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Chromium, iron, gold and manganese in Amapá and northern Pará, Brazil

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ABSTRACT: Information is presented on the geology and mineral deposits in greenstone belts and mafic-ultramafic complexes in Amapá and northern Pará, with the emphasis in iron, gold, manganese, and chromium. At Santa Maria, the Vila Nova Group presents deposits of iron and gold, the latter in carbonatic metasediments crossed by a north-south shear. The group is intruded by the Bacuri Mafic-Ultramafic Complex, with mineable deposits of chromite and magnetite. The overlying 21 Grande Formation presents minor gold mineralization. At Serra das Coambas there is a significant show of iron formation, and, at its flank, the 21 Grande Formation presents extensive areas exploited by gold miners for gold. Serra do Ipitinga, in Pará, contains the greatest units of iron formation of the area, accompanied by frequent shows of alluvial and primary gold mineralization. The distribution of manganeseiferous metasediments identified by mining companies indicate that they were deposited in an about 90 km long narrow basin oriented to northwest, with Serra do Navio near its center. The exposures of iron formation indicate that they were deposited on a belt greater than 350 km long and 100 km wide, oriented and still open to northeast, covering areas of different ages of metamorphism and tectonical stabilization.

KEYWORDS: greenstone belts; mafic-ultramafic complexes; manganese sedimentary basin; iron sedimentary basin; patterns of gold mineralization.

INTRODUCTION

Following our description of the geology of the Amapari Greenstone Belt near Serra do Navio, Amapá, and its deposits of manganese, iron and gold (Scarpelli & Horikava 2017), we now expand laterally the limits of our area of observation and describe other areas of the Paleoproterozoic Maroni-Itacaiúnas Tectonic Province (MIP) presenting similar geology and mineralization. Actually, the area object of the present note covers the MIP from the coast of Amapá, at east, to the headwaters of the Ipitinga River, in the north of the Pará State, at west. As it happened with the first article, the details now disclosed come from direct field observations made by the authors, with data from published and unpublished reports of several geologists and mining companies which the authors worked for or visited, amongst them Indústria e Comércio de Minérios S.A. (ICOMI), Unigeo Geologia e Mineração, Minorco Exploração, MMX Mineração, Extrativa Mineração, El Dorado Gold and others mentioned in the text.

Over this larger area, the MIP is similar to what was described in the previous article, but with regional variation

in the ages of the younger granitic intrusives, variations in the stratigraphy of the greenstone belts, locally distinct metamorphic phase, alkaline intrusives at west, and, quite important, a layered mafic-ultramafic intrusive, with magmatic seams of chromite.

After the description of the general geology of the complete area, we focuses in the Amapari Greenstone Belt at the Vila Nova River, site of deposits and mines of gold and iron in the greenstone, and of chromite and iron in the intrusive Bacuri layered mafic-ultramafic intrusive complex. We revise the published information, updating it with observations recently made in the field by one of the authors. We show that exposures at new mining excavations and aero-geophysical information demonstrate that the mafic-ultramafic complex is intrusive in the Vila Nova Group, similarly to what we saw at the area of the Serra da Canga (Scarpelli & Horikava 2017), and that the auriferous quartzite-conglomerate unit of the area occurs at the top, and not at the base, of the column of metasediments, actually overlaying the Vila Nova Group. Examining the Água Boa auriferous deposit, we saw a very good degree of similarity between the principal structural control of the gold mineralization of this

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deposit with that of the Tucano Mine, practically outlining a pattern worth to follow in general exploration for gold in the MIP. Regarding iron ore, information is brought now, by the first time, of the good commercial products obtained with the mining of the weathered portion of the upper mafic unit of the Bacuri Complex.

Next, after a description of the geology and the deposits of iron and gold of the Serra das Coambas, at the Cupixi River, we bring the location and geological information characterizing all occurrences of iron and manganese so far identified in the Vila Nova Group, in Amapá and north of Pará. It is worth mentioning here that the iron deposits of the Ipitinga River are the larger than all others of the group, visibly reaching billions of tons of mineable ore. The geographic distribution of these occurrences allowed us to outline the extension and limits of the basins of deposition of the manganese and of the iron-rich sediments of the Vila Nova Group, showing that there were local variations in the tectonic and metamorphic regimes that affected them.

After an analysis of the styles and characteristics of the two dominant types of hydrothermal gold deposits in the Vila Nova Group, with details of a few deposits of these types, we call the attention to areas where possibly there are other layered mafic-ultramafic intrusives with potential for chromite and/or platinum group elements, and bring up information about two titanium-bearing alkaline intrusives at the west of the area.

We conclude the article with a summary of the geologic history of the area and its mineral deposits so far identified, followed by suggestions for forthcoming explorations for iron, gold, base metals, manganese, chromite and other mineral commodities of the area.

GENERAL GEOLOGY

Most of the area of the MIP in Amapá and North Pará is constituted by granitoids (gneisses, migmatites and intrusive granitic rocks), which form the basement for the belts of greenstones and associated syntectonic granitic intrusives. This setting is intruded by layered mafic-ultramafic complexes, alkaline rocks and diabase dikes (Tab. 1). The greenstone belts, which host the most important mineral deposits so far seen, are relatively simple to identify, due to the dominant pattern of their topography, formed by sub-parallel and long ridges, due to alternation of rocks with different resistance to weathering and erosion. In contrast, the mafic-ultramafic intrusions are deeply weathered and appear with a subdued topography, usually with a thick cover of secondary limonitic duricrust (canga); they are identified, or inferred, with the help of geophysical and geochemical methods. Alkaline intrusives form isolated peaks in the western part of the area. Diabase dikes, common everywhere in the area, are more frequent in the northeast, where they strike north and are related to the Atlantic Magmatic Province.

Using ages of granitic intrusives, Rosa-Costa (2006), Barreto *et al.* (2013) and Klein *et al.* (2014) have found that the area could be divided into three distinct sectors. At the center and elongated to northwest, the Amapá Block is Archean, flanked at northeast by the Lourenço Domain and at southwest by the Carecuru Domain (Fig. 1), both presenting gneisses and migmatites formed or reworked during the Paleoproterozoic. Paleoproterozoic ages were also obtained from the syntectonic granitic intrusions associated with the greenstone belts, for the layered mafic-ultramafic intrusions, and for a granulitization event observed in the eastern portion of the Amapá Block (João *et al.* 1978),

Table 1. Stratigraphic column of the Maroni-Itacaiúnas Tectonic Province at Northern Brazil.

