá stands as presented with Table 3. Obviously, there are several units yet to be identified and described.

3.1. The Porto Grande (Areia Branca) Formation

The most impressive exposure of this unit occurs near the Araguari River, in the town of Porto Grande (Figure 5). It is represented by a thick pile of bright-white and clean littoral sands, partially overlying the basement gneisses. The sand unit reaches a thickness of 15 metres (Figure 6) and has been mined for construction purposes for more than 65 years. Its location and thickness suggest that it was deposited at the mouth of a braided stream, possibly the ancient Araguari River. In this place, the sands were well classified and cleaned from clay and silt by fluvial and/or marine waters. The unit has good parallel bedding (Figure 7) and is composed mainly of quartz, with minor amounts of zircon, black tourmaline and ilmenite. Grain size is fine to medium, occasionally gravelly. Shape analysis (using the criteria presented by Dutro Jr. et al. 1948) indicates low orders of sphericity and roundness: roundness ranges from 0.1 to 0.78, averaging 0.4, and sphericity ranges

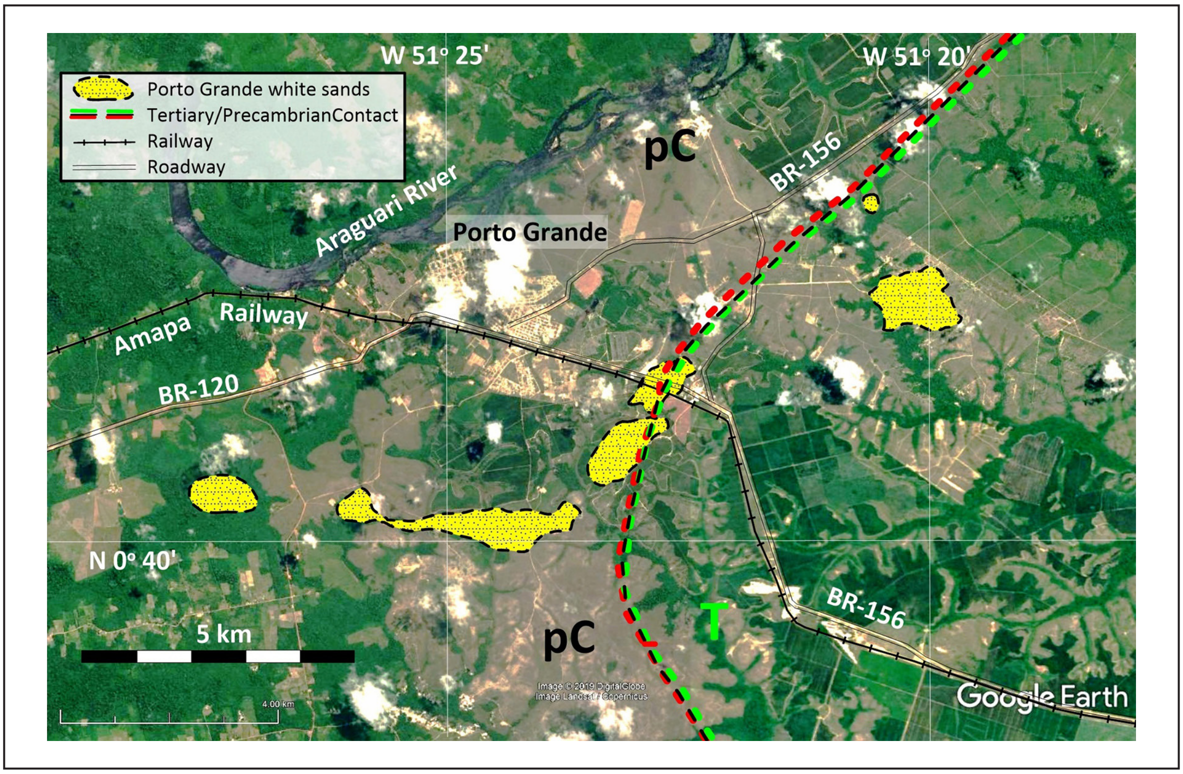
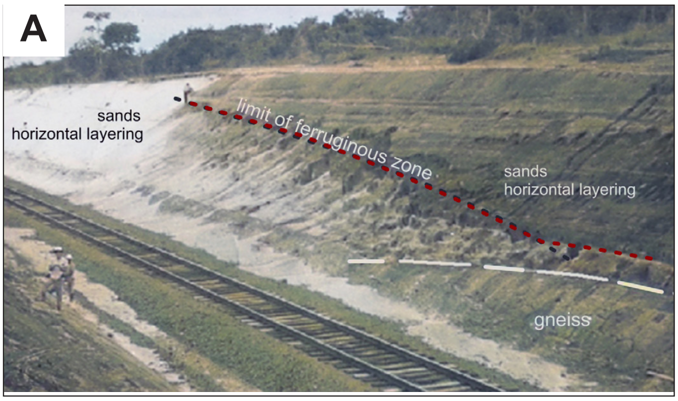


Figure 5. Main area of occurrence of the Porto Grande (Areia Branca) Formation, similar to the Zanderij unit of Suriname and the White Sand of Guyana. At the left, it overlyes Precambrian gneisses and, at the right, Tertiary sediments. Figures 6 and 7 show the larger exposures of the unit.