Age	Unit		Lithologies	Mineralization
Quaternary			Alluvial sediments	Au, Sn, Ta
Triassic	Cassiporé		Diabase dikes	
Neoproterozoic			Alkaline intrusives	Ti
Paleo-Proterozoic	21 Grande Formation		Quartzites and metaconglomerates	Au, Diamond
	Intrusive layered complexes	Canga	Mafic-ultramafic layered complexes	Cr Possible Ni, PGE
		Bicicleta		
		Bacuri		
	Syntectonic acid intrusives		Granites, monzogranites, granodiorites	Sn and Nb/Ta pegmatites
	Vila Nova Group	Coambas Formation	Platform marine metasediments	Fe, Mn
		Santa Maria Formation	Platform marine metasediments	Fe, Au
		Serra da Canga Formation	Platform marine metasediments	Fe, Au, Mn
		Serra do Navio Formation	Littoral/marine cyclothem	Mn
		Jornal Formation	Orthoamphibolites	
Archean to Paleo-Proterozoic	Basement		Gneisses, migmatites, granitoids	

affecting basement rocks and overlying greenstone rocks (Scarpelli 1969, Rosa-Costa *et al.* 2014). Large areas of the Amapá Block present isolated and short remnant ridges of quartzites and mica schists amidst the Archean gneisses and migmatites.

The gneisses, migmatites, greenstone belts and mafic-ultramafic intrusive are metamorphosed to the Amphibolite Facies, with retrograde metamorphism to Chlorite Facies in a few faults, shear zones and areas affected by hydrothermalism. The dominant foliation is towards northwest, the direction of elongation of most greenstone belts, their fold axis and shear zones.

A detailed petrographic study of the Amapari Greenstone belt at Serra do Navio has shown that it was subject twice to regional metamorphism, with an intermediate episode of thermal metamorphism caused by syntectonic granitic intrusions. Local fold axis and elongation of greenstone to north and northeast suggest that these structures might be remnants of the first regional metamorphism (Scarpelli & Horikava 2017).

The Vila Nova Group, which is the main constituent of the greenstone belts, is composed by a unit of orthoamphibolites at base, overlain by fine-grained clastic and chemical metasediments, passing upwards to metamorphosed silts and sands. At a few sites, the sequence ends up with metaconglomerates and quartzites of the 21 Grande Formation (Tab. 1).

The Jornal Formation orthoamphibolites are massive, medium to coarse grained, nematoblastic without a clear layering, formed mostly by hornblende, plagioclase, quartz and accessory magnetite. Occasionally, there are intercalations of quartz-mica schist, well banded actinolite schists and other schists (Scarpelli & Horikava 2017).

At the base of the metasediments, the Serra do Navio Formation is a littoral/marine cyclothem constituted by alternation of layers of fine-grained clastic metasediments, marbles, metamarls and metachert. Each cycle presents at base rocks rich in calcium carbonates in association to quartz-mica schists and metachert. These rocks are covered by a well foliated biotite schist and, closing up the cycle, with graphite schist locally with a lens of fine to medium-grained spessartite-bearing rhodochrosite marble. Gondites, formed by coarse-grained spessartite, manganese silicates and graphite, appear in the transition zone between the manganeseiferous marble and the graphite schists (Scarpelli & Horikava 2017). This formation was only seen around Serra do Navio. Under weathering, the shallow portions of the lenses of rhodochrosite were altered into masses of high-grade manganese oxides, predominantly made of psilomelane and pyrolusite (Scarpelli & Horikava 2017).

The Serra da Canga Formation overlies the Serra do Navio Formation and has a larger regional distribution. It is formed by platform marine metasediments, with a basal unit of actinolite and cummingtonite schists, covered at a few sites with fine-grained clastic and chemical sediments, somewhat resembling those of the Serra do Navio Formation and presenting a narrow passage of graphite schist, gondite, and manganeseiferous schists. Above it, there are fine-grained clastic metasediments with lenses of metachert and calcium-magnesium metamarls and marbles, commonly presenting muscovite-biotite schists, quartzites and amphibole schists. Towards the top, the sequence becomes poor in carbonates and richer in iron, presenting units of well banded silicate and oxide iron formations, with variable percentages of grunerite, cummingtonite, diopside, magnetite, quartz and biotite, and higher up in the column, units of hematite itabirites. The upper part of the formation is made of fine-grained clastic metasediments, metamorphosed into garnet muscovite quartzites. At a few sites, large masses of iron formation are mined for iron ore. The manganeseiferous passages are marked by surface accumulations of low-grade blocks of weathered gondites and manganese impregnated schists. Economic concentrations of gold occur in hydrothermal systems hosted in faults and shear zones. Some, oriented about north-south, seem to be product of reactivation of structures from the first phase of regional metamorphism (Scarpelli & Horikava 2017).

The 21 Grande Formation is constituted by fluvio-littoral quartzites with interlayers of polymictic to oligomictic

Figure 1. The Archean and Paleoproterozoic areas of the Maroni-Itacaiúnas Tectonic Province (MIP) in northern Brazil, their granite-greenstone units, and mafic-ultramafic and alkaline intrusions. Limit of RENCA is shown. Based on Tassinari and Macambira 2004, and Barbosa *et al.* 2013.

metaconglomerates. Alluvial derivatives of these rocks are locally exploited for gold and diamonds.

The syntectonic granitic intrusives associated with the greenstones appear as domes elongated parallel with the strike of the greenstones, and quite often present a foliation parallel with the foliation of the intruded rocks. Pegmatites related to the granites intrude the greenstones, and some are mineralized with cassiterite and columbite-tantalite, which are recovered by gold miners from alluvial flats.

Mafic-ultramafic layered sequences intrude the Vila Nova Group, as seen at the Canga and Bicicleta Complexes (Scarpelli & Horikava 2017). At Santa Maria do Vila Nova, they present important mineralization of chromite.

GEOLOGY AND MINERAL DEPOSITS AT SANTA MARIA DO VILA NOVA

At the mid-course of the Vila Nova River, Santa Maria constitutes the last tip of the extension of the Amapari Greenstone to the southwest, where it appears forming short and adjacent synclines with axis and foliation to the northwest.

Due to lack of outcrops and widespread cover of canga, the limits of the geological units are undefined over large areas. An acceptable geological map of the area is shown with Figure 2, based on the work of Spier and Ferreira Filho (2001), updated with information collected in the field by the first author and reports of Mineração Vila Nova, Eldorado Gold and Amapari Mineração, the latter a subsidiary of ICOMI.

Although the area was object of one of the first studies of the Precambrian in Amapá, for the iron formation that crops out at the margins of the Vila Nova River, due to the scarcity of outcrops and lack of core drilling, not much is known about the stratigraphy of the Vila Nova Group in the area.

There are poor exposures of the Jornal Formation orthoamphibolites, and the group is represented mostly by the metasediments of the Santa Maria Formation, the local equivalent of the Serra da Canga Formation, constituted by units of iron formation and fine-grained, limy, siliceous, and schistous metamarls, usually including layers of chert and fine-grained quartzites. The units of iron formation vary from itabirites to quartz-magnetite itabirites, and to magnetite-silicate iron formations. Most of what is known about the formation was learned with the exploration and exploitation work for gold and iron.