Figure 6. Two views of the white sands of the Porto Grande (Areia Branca) Formation, at the Km 103 of the Amapá Railway, at the elevation of 66 meters. (A) As seen in 1966 in the railway cut. For scale, geologist J. Maruo stands over the sand wall at the upper center of the photo. (B) At the same site, during 2007, when the face of the cut has been moved back more than 50 meters from the railway, with the removed sand used for construction purposes. (Photos by the author. Photo A, taken in black-and-white, was slightly colorized).



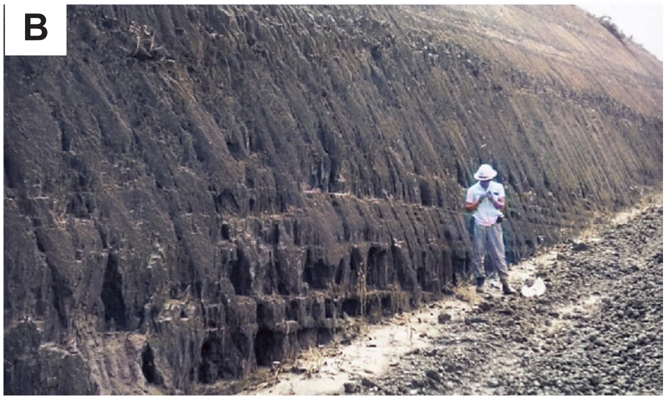


Figure 7. Two views of the outcrop of Km 103 of the Amapá Railway. (A) A lateral view of the same wall shown in Fig. 6 (A). At the lower right, a white line marks the contact of the sands with basement gneiss. The gneiss is intensely weathered and the sand above is impregnated with limonite, formed after ascending iron-bearing waters during dry seasons. The lower limit of the ferruginous zone is shown with a stippled red line. (B) Further to the right, in the same cut, limoniterich bands, outlined by rain waters, mark the sub-horizontal stratification of the sand. (Photos by the author, 1966. Original photos, in black-and-white, were slightly colorized).

from 0.1 to 0.4, averaging 0.2. This unit is similar to the Zanderij Unit of Suriname and to the White Sands Unit of Guyana, to which it seems to correlate. Towards the east, it appears here and there, with smaller thickness, and always close to the course of the Araguari River. Many of these other occurrences are also mined for construction purposes.

At Cutias (Figure 4), in the mid-way between Porto Grande and the sea, the white sands appear with only a few meters of thickness, but covering a larger area. In this location, the unit contains small lenses of clean conglomerate at its upper part (Santos et al. [2003]; IEPA 2003). Near Tartarugalzinho, in the place where Bezerra et al. (2015) defined the Itaubal Formation, the white sands appear as small lenses interlayered with well stratified layers of yellowish sands, clays and silts (Figure 8).

3.2. The Itaubal Formation

In this article, the name Itaubal Formation is limited to the sediments that occur below the Pedra Branca Formation, separated by the unconformity described by Bezerra et al. (2015). The type-site of the formation are road-cuts of roadway BR-156, near Tartarugalzinho. The unit is made of well stratified fluvio-marine lenses and layers of arkosic sands, silts and muds, indicating alternating environments of high and low energy of transport of the clasts (Figure 9). At the surface, the unit is weathered into a brownish lateritic soil, with small iron concretions. The better outcrops appear in road cuts at the margins of incised valleys. In these locations, it is possible to see its richness in coarse and fine sands and shales, with a plane-parallel stratification.

3.3. The kaolin-bearing Pedreira Formation

Exposures of sedimentary white kaolin, apparently ideal for the production of kaolin and for the formation of bauxite by weathering, are observed only in the deeper cuts of the Amapá Railway at the South of Porto Grande (Figure 10). In most of the exposures, the kaolin appears massive, with the layering locally marked by a few horizontal planes of fine-grained

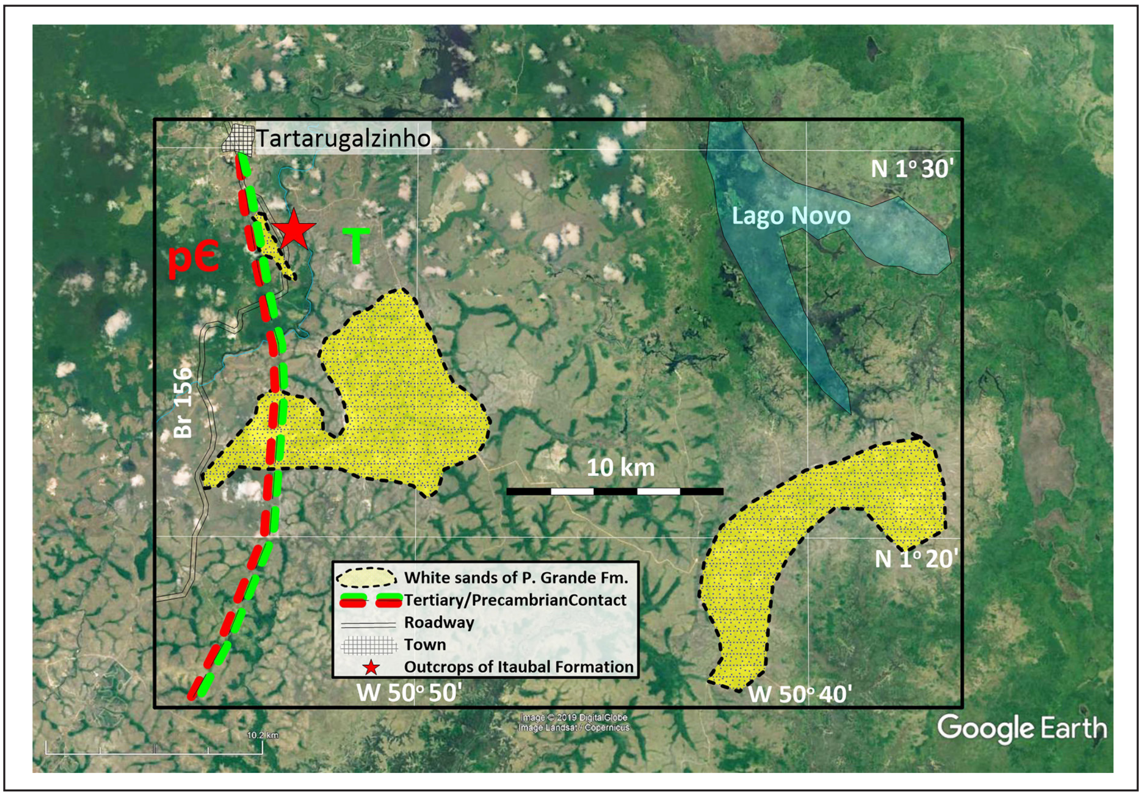


Figure 8. Area at the south of Tartarugalzinho. At the upper left, a red star marks the road cuts where the Itaubal Formation was defined. The white sands that cover the formation are recognizable in satellite images by the whitish color of the soil.

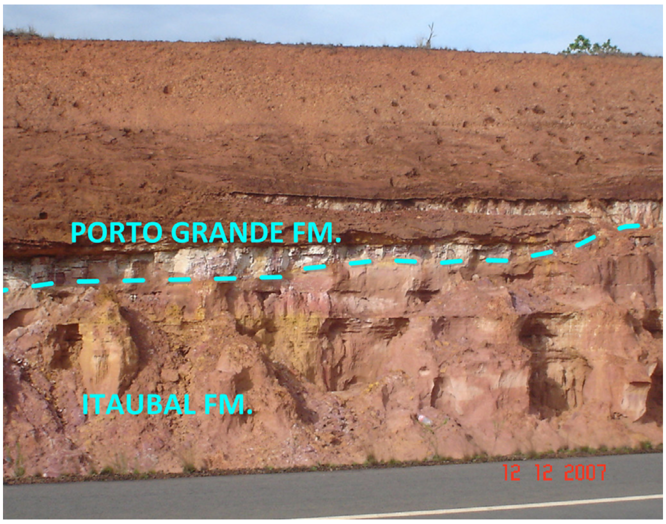


Figura 9. Area of definition of the Itaubal Formation (Bezerra et al. 2015), composed by fluvio-marine sands, sandy clays, silts, arkoses, and conglomerates, comparable with the Coropina Formation, of Guyana and Suriname. They also identified an erosional unconformity at its top, with the upper sequence containing lenses of white sands correlatable to the Porto Grande Formation. (Photo by the author, 2007).

quartz. At one place, it appeared concordantly overlaying a layer of siltstone. The better outcrops appear between kilometers 45 and 65 of the railway (Figure 11). Results of chemical assays and screen tests of samples taken of these two outcrops, in 1967, are shown in Figure 12 and Table 4. Both samples were composed of very white and fine clay, with grain size averaging 11 and 12 µm. Aluminum and silicon constitute the bulk of the samples, with silicon to aluminum ratios of 1.3 and 1.4. Their iron content was of 2.6% and 2.8%. Due to the weathering of the area, the cut exposures are today rusted by iron hydroxides.

The application of the criterion presented by Twenhofel and Tyler (1941) to qualify the granulometric pattern of the two samples indicated that both are quite homogeneous and well classified. For the two samples, the deviations of the quartiles