The overlying 21 Grande Formation is composed by fluvial to littoral quartzites and metaconglomerates folded into a syncline occurring at the right margin of the Vila Nova River. Its name is taken from the 21 Grande Creek, that drains through the center of the syncline. While Spier and Ferreira Filho (1999) considered these rocks to constitute the base of the metasediments

of the Vila Nova Group, they actually overlie it, as they cover a unit of banded iron formation which extends from Samacá, in the south, to Travessão, in the north, whose continuity is shown with an aeromagnetic map of CPRM (Fig. 3).

Appearing immediately to the south of the Vila Nova Group, the Bacuri Complex is an important mafic-ultramafic layered sequence. Based on what they saw at the chromite mine area, Spier and Ferreira Filho (2001) presented the Bacuri Complex as older than the Vila Nova Group, since that the chromite-bearing intrusives appear there in contact with the basement, without any sign of the Santa Maria Formation. Recent exploitation for chromite and iron by Mineração Vila Nova further west, at Samacá, revealed that the complex actually overlies the Santa Maria Formation, which is also locally cut by narrow dikes of serpentinites.

As such, the Bacuri Complex is younger than the Vila Nova Group, in accordance with what was observed at Serra da Canga, where the Canga and Bicicleta Complexes intrude the Serra da Canga Formation (Scarpelli & Horikava 2017). More information about the complex is presented in the description of mining.

The largest structure at Santa Maria is a north-south shear that, at east, deformed the layers of the Bacuri Complex and folded the units of the Santa Maria Formation to north-south, also creating conditions for gold mineralization.

Iron ores of the Santa Maria Formation

Only small tonnage of iron ore was exploited from the deposits that attracted several companies to the area. They are made of units of banded iron formations similar to those of the Serra da Canga Formation (Scarpelli & Horikava 2017), outcropping at the margins of the Vila Nova River, and continuing to the north and northwest along ridges of 40 to 60 m of elevation above the water level of the river.

The larger group of deposits, Bacabal, Leão and Lagos, at the northeast of the area, are under control of Eldorado Gold. Outcropping at both sides of the Vila Nova River, the iron formation is 5 to 40 m thick and has a high angle of dip. It strikes northwest, and is bent to the north where it gets close to the shear (Figs. 2 and 4).

Hematite, in massive and laminated forms, is the dominant mineral, followed by magnetite, martite, quartz and residual clays left after the weathering of interspersed silicates. It was drilled by Hanna Mining in the middle of the last century and recently redrilled by Eldorado Gold Corp., who outlined an indicated resource of 10 million tons at 61.6% Fe, plus 2 million tons inferred, from the surface down to a depth of 120 m (Juras 2007). A large part of this resource occurs below the water level of the Vila Nova River. The drilling was limited to the shallow part of the deposit, and, besides the iron formation, it only recovered weathered and friable fine-grained and clayey schist with quartz and sericite.

Figure 2. At Santa Maria, the Vila Nova Group is intruded by the Bacuri Complex and is covered by the 21 Grande Formation. A north-south shear zone deforms the layering of the metasediments to north-south and limits the extension of the Bacuri Complex to the east. Mining for iron is done with iron formations of the Vila Nova Group and with magnetite rich mafic layers of the Bacuri Complex. Chromite is obtained from an ultramafic unit of the complex. Gold is taken from hydrothermal deposits at where the shear zone crosses the metasediments of the group, and from metaconglomerates of the 21 Grande Formation. Another potential complex might be present at south under a thick cover of duricrust. Limits of Figures 3, 4 and 7 are shown.

Figure 3. Analytical signal magnetic contour map of the northern part of Figure 2, outlining, at west, the northeastern lineament marking the magnetite-rich northern branch of the Bacuri Mafic-Ultramafic Complex, and the hidden extension of iron formation to northwest, connecting Km 7 to Travessão, under the 21 Grande Formation (Geophysical map from CPRM 2004d).

Figure 4. Geologic map and cross section of the Santa Maria iron deposit, as presented by Eldorado Gold 43-101 report (Juras 2007). The ore is made of well foliated hematite schist, passing to itabirites at north.

Other occurrences of iron formation, such as Travessão and Km 7, are controlled by Mineração Vila Nova, who explored them with mapping and drilling, but have not disclosed the results. The outcrops expose massive magnetitic itabirite, rich in martite and silicates.

Gold mineralizations of the Santa Maria Formation, the Água Boa Mine

Hydrothermal gold mineralization extends for about 10 km along the north-south shear zone at the east of the Bacuri Complex, with the mineralization exposed at both margins of the Vila Nova river by mining excavations and core drilling. It occurs inside a 100 to 400 m wide zone of carbonatization, passing inwards into zones of sericitization and silicification. The host rocks, striking north-south, are paramphibolites and carbonatic quartz-biotite-chlorite schists, intruded by subparallel dikes of serpentinites and tremolite amphibolite related to the Bacuri Complex.

The gold occurs in the more silicified areas, in free form and with pyrite in swarms of veins and veinlets of fine grained silica (Figs. 5 and 6), with each swarm reaching tens of meters of width and hundreds of meters of extension.

The mineralization was identified by ICOMI (Spier & Ferreira Filho 1999) and was exploited open cast by Mineração Água Boa, who, from 1991 to 1997, mined more than 900,000 tons at 2.7 g/t Au, extracting the gold with heap leaching, after crushing and milling. The total production surpassed 2.5 tons of gold.

During the operation, gold miners invaded a part of the property north of the Vila Nova River and have stayed there ever since, producing an unknown quantity of gold.

Figure 5. At Vicente, the auriferous mineralization occurs in tectonic swarms of veins and veinlets of fine grained silica, in a more than 400 m thick zone of hydrothermally carbonatized and sericitized schists of the Santa Maria Formation.

Figure 6. At Água Boa, small veins and veinlets of auriferous silica in sheared and hydrothermally altered schists of the Santa Maria Formation. Note superposed sets of fractures, faults and veins. The distribution of the gold is not uniform, varying from a few to tens of grams per ton.

Early in this century, a part within the area north of the river was mapped and drilled with short holes, which led to the identification of a shallow resource of 0.5 million tons at 2.4 g/t gold, amenable for surface mining.

The mineralization is open in depth, and the geochemical and geologic data indicate that it follows the shear to the north and the south of the exploited areas. With the lack of activities of mining companies, these deposits continue to attract gold miners.

The Bacuri Mafic-Ultramafic Layered Complex and mining of chromium and iron

The Bacuri Mafic-Ultramafic Layered Complex is Paleoproterozoic, determined with an age of 2.22 ± 0.12 Ga obtained by Sm-Nd (Pimentel *et al.* 2002). As shown with Figure 2, in the east, it is limited by the north-south shear zone, next to which it reaches maximum structural complexity, is in contact with basement gneisses at the south, intrudes the Vila Nova Group at west and is overlain by the 21 Grande Formation at north. There are two distinct branches of the intrusion, one at north and the other at south, both subvertical and oriented to southwest. It seems that the two branches occupy subvertical fractures extending

from the shear, possibly opened during the development of the shear.