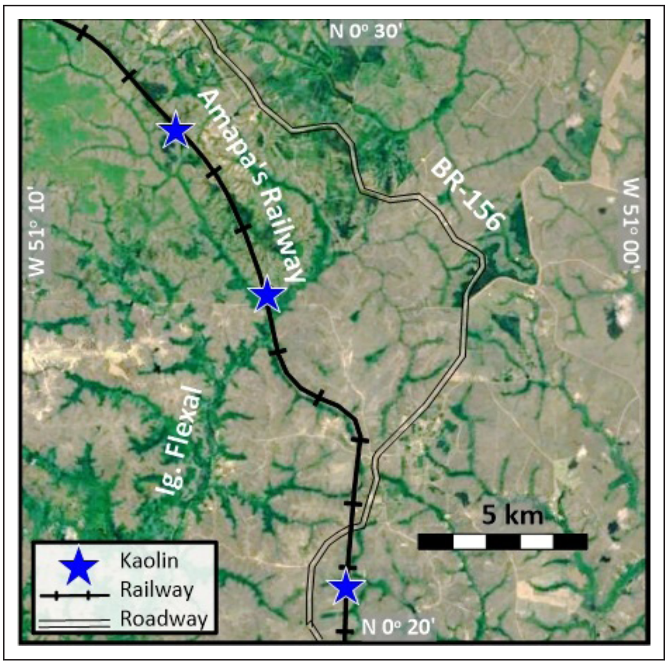


Figure 10. Location of better outcrops of the Pedreira Formation in cuts of the Amapá Railway, as identified in 1966.

Figure 11. A block of kaolin of the Pedreira Formation preserved unoxidized in a cut of the Amapá Railway, south of Porto Grande. Laterally. It is flanked by faults that limited the oxidation. Outside the block, the formation appears as a reddish clayey soil, impregnated by secondary limonite. The unit presents a faint stratification indicating a small angle of dip to the southeast. The outcrop is at elevation of about 40 meters above sea level. A sample of the center of the block was taken and analyzed (Figure 12, and Table 4). This picture was taken during 1966, twelve years after the opening of the cut. Today the rock is oxidized and details are difficult to be recognized. (Photo and geological section by the author; original photo, in black-and-white, was slightly colorized).

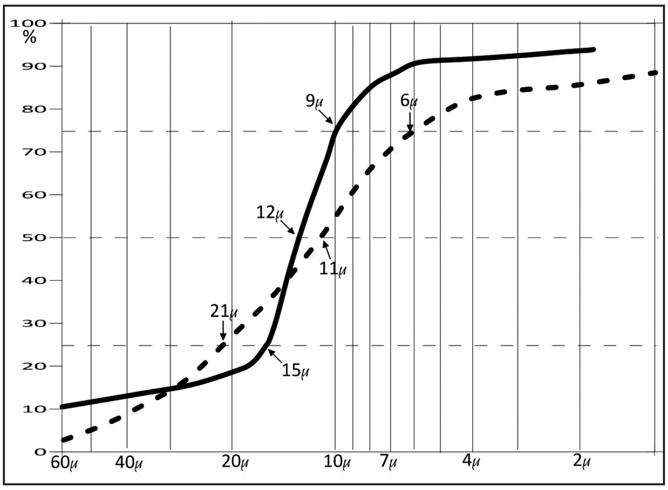


Figure 12. Grain-size distribution of samples of two outcrops of kaolin exposed in the Amapá Railway (Figure 11), spaced by more than 15 kilometers. Analysis of the results are presented in the text of the article and in Table 4.

TABLE 4. Details of two samples of kaolin of the Pedreira Formation.

Characteristics		Sample A	Sample B
Color		bright white	bright white
Chemical* composition	Fe_2O_3	2.8%	2.6%
	SiO_2	52.4%	49.3%
	Al_2O_3	40.6%	35.0%
	fire loss	4.1%	12.9%
	total	99.9%	99.8%
Average grain size		11 μ	12 μ
75% of grains smaller than		21 μ	15 μ
25% of grains smaller than		6 μ	9 μ
Statistics of granulometric distribution	deviation (Q1–Q3)	7.5 μ	3.0 μ
	sorting coefficient	1.87 μ	1.30 μ
	skewness	1.04 μ	0.94 μ

*Chemical analysis and granulometric distribution of samples of kaolin taken from two outcrops of the Amapá Railway. The assay and screen tests were done in 1967, by the Analytical Laboratory of the Mining Division of Indústria e Comércio of Minérios S.A. – ICOMI, Serra do Navio, Amapá.

Q1 and Q3, from the media Q3, were of 7.5 μ and 3.0 μ, with sorting coefficients of 1.87 μ and 1.30 μ, and skewness of the grain-size of 1.04 μ and 0.94 μ. At the surface of topographic shoulders at the margins of the Pedreira River, there are exposures of a kaolin-rich rock, possibly of the Pedreira Formation, partially hardened by recent silicification and limonitization (Figures 13 to 17).

In Guyana and Suriname, the Pomeroon and the Upper Onverdacht Formations, which are the mother units of the bauxite deposits, are also kaolin-rich (Figure 3) (Monsels 2016; Aleva 1981). Considering the similarities between the column of sediments in Guyana and Suriname with the units in the southeast of Amapá, it seems reasonable to consider that the Pedreira Formation might corresponds to those formations. A correlation with the Alter do Chão Formation is also possible. Due to the scarcity of outcrops of the formation, a drilling work is necessary to have an idea of the thickness of the layer or layers of kaolin of the Pedreira Formation. The topography of the area in which this sediment occurs, suggest that it might be, at the least, thicker than 20 meters.