As described by Spier & Ferreira Filho (2001), the southern branch contains a semi-continuous level with chromitite, which was intensely mined at shallow depths. This branch, shown with Figure 7, has a thickness of about 950 m and was detailed and mined for about 13 km, from the limiting shear to Samacá, in the west. It is formed by a basal 500 m thick leuco orthoamphibolite, an intermediate 30 to 150 m thick unit of serpentinized ultramafics, and a 300 m thick upper unit of mafic orthoamphibolites.

The lower and the upper orthoamphibolites do not present indications of internal layering, and are composed of hornblende, plagioclase, some biotite and accessory ilmenite and titanite, differing in color and texture. The leuco orthoamphibolites have a granoblastic texture, more plagioclase than hornblende and weathers to a white saprolite. The mafic orthoamphibolites, which are similar to the orthoamphibolites of the Jornal Formation, have a nematoblastic texture, more hornblende than plagioclase, and weathers into a dark-brown ferruginous saprolite.

The intermediate ultramafic unit is made of serpentine, tremolite, chlorite, talc, magnetite and antophyllite, and presents several horizons of chromitite, with the greater and

Figure 7. Geologic map of the Bacuri chromite horizon adapted from Spier and Ferreira Filho 2001. The horizon sits at the contact of the ultramafics with the leuco orthoamphibolite, and is divided, or split, in ten isolated deposits: B7, B5, B3, B1, C1, C3, C5, C7, C9 and C11. The Samacá deposit, further to the west, is not shown. The tectonic pressures that folded and broke the unit came from the shear zone, at east. Below, enhancement of ore body B1, also shown with sections B-B' and C-C'; traces of sections are shown with enhancement A, center-below.

more important of them appearing right at the base of the unit, in contact with the leuco orthoamphibolite. Above this horizon, the chromite appears mostly in small lenses and disseminations (Spier & Ferreira Filho 2001).

These rocks are metamorphosed to the Amphibolite Facies. Overall, they are highly deformed by strong westwards tectonic pressures (Fig. 8), with the horizons of chromitite locally reaching a near-ductile stage of deformation (Fig. 9), which led to boudinage, lateral discontinuities and variations of thickness, with asbestus, serpentine and biotite found in tectonized zones.

The northern branch was identified when the chromitite body of Samacá was mined. It overlays the southern branch and is poorly studied, being composed mostly by mafic orthoamphibolites, with frequent passages of pyroxenites and serpentized dunites. Its basal portion is quite rich in magnetite, which appears disseminated and as masses of magnetites. This branch is marked by a strong and straight 8 km long magnetic anomaly and does not present the complex folding that characterizes the southern portion (Fig. 3). The

Figure 8. The B1 chromite ore body stretched and pushed westwards along the foliation. Granitic pegmatites fill spaces opened with the tectonism. Geologists C.A. Spier and J.M. de Souza.

magnetic anomaly indicates that it does not continue westwards from Samacá.

Above background values of chromium and presence of grains of chromite in stream sediment indicate an unmapped extension of the complex, southwestwards of Samacá for at least 15 km.

Chromite mining

The complex and the deposits of chromite were found by ICOMI after the identification of a few blocks of chromitite in the course of an exploration program (Spier & Ferreira Filho 1999). With soil sampling, 13 km of mineralization were identified, from the shear zone to Samacá. Detailed geological and drilling works were done in the eastern 7 km of that extension.

The strong compression to which the intrusives were submitted imprinted a foliation to the chromitite, dividing it into lensoidal bodies with thicknesses of 3 to 30 m, averaging 12 m, and lateral extensions of up to 250 m. Drilling limited to about 300 m of depth allowed the estimation of 9 million tons of indicated resources of chromite ore (Spier & Ferreira Filho 1999).

The ore is constituted by 60% of chromite grains of small to medium size, in a matrix of serpentine, chlorite and tremolite. It appears in three types: indurated and mixed with iron oxides at the lateritic cap, friable until 60 to 120 m of depth, and fresh below these depths (Spier & Ferreira Filho 1999).

Mining was initiated in 1989 by CFA - Companhia Ferro Ligas do Amapá, a subsidiary of Companhia Auxiliar de Empresas de Mineração (CAEMI), the principal shareholder of ICOMI. In 1997, the mine was sold to Mineração Vila Nova, a subsidiary of Elkem. A few years later, Mineração Vila Nova was sold to FASA S.A. (Monteiro 2003).

Mining was done in 12 pits opened along the mineralized structure, and the run-of-mine surpassed 3.1 million tons,

Figure 9. Hand samples of chromitite, polished and rough, showing the strong deformation of the broken and laterally stretched ore.

averaging about 34% Cr_2O_3 , at a strip ratio of 6:1, waste to ore, in tons. The ore was crushed, washed, screened, and cleaned with spirals, resulting in the production of 1.4 million tons (Monteiro 2003), at 55 to 60% Cr_2O_3 , 11 to 17% Fe, 8 to 13% Al_2O_3 and 8 to 12% MgO (Spier & Ferreira Filho 1999). The typical product would have a Cr:Fe ratio between 2.4 and 3.4. The exploitation with open pits practically exhausted the shallow portions of most ore shoots and is presently suspended for economic or logistical reasons.

From the initial indicated resource of 9 million tons, there are more than 3 million tons to exploit, most of which for underground work. An incline was opened to access the ore bodies at depth, but it is abandoned and flooded. As far as the resource is concerned, there is more to be found at depth and along the strike of the mineralization. It seems interesting to explore the extension of

the mineralization to the southwest, where the tectonism might have been weaker.

Although some samples confirmed presence of gold and platinum group elements (PGE), no dedicated effort was made for a proper evaluation of the opportunity.

Iron ore of the Bacuri Complex, the Samacá Deposit

The opening up of the chromite deposit at Samacá exposed the magnetite-rich orthoamphibolite at the base of the northern branch. Initially indicated with an aeromagnetic survey of CPRM (CPRM 2004d), shown with Figure 3, its actual location and extension were determined with a ground magnetic survey. It was then core drilled on a 100×20 m grid, with the holes limited to its weathered portion (Fig. 10). The exploration confirmed the continuity

Figure 10. Shallow drill section of the northern branch of the complex, adapted from two sections produced by Vila Nova Mineração, showing the areas with more and with less than 41% Fe in situ, and relative magnetic intensity of the drill cores. The cores are made of weathered orthoamphibolites with passages of metapyroxenites and a few serpentinites (lithology not shown in the figure).

Figure 11. At left, a close-view of the saprolitic iron ore and, in the far-side, the limit of the Samacá chromite pit, in the southern branch. At right, a road opened along the axis of the east-west magnetic anomaly that marks the northern branch of the Complex. .

of the magnetite-rich belt for more than 7 km and 270 to 400 m of width, with the mineable weathered zone reaching 50 to 70 m of depth (Fig. 11), defining a not declared total resource of about 100 million tons.

Recovery of magnetite and martite reaches about 20% of the material. After crushing, washing and screening, the final product assays about 57–60% Fe and 12% of silica plus alumina. Phosphate values are low. It seems worthwhile to examine these concentrates for the presence of vanadium accompanying the iron.

21 Grande Formation, Gold and Diamonds

The isolated syncline that contains the 21 Grande Formation has a fold axis to the east, extending 6 km east-west and 6 km north-south (Fig. 2). According to Spier & Ferreira Filho (1999), it is composed of clean quartzites, muscovite quartzites and metaconglomerates. As the metaconglomerates are thicker and more continuous at its northern limb, it is assumed that the source areas were in the north.

At the base of the syncline, there is a quartz-mica schist containing tourmaline, feldspars and fuchsite, covered by a 5 to 20 m thick pebbly quartzite which, at its upper part, presents a 5 to 20 cm thick auriferous zone made of tourmaline-bearing lines of fine-grained quartz, and concordant lenses and veinlets of silica. This zone, albeit containing indications of hydrothermalism, is concordant to the bedding, and was used as a marker guide in geological mapping (Spier & Ferreira Filho 1999).

On an erosional contact, this marker guide is covered by a more than 20 m thick polymictic metaconglomerate with interlayers of quartzite. It is matrix supported and presents badly sorted large pebbles and cobbles of quartz, quartzite and mica quartzites, with pebbles of schists and ultramafic rocks near the base. The matrix is composed of fine-grained quartz, plagioclase, tourmaline, muscovite, fuchsite and chromite (Spier & Ferreira Filho 1999).

Covering the metaconglomerate there is a sequence of medium-grained feldspar-sericite quartzites, with intercalations of oligomictic metaconglomerates, with better rounded and classified pebbles.

Throughout the syncline, there are centers of alluvial gold mining by gold miners, principally in valleys draining from the contact between the tourmaline-bearing marker guide and the basal metaconglomerates. Besides gold, on a few occasions, good quality diamond stones were also recovered. The activity is weak, but has been maintained intermittently for decades.

ICOMI explored the main unit of metaconglomerate, exposed at the northern portion of the area. With drilling and underground work, ICOMI found that the

gold distribution is erratic and concentrated at the base of the metaconglomerates, close to the marker guide. The limited work was enough to indicate a resource of 1.3 million tons at 0.84 g/t gold (Spier & Ferreira Filho 1999).

GEOLOGY OF SERRA DAS COAMBAS

In the mid-course of the Cupixi River, 40 km southwest of Serra do Navio, the Vila Nova Group forms the Serra das Coambas (Fig. 12), which is an overturned homoclinal structure striking north-northwest and dipping at about 70 to 80° to west. With about 20 km of extension, the ridge reaches the elevation of 250 m above sea level, and at its central part exposes a 5 km thick section of the group. As a homocline, the structure is an ideal place to define the lithologies and stratigraphy of the group, but the deep weathering inhibits observation of the lithologies less resistant to weathering and erosion, such as the carbonatic metasediments. Information presented here came from geological

Figure 12. Geological map of Serra das Coambas, emphasizing the iron formations of the Coambas Formation, and the auriferous areas in the 21 Grande Formation, the latter possibly controlled by northeastern shear zones. (Map based on the information gathered by the authors and ICOMI).

work by the authors and ICOMI before 1985. Recently, CPRM made a short visit to the area (Barbosa *et al.* 2013, Barbosa *et al.* 2015).

Besides the pervasive northwest foliation and the concordant shears that mark the Vila Nova Group, the area is also affected by a series of faults striking northeast and shears striking northwest, which seem to be responsible for the curved form of the ridge in the south, and were possibly influential in gold mineralization at the center north of the area, next to the Braço do Cupixi River.

Basement gneisses and granitic intrusives appear at both sides of the ridge. Locally, amidst the gneisses, there are small ridges oriented to the northwest and made of remnants of quartzites and schists which resisted gneissification. The alluvial sediments in these areas often present a good quantity of ilmenite.

In the low-land area at west of the ridge, there are pegmatites and alluvial deposits exploited for tantalite.

The Jornal Formation occurs in the west side of the ridge, in contact with the gneisses and dipping west. It is constituted by a few hundreds of meters thick section of ortho-amphibolites, associated to chlorite schists, hornblendites and minor talc schists.

Coambas Formation, and iron mineralization

The name Coambas Formation is used for the sequence of metasediments similar to the Serra da Canga Formation that covers the Journal Formation and constitutes the bulk of the ridge that forms the Serra das Coambas.

The quartzites contain magnetite, sillimanite, garnets, and muscovite. The first in the west, near the Journal Formation, also contains fuchsite. A few outcrops of quartz-biotite-garnet schists appear in steep slopes between ridges. No outcrops of carbonatic rock were seen. In the eastern flank, there are fine grained quartz-muscovite schists, possibly metapelites or metasiltstones.

At the higher part of the ridge, there are two units of banded magnetite iron formation, with masses of compact martite. These units have tens of meters of thickness and extend for several kilometers, locally covered by a thick limonitic duricrust cementing blocks of the iron formation. Hematite schists and itabirites were seen in trenches. With more than 15 km of extension, these resources of iron might be worthwhile to be taken into consideration.

At the western flank of the ridge, near the lower unit of iron formation, there are exposures of weathered schistose and siliceous rocks impregnated with secondary manganese hydroxides, in a similar way to what is seen at the base of the Serra da Canga Formation.

21 Grande Formation

At the east, separated from the ridge metasediments by a fault zone, there is a sequence of metasediments of the 21 Grande Formation. Next to the fault, there is a dominance of badly sorted polymictic metaconglomerates, with pebbles of quartz veins, quartzites, iron formation, schists and gneisses forming less than 50% of the unit. To the north, northeast and southeast, they are covered by quartzites and micaceous schists. Ilmenite is common in stream sediments of its southern part.

Gold mineralization

Where affected by the shear and faults, the 21 Grande Formation is highly fractured and silicified, with gold mineralization associated to quartz veins and veinlets, similar to what is seen with Figure 6. Active rudimentary gold mining are installed at Baixão (Fig. 12) for primary and alluvial gold.

Other minor centers of gold concentrations occur in the general area, some amidst remnants of schists and quartzites in the gneissic terrane. It seems reasonable to consider that primary mineralization might also occur up on the ridge, in the chemical sediments of the Coambas Formation.

OTHER MINERAL DEPOSITS AND OCCURRENCES

Next, we present information about other occurrences of manganese and iron formation in the greenstone belts, aiming to visualize the extent of their basins of deposition. This knowledge is a product of decades of exploration work done by ICOMI and other mining companies, that looked for manganese and iron in all of the greenstone belts and blocks shown with Figure 13, which is an updated version of Figure 2 of the article of Scarpelli & Horikava (2017). Details of a few occurrences and possibilities for gold, chromium and other metals are also presented. All occurrences are listed in Table 2 and shown with Figure 13.