Regarding its lateral continuity, there are no record of other outcrops besides those seen during more than 30 kilometers of the railway, which runs perpendicular to the strike of the sedimentary beds. It is assumed that, as the other sediments, the unit will continue northeastwards from the railway cuts, towards Cutias and Tartarugalzinho, as it happens with the Porto Grande Formation.

Figure 13. Bed of kaolin seen on a topographic shoulders at the southwestern margin of the Pereira River (Figure 14). It is slightly silicified and limonitized along fractures and spaces. It seems to be a young duricrust, under development on a layer of the Pedreira Formation.

3.4. Exposures of indurated bauxite-like soil

Next to the south of the town of Ferreira Gomes, on topographic shoulders, there are exposures of 5 to 10 meters thick iron and alumina-rich paleoduricrust, developed in the upper part of a column of sandy, siltic and clayey sediments. It is rich in free quartz, lighter colored clays and nodules of iron

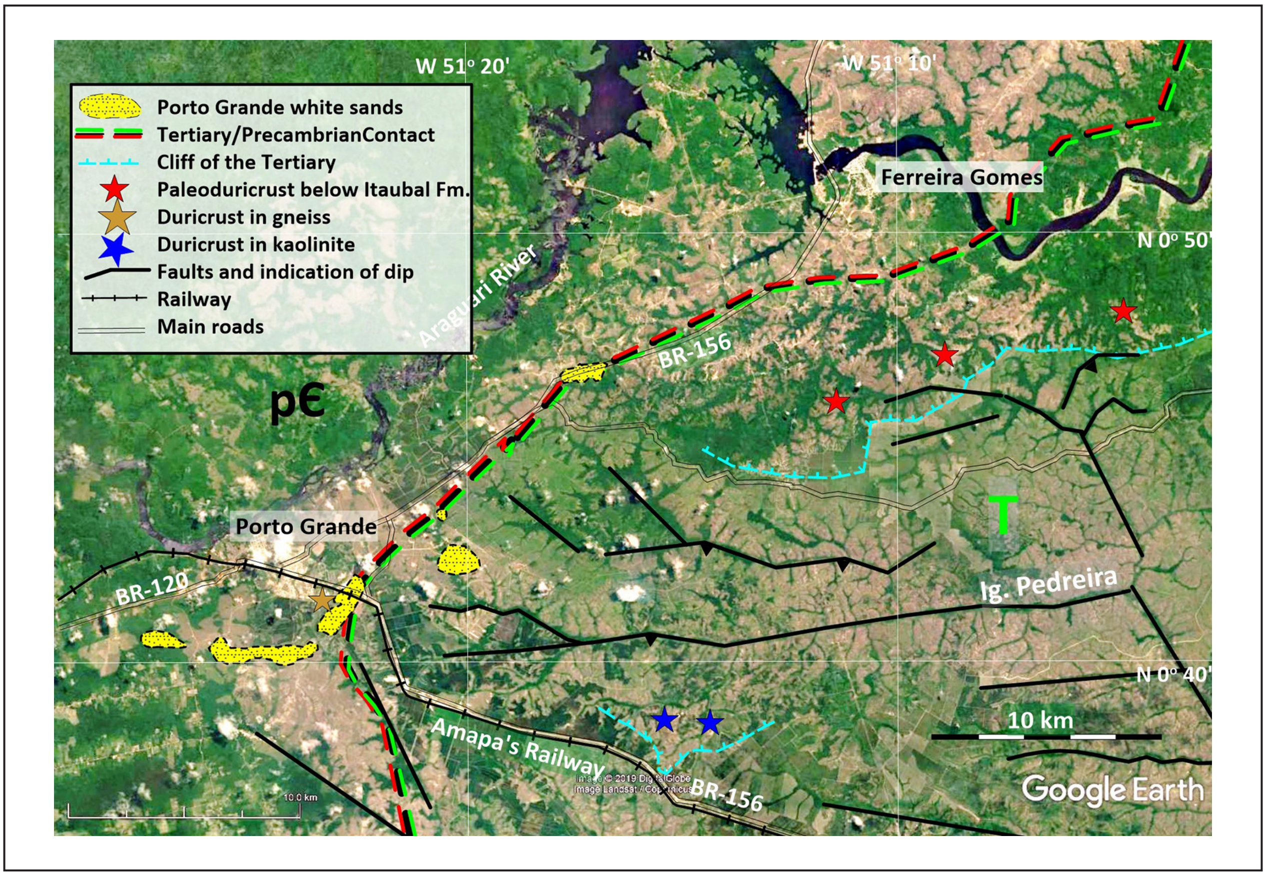


Figure 14. At the south, in blue, location of the duricrust in a layer of kaolin shown in Figure 13. North of it, near Ferreira Gomes, shown in red, there are exposures of paleoduricrust, shown in Figures 15 and 16, occurring below the Itaubal Fm., in a setting similar to what is observed in Guyana (Figure 3). These duricrusts appear in cliffs, with a suggestion of dip to the southeast. Not shown in the map, near Porto Grande there is a duricrust developed in gneiss overlayed by the Pedra Grande Formation (Figure 17).