Deposits and occurrences of manganese

Apart from the manganese oxide deposits of Serra do Navio, which occur in the cyclothem of the Serra do Navio Formation (Scarpelli & Horikava 2017), all other identified occurrences of manganese were found at the base of the Serra da Canga Formation.

These occurrences are represented by oxidized gon-dites and by mangesiferous schists. The gondites are constituted by coarse-grained spessartite in a matrix of

quartz and other silicates, often appearing close to a narrow band of graphitic schist. On the surface, their area of occurrence is marked by the presence of dark-brown blocks of weathered gondite. At depth, the gondites appear as layers that could be followed by drilling. The manganeseiferous schists appear on the surface in the form of masses of weathered schists impregnated and partially replaced by manganese oxides and hydroxides. Sometimes, the replacement is intense, forming small blocks of massive ore. They represent the weathered products of fine-grained manganese-bearing metamorphs, and, as such, they are limited to the near-surface, without significant extensions in depth.

Expressive volumes of gondites were found in three sites: Serra do Veado, Serra Grande and Sucuriçu. At Serra do Veado, immediately to the north of the mining area of Serra do Navio, gondites appear along the top of a 3 km long ridge striking north, and were explored with trenching, pitting and 36 shallow core holes. The resource estimated with this work reached 400,000 tons, and it was considered

that with washing and screening 120,000 tons at 33% Mn could be produced.

At Serra Grande, 10 km northeast of Serra do Navio (Fig. 2 of Scarpelli & Horikawa 2017), gondites are exposed along the top of a 200 m high and 6 km long crest, marking a syncline plunging south. With 27 shallow core holes, a resource of 340,000 tons at 22.5% Mn was estimated. The gondite appeared with 1 to 9 m of thickness, and a passage of graphitic schist was seen in two holes. It was considered that a product assaying 27% Mn could be obtained with washing and screening.

Similar results were obtained at Sucuriçu, where a 4 km long line of blocks of gondite striking northwest was explored with mapping and 23 core holes. The estimated resource reached 60,000 tons at 33% Mn.

All other occurrences of manganese (Geladeira, Sete Ilhas, Monguba, Coambas and two at Santo Antonio) are composed of weathered manganeseiferous schists, appearing as residual masses varying from massive blocks of manganese oxides and hydroxides to schists impregnated with

Figure 13. Sites where manganese, iron, gold, chromium and titanium were identified in the MIP of Amapá and North Pará. The manganese and the iron are limited to well defined belts, possibly representing their depository basins. The manganese belt is centered at Serra do Navio and oriented to northwest. The belt of iron formation is wider and oriented and open to east-northeast. Also shown are areas of Figures 2 and 12 of this article, of Figure 2 of the former article and the limits of RENCA.

Table 2. Mines and occurrences.

Name	Metal	Type	Other metal	Location	
				North	West
Serra do Navio	Mn mine	Manganesiferous cyclothem		-51.984	0.885
Serra do Veado	Mn	Gondite		-51.985	0.901
Serra Grande	Mn	Gondite		-51.955	0.991
Sucuriçu	Mn	Gondite		-52.138	1.080
Santo Antonio Mn	Mn	Weathered carbonartics chist		-51.859	1.050
Santo Antonio Mn	Mn	Weathered carbonartic schist		-51.845	1.061
Geladeira	Mn	Weathered carbonartic schist		-52.337	1.228
Sete Ilhas	Mn	Weathered carbonartic schist		-52.306	1.161
Monguba	Mn	Weathered carbonartic schist		-51.806	0.640
Coambas	Mn	Weathered carbonartic schist	Fe	-52.218	0.633
Coambas	Fe	Iron fm.	Mn	-52.218	0.633
Ipitinga	Fe	Manganesiferous iron fm.	Mn	-53.336	0.276
Amapari	Fe mine	Iron fm.	Au	-51.863	0.819
Tartaruga	Au	Iron fm.	Fe	-50.921	1.484
Tartarugal Grande	Fe	Iron fm.	Au	-51.086	1.331
Sólida	Fe	Iron fm.		-51.126	1.012
Araguari	Fe	Iron fm.		-51.606	0.821
Dragão	Fe	Iron fm.		-51.754	0.748
Mutum	Au	Iron fm.	Fe	-51.671	0.800
Sucuriçu	Fe	Iron fm.		-52.050	1.056
Matapi	Fe	Iron fm.		-51.425	0.693
Pelado	Fe	Iron fm.		-51.689	0.441
Piaçacá	Fe	Iron fm.		-51.547	0.383
Bacabal	Fe	Iron fm.		-51.747	0.403
Travessão	Fe	Iron fm.		-51.860	0.438
Samaúma	Fe	Iron fm.		-52.378	0.141
Morro Ferro	Fe	Iron fm.		-52.615	0.217
Carecuru	Fe	Iron fm.		-53.351	-0.058
Ipitinga	Fe	Iron fm.		-53.229	0.181
Ipitinga	Fe	Iron fm.		-53.710	0.469
Tucano	Au mine	Iron fm.	Fe	-51.878	0.857
Água Boa	Au mine	Carbonatic metasediment		-51.733	0.405
Village Antonio	Au	Carbonatic metasediment		-52.156	1.032
21 Grande	Au	Quartzite, metaconglomerate		-51.807	0.427
Baixão	Au	Quartzite, metaconglomerate		-52.204	0.672
Carará	Au mine	Quartzite		-53.112	-0.088
Salamangone	Au mine	Gneiss		-51.640	2.288
Bacuri	Cr mine	Mafic-ultramafic		-51.752	0.337
Bacuri extension	Cr	Mafic-ultramafic		-51.995	0.310
Samacá	Fe mine	Mafic-ultramafic	Cr	-51.824	0.357
Serra da Canga	Cr?	Mafic-ultramafic	PGE?	-51.894	0.963
Breu	Cr	Mafic-ultramafic		-51.672	0.095
Santo Antonio	Cr?	Possible mafic-ultramafic		-51.865	1.109
Maraconáí	Ti	Alkaline intrusive		-53.408	-0.555
Maicuru	Ti	Alkaline intrusive		-54.252	-0.494

manganese oxides. They appeared spread over areas of several hundreds of square meters, as at Monguba, or forming lineaments of up to 4 km long, as at Geladeira. In all cases, they do not have continuity in depth.

The regional distribution of these occurrences of manganese demonstrates that there was indeed a belt of deposition of manganese from Monguba in the south to Geladeira in the north, with the better ores deposited along a central axis, from Serra do Navio to Serra do Veadó, to Serra Grande, and to Sucuriçu.

This belt of occurrences represents a limited and narrow basin, appearing today with 90 km of elongation to north-west and 70 km of width.