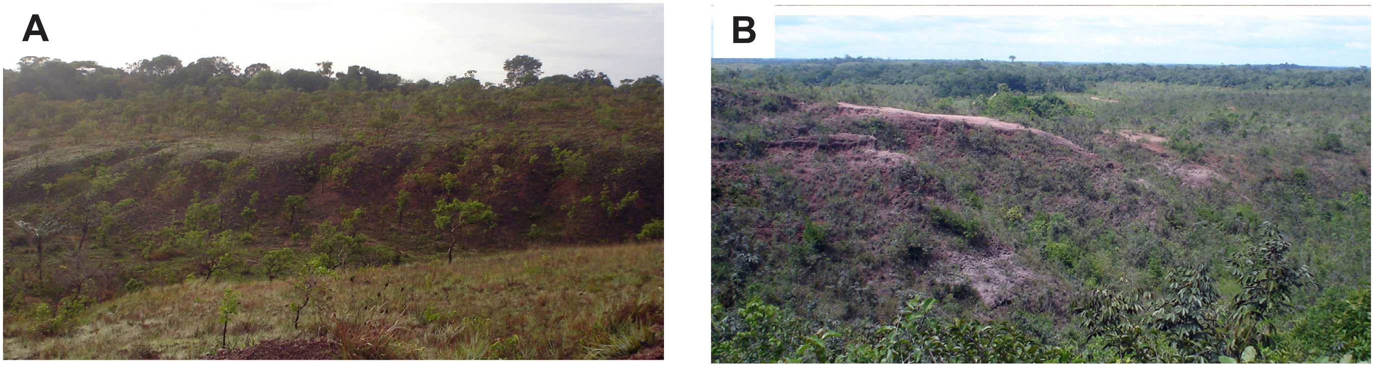


Figure 15. At the south of Ferreira Gomes, topographic shoulders exposing iron and alumina-rich paleoduricrust developed in clastic sediments. They are covered by the Itaubal Formation, and cover older arkosic silts and sands. (A) A view towards the south, parallel with the direction of the dip of the sediments. (B) View to the west, showing how the paleoduricrust cap the underlying sediments, which dip to the south (left). (Photos by the author, 2007).

Figure 16. Close views of the iron and alumina-rich paleoduricrust outcropping at the south of Ferreira Gomes (Figure 15). The textures are nodular, columnar and cellular, similar to those of the bauxite of Guyana and Suriname. The material derives from arkoses and is composed by fine-grained aluminum hydroxides and silicates, iron hydroxides and residual quartz. The content of reactive silica is high, inhibiting its use as bauxite. (Photos by the author, 2007)

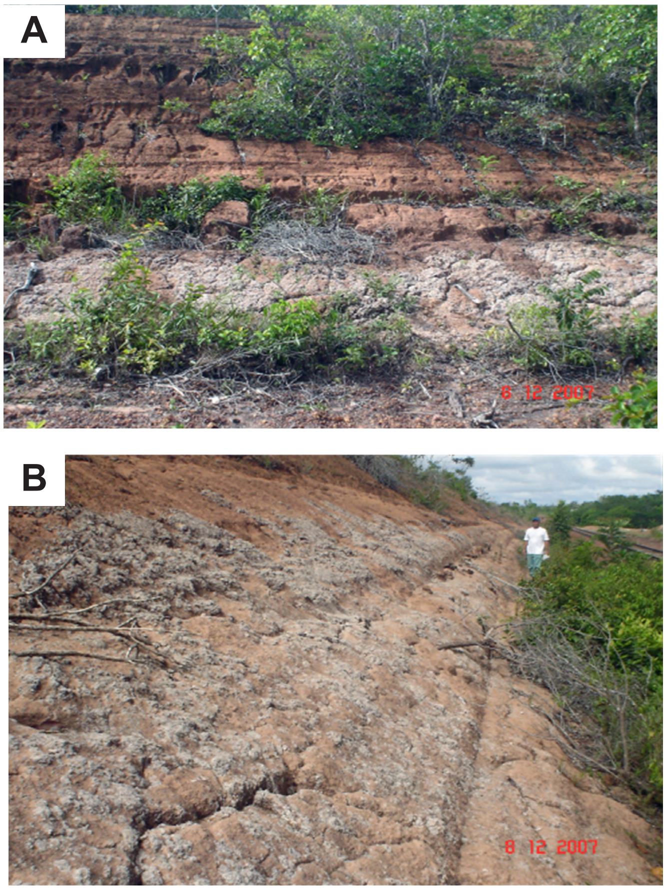


Figure 17. At the Km 106.5 of the Amapá Railway, views of a duricrust developed over basement gneiss. (A) The weathered and leached gneiss is covered by the well stratified and ferruginized Porto Grande (Areia Branca) Formation. (B) Close view of the gneiss, leached of iron and enriched in clayey aluminum silicates, with textures suggestive of alteration by the activity of organisms. It did not reached quality grade bauxite due to a high content of reactive silica. (Photos by the author, 2007)

and aluminum hydroxides (Figs. 14, 15 and 16), and presents columnar structures which are characteristic of bauxite deposits. Due to the high percentage of quartz and iron, the grade of aluminum is low and it does not reach economical grades. They are quite important as a demonstration that bauxite can be found in the area. The paleoduricrust is overlain by the Itaubal Formation, and collectively, they dip with a very low angle to the south. Its presence clearly indicates the occurrence of a period of intense lateritization prior to the deposition of the Itaubal Formation. It is evident that, in the event of a layer of kaolin being exposed to such meteorological conditions, it would undergo a transformation into bauxite.