The only other occurrence of manganese seen in the general area was at Ipitinga, in the form of a manganiferous iron formation, continuous for 10 km. After the observation of manganese-rich magnetic blocks on the surface, two small areas were drilled, exposing an oxidized iron formation with quartz, magnetite, hematite and garnets, and with manganese oxides and limonite replacing silicates and/or carbonates. The limited work identified a resource of 200,000 tons with more than 30% Mn and 30% Fe.

Other occurrences of iron formation in the Vila Nova Group

The occurrences of iron formation in the Vila Nova Group are distributed over a 350 × 150 km belt oriented to the northeast (Fig. 13), which seems to mark its depository basin. It is interesting to consider that the larger of these occurrences are disposed in a line from Tartarugal, in the northeast, to Ipitinga, in the southwest, passing through Araguari, Tucano-Amapari, and Coambas.

Tartaruga

Next to the village of Tracajatuba, an occurrence of iron formation mined for gold by gold miners is being explored for gold by Beadell Resources.

Tartarugal Grande

At the margins of the Tartarugal Grande River and near a zone of granulitization, the occurrence is made of coarse-grained quartz-magnetite iron formation. It is being explored by Greiphil Mineração S.A. and SPG Mineração S.A. In its concession, Greiphil obtained a drill indicated resource of 67 million tons averaging 35% Fe, and informed that metallurgical tests have shown that with this resource it would be possible to produce 18 million tons of concentrates at 62% Fe (Greiphil 2017b).

Russian steel and mining company Severstal has concluded an exploration of the area of SPG, declaring a resource base of 0.5 to 1.5 billion tons of direct shipping magnetite-rich

ore, with 40% Fe, and hematite-rich ore assaying 60-65% Fe (SPG Mineração S.A. 2017).

Sólida

In an area of granulites, Sólida Mineração S.A. exploited a shallow portion of a coarse-grained banded quartz-magnetite iron formation, hosted in quartz-feldspar granulites. The iron formation has 15 to 20 m of thickness and is made of alternating layers of quartz and magnetite, with masses of compact magnetite representing up to 40% of the unit. Details of the iron formation and associated rocks, with the structural trend, indicate that it is indeed an iron formation of the Vila Nova Group, metamorphosed to the Granulite Facies.

Araguari

At the Araguari river, midway from the confluences with the Falsino and the Amapari River, an iron formation extends over both margins and is very well outlined on the aeromagnetic map of CPRM (CPRM 2004b). Its size and extension seem expressive, but are not yet detailed.

Amapari

This iron formation is 30 km long and is mined by Beadell and Jindal for iron ore and gold (Scarpelli & Horikava 2017).

Dragão

A 2.5 km long lens of iron formation, at the strike extension of the Amapari deposit to the southeast.

Mutum

A small occurrence of iron formation with a possibly important mineralization of gold, under exploration by Beadell Resources (Scarpelli & Horikava 2017).

Sucuriçu

A small exposure of iron formation was found near the eastern margin of the Sucuriçu River.

Matapi

A 9 m thick unit of banded iron formation appearing in a relatively flat and lowland topography, a few kilometers from the Amapa Railway, near the city of Porto Grande. It is explored by Greiphil Mineração (Greiphil 2017a).

Pelado

One east-west and single horizon of iron formation appears as two lenses, each one with 2 km of extension, 40 m of thickness, and dipping south (Souza 2014). The lenses overlay a zone of carbonatic schists, with orthoamphibolites of the Journal Formation at base. The iron formation grades from massive hematite-magnetite at base,

to quartz-magnetite-hematite itabirite at the middle, and to a silicatic iron formation at the top. The two basal units have about 20 m of thickness and are considered mineable.

Piaçacá

Representing the continuity of Pelado to the southeast, it is a 1.3 km long lens of iron formation striking N60°W, composed by quartz and magnetite, locally replaced by quartz-hematite schist. The topography is low and flat, a few meters above the water level of the Piaçacá River, inhibiting resources for surface mining.

Bacabal, Travessão and Coambas

Described in this article.

Samaúma

Ridges composed of lithologies of the Vila Nova Group, such as carbonatic schists, banded iron formations, magnetite quartzites, quartz-mica schists, orthoamphibolites, talc schists, chlorite schists, amongst others (Barbosa *et al.* 2013, Barbosa *et al.* 2015).

Morro do Ferro

An isolated hill with an area of 1.0×0.4 km covered by blocks of banded and magnetitic iron formation.

Carecuru

Banded iron formation associated to metasediments of the Vila Nova Group, as observed by the field team of the RADAM Project (Lima *et al.* 1976).

Ipitinga Greenstone Belt

The largest and unexplored iron deposit of the Vila Nova Group occurs in this more than 120 km long belt, oriented to northwest, and at the immediate south of the Ipitinga River. Initially reported in 1972 by a team of the RADAM Project in which the first author participated (Lima *et al.* 1976), the belt extends from about $53^\circ \text{W} - 0^\circ 15' \text{N}$ to $54^\circ \text{W} - 0^\circ 40' \text{N}$, with the iron formation occurring along this extension. It appears in a sequence containing quartzites and carbonatic, calc-silicatic and micaceous schist, overlaying orthoamphibolites to the northeast. The units of iron formation appear as layers of hematite schists and banded quartz-magnetite and are folded into synclines. At several sites, the ridge is covered by massive limonitic duricrust cementing blocks of hematite schist, and locally there are lakes, similarly to what happens at the Serra dos Carajás. Resources of billions of tons of iron ore are expected. As previously mentioned in this article, there is a manganesiferous iron formation, registered in Table 2 and Figure 13. A geological

map with details is presented by CPRM (2017) and Carvalho (2017).

Gold mineralization in the Vila Nova Group

A common type of gold deposit in the Vila Nova Group is made of massive veins of very fine-grained silica, with few pyrite grains, hosted in planes of fractured and/or foliation of hard and brittle rocks, such as quartzites, with the hydrothermal alteration of the host rock limited to the immediate contacts with the vein. Veins in fractures tend to be more homogeneous and continuous than veins deposited along planes of foliation, which usually pinch and swell. The Carará vein (this article), in the Ipitinga district, seems to be a good example.

Veins in iron formation are rich in sulfides, a result of reactions of the rock with the hydrothermal solutions, that capture iron to form the sulfides, dumping the gold with the sulfides and silica. The frequency of sulfides and the gold grades depends of the flux of the solution through the more durable open structures and the reactivity of the hosts, with high-grade ore shoots usually being formed. The Tucano deposit is a good example (Scarpelli & Horikava 2017).

Fine-grained and carbonatic metasediments are favorable for wide zones of hydrothermal alteration, in preparation for mineralization. Usually, there is a halo of carbonatization and chloritization enveloping a zone of sericitization, and, near the center, a zone of silicification that works like hard and brittle rocks. The Água Boa deposit is a good example, and Village Antonio might be another.