Another occurrence of bauxite-like soil is observed at the Km 105.5 of the Amapá Railway, at the elevation of 66 meters. It was formed on a gneiss, weathered into an indurated bauxite-like alumina and iron-rich soil. The altered gneiss is covered directly by the Porto Grande Formation, demonstrating that the alteration preceded the deposition of the sand (Figure 17). Irregular masses of brownish clays distributed through the bauxite-like material suggested that it was affected by bioturbation, or pedoturbation.

4. Kaolin and bauxite ore deposits

4.1. Exploration for kaolin

The exposure of a layer, or layers, of kaolin along tens of kilometers of the Amapá Railway, and striking perpendicular to the direction of the railway, demonstrates that there is a large potential for the presence of economical kaolin in the area. Any exploration work for the deposit would involve the definition of the layer or layers of kaolin in the area, their thickness, quality and extension, besides the definition of the local stratigraphy. Samples should be taken at several sites, for the definition of continuity and quality.

The possibility of the presence of large volumes of the kaolin is supported by the strike and the low angle of dip of the layers, the flatness of the topography, and the observation that light colored clays dominates at the base of the slopes over a large area, from the Amapá Railway to near Cutias, and Tartarugalzinho, at the east (Santos et al. [2003]; IEPA 2003). Figure 18 presents the more favorable areas for the identification of kaolin, but it would be of no surprise if the kaolin-bearing layers extend beyond the limits shown in the figure.

4.2 Exploration for bauxite

The favorable indicators of the possibility of existence of hidden deposits of bauxite in the sedimentary cover of the coast of Amapá, are:

1 - A stratigraphic sequence similar to that of Guyana and Suriname.

2 - The similarity of the white sands of the Porto Grande Formation with the White Sands and Zanderij Units of the Berbice and Coesewijne Formations (Figure 02), of Guyana and Suriname.

3 - The sediments that constitutes the Itaubal Formation, corresponding to the Coropina Formation of Guyana and Suriname (Bezerra et al. 2015), overlaying the 'bauxitic' paleoduricrusts.

4 - The presence of a ferruginous and aluminous paleoduricrust below the Itaubal Formation, indicating that the sediments below this formation were once exposed to a long period of weathering and surface concentration of aluminum and iron.

5 - The presence of thick layers of kaolin in the sediments that underlies the Itaubal Formation. These layers might correspond to the Pomeroon and Onverdacht Formations of Guyana and Suriname, respectively.

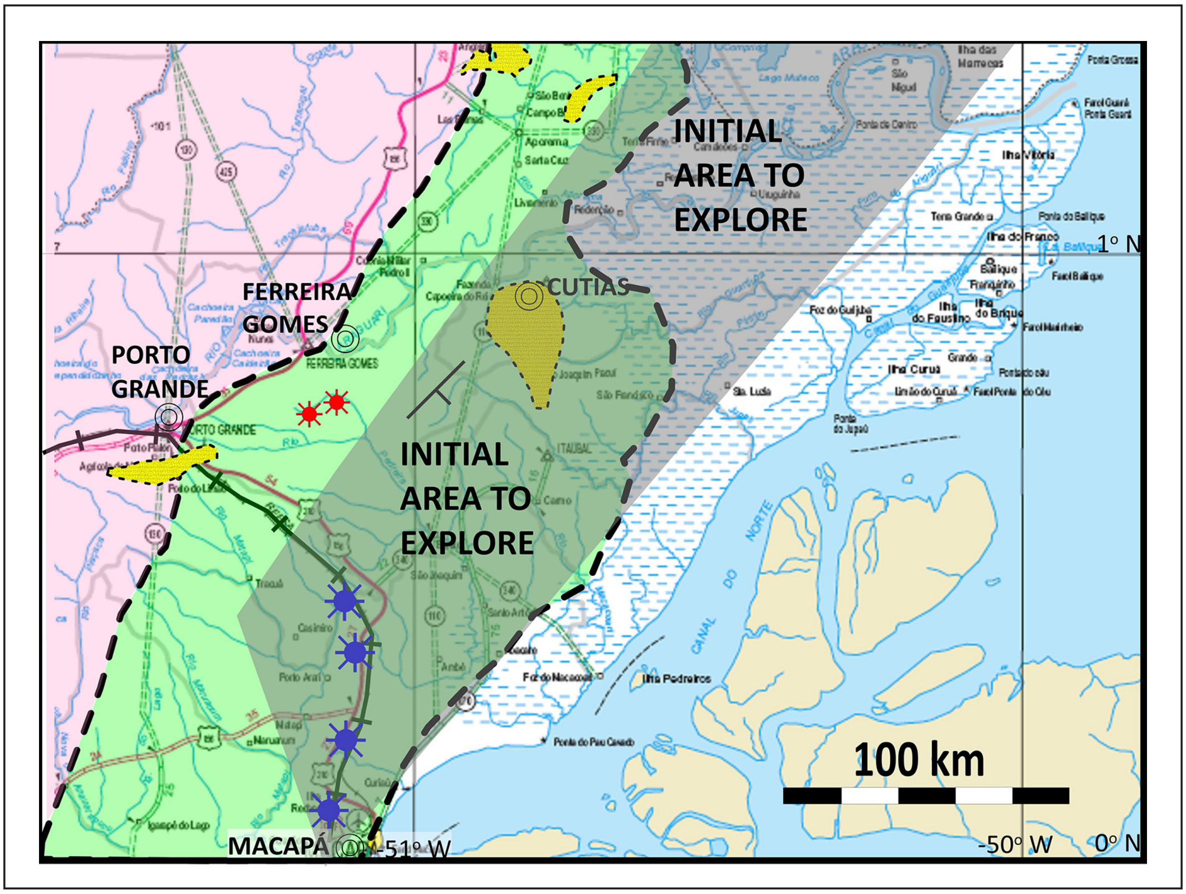


Figure 18. Area of possible extension of the Pedreira Formation in the southeast of the State of Amapá. The area, covering about 30,000 km^2, was delineated considering the exposures of the formation in the cuts of the railway, in the duricrust shown with Figure 13, the strike of the unit, and the occurrences of the Porto Grande Formation along the southern margin of the Araguari River.

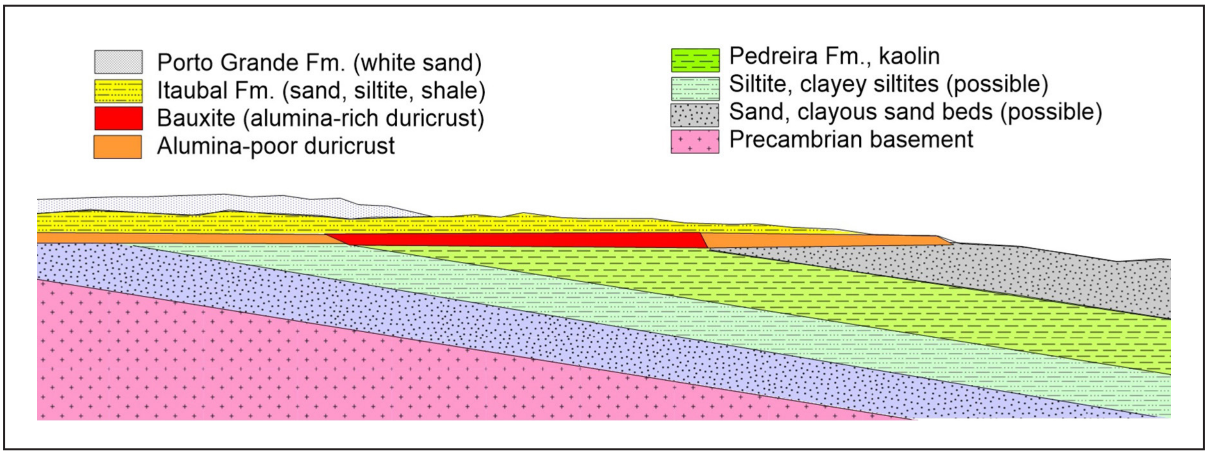


Figure 19. Possible geological section of the column of sediments at the coastal area of Amapá, based on the section of the Lelydorp mine (Figure 3), to be used as an initial model during exploration of kaolin and bauxite. It shows two sequences of sediments, one near horizontal, above, corresponding to the Porto Grande and Itaubal Formations, overlaying an older that contain the Pedreira Formation, and dipping to the southeast. The contact between the two sequences is marked by a paleoduricrust, that might be a good-grade bauxite where developed on a layer of kaolin. Not oxidized portions of the kaolin layers would represent important sources of high quality coating clays.

6 - As it happens in Guyana and Suriname, duricrusts developed over a kaolin layer, like that of the Pedreira Formation, could constitute mineable bauxite.

A model section indicating where to look for the presence of a bauxite deposit in the area is presented with Figure 19. It shows a sequence of sediments overlaying the basement gneisses, and dipping towards the sea, or to the Amazon River. Hidden below a cap of younger layers, represented by the Itaubal and Porto Grande Formations, there is a sequence which was once exposed to weathering, with its upper surface transformed in a ferruginous or bauxitic paleoduricrust. The bauxite would be found where the duricrust developed over layers of kaolin, like those presented by the Pedreira Formation.

5. Conclusions

The Cenozoic sedimentary sequence of the coastal zone of the State of Amapá has clear and ostensive potential for large deposits of kaolin, that can be used for industrial purposes. In addition, the similarities between these sediments and the bauxite-bearing sequence of the coast of Guyana and Suriname, indicate that it is quite reasonable to explore the area also for mineable deposits of bauxite where the Pedreira Formation was exposed for long periods of weathering.

Authorship Credits

Author	A	B	C	D	E	F
WS						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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