Ipitinga Greenstone Belt

Many alluvial and quartz vein deposits of gold are being exploited by gold miners along more than 100 km of extension of the Ipitinga Greenstone Belt. Most occur in quartzitic rocks and are semi-parallel to the foliation of the rock. Based on the description of Klein and Rosa Costa (2003), and our own observations, it seems that they fit into the model of hard and brittle rock, described above. See, below, details of Carará.

Carará

Exploitation of auriferous alluvia derived from this deposit was initiated more than 60 years ago. Mining of the vein is now conducted by Mineração Carará, with surface and underground operations based on a declared reserve of 200,000 tons at 21 g/t Au (10 tons of gold). The host rock is a fine to medium grained quartzite presenting discrete bands with anhedral black tourmaline and occasional small quartz pebbles, occurring south of a sequence of non-magnetic amphibolites. The vein is made of saccharoidal silica with

a few grains of pyrite, and is lodged in a zone of displacement nearly concordant with the foliation of the quartzite. It extends to the northwest for 850 m, with a steep dip to the southeast, varying in thickness from a few centimeters to 3 m. The wall rock is sericitized and presents euhedral black tourmaline at the immediate contact with the vein. Gold values appear up to about 0.5 m distant from the vein. Veinlets of fibrous black tourmaline cut the vein (most of this information was obtained from Klein & Rosa Costa 2003).

Village Antonio

Alluvial workings were intense along an 8 km long straight structure oriented to N10°W, marked by the two consecutive valleys of the Antonio and Panel Creeks, respectively to the south and to the north. While the local drainage pattern is dendritic, with narrow valleys and steep slopes, these two valleys are straight and more than 100 m wide. They cross an area of metasediments of the Vila Nova Group striking N50°W, with only a few exposures of weathered biotitic, micaceous and carbonatic schists. Auriferous quartz veins and pegmatites are seen at a few excavations.

Gold mineralization in the Lourenço domain

Not covered by Figure 13, the Lourenço and the Cassiporé districts, at the northeast of Amapá, present several occurrences of gold, the largest being Salamangone (Fig. 1), where auriferous quartz veins cross gneisses, possibly paragneisses, following the model of mineralization in hard and brittle rocks. The belt of mineralization strikes approximately to north and is being exploited for centuries. The interested reader will find detailed information accessing Nogueira *et al.* (2000), Nogueira (2002), Bettencourt & Nogueira (2008), Bettencourt *et al.* (2016), Klein *et al.* (2014) and CPRM (1997).

Other possible areas of mafic-ultramafic sequences

Bacuri Complex Extension

The presence of ultramafic rocks for at least 14 km southwestwards of Samacá is indicated by high values of chromium and presence of chromite in stream sediments.

Breu

At south of the Bacuri Complex there are at least three short aeromagnetic anomalies (Barbosa *et al.* 2013) oriented east-northeast, in areas of low topography and covered by limonitic duricrust, characteristics suggestive of another center of mafic-ultramafic rocks. At Igarapé do Breu, there are blocks of chromitite associated with basic and ultrabasic rocks (Queiroz 1986).

Santo Antonio

At the Santo Antonio River, 4 km upstream of the confluence with the Araguari River, there is a straight, strong and 17 km long magnetic anomaly oriented to N80°E, geophysically identical to that of the northern branch of the Bacuri Complex, 80 km to the south (Fig. 14). Part of the area is also covered by limonitic duricrust (Rosa-Costa *et al.* 2014). Interesting, both sit on the same north-south fracture line indicated by the aeromagnetic survey.

Alkaline rocks with titanium

Maraconá and Maicuru

At the southwestern limit of the area, these two alkaline intrusive contain resources of ilmenite and anatase, related to pyroxenites, peridotites and serpentinites. The presence of carbonatite is a real possibility.

CONCLUSIONS AND SUGGESTIONS FOR EXPLORATION

The work done by the mining companies indicates that the greenstone sequence and their remnants always present at base a unit of orthoamphibolite derived from basalts (Scarpelli & Horikawa 2017), indicating an extensive episode of extrusion of basalt (Jornal Formation) over the shield, covering areas with granites and granitoids of Archean and Paleoproterozoic ages.

Subsequently, the southern portions of the volcanics were covered by littoral and marine sediments, initially in discrete rift-like environment where manganese-bearing carbonates were deposited, and then over a marine platform, which received chemical and fine-grained clastic sediments, with iron formation at the top (Vila Nova Group). In the Paleoproterozoic, the area was submitted to tectonism, regional metamorphism and intrusions of granitic rocks with thermal metamorphism of the affected metasediments.

Furthermore, also in the Paleoproterozoic, the metamorphosed volcanics and sediments were intruded by mafic-ultramafic layered sequences (Bacuri, Canga, Bicicleta and others), and the complete column was subject of another episode of regional metamorphism, reaching the Amphibolite Facies. Erosion of parts of the sequence upraised above the water level gave origin to the deposition of quartzites and conglomerates (21 Grande Formation) in localized fluvial-littoral environments.

The described development of these greenstones indicates that they were formed in only one cycle of volcanism and sedimentation, without subsequent episodes of volcanism,

which in other greenstone areas are demonstrated by the presence of rhyolites, andesites, tuffs, volcanic breccias and other lithologies. Another difference comparing to another greenstone-bearing areas is the presence of granulitized portions of the greenstones in some areas, as that which contains the Sólida iron ore deposit. The layering observed in the granulites of the Falsino River (Scarpelli 1969) also leads to the suggestion that at least a part of these granulites were produced by metamorphism of the greenstone rocks.

As far as mineral deposits are concerned, the greenstone and the reported intrusions are favorite targets for exploration of iron, gold, manganese, base metals, chromium, platinum group elements, cassiterite, tantalite, titanium and carbonatite related minerals. Some details are presented in sequence.

Metasedimentary iron

The principal iron ores are made of primary or weathered iron formation of the Serra da Canga Formation (itabirites and banded magnetite-quartz-silicates-hematite rock). Products: High-grade lumps and pellet size fragments,

and fines. Examples: Amapari, Ipitinga, Sólida, Vila Nova (Eldorado), Coambas.

Mafic rock iron

A good iron ore is represented by magnetite recovered from weathered portions of magnetite-rich mafic layers of layered mafic-ultramafic complexes. Products: high-grade pellet size fragments, and fines. Example: Bacuri complex.

Hydrothermal gold

Deposits resulting of hydrothermal mineralization in faulted and fractured zones, and appearing as veins, disseminations and lodes, with sulfides and fine-grained silica with/without carbonates, in fault and fracture zones of brittle and ductile metamorphosed rocks, respectively, like Tucano and Agua Boa.

Sedimentary gold

Gold is also seen as primary concentrations in layers of metaconglomerates of the 21 Grande Formation. Occasionally,

Source: CPRM (2004a, 2004c).

Figure 14. The total field magnetic anomaly related to the northern branch of the Bacuri Complex (B) is identical in shape and pattern to a total field magnetic anomaly at the Rio Santo Antonio, (A) 80 km to the north. At (C) the total field map of the general area, with arrows indicating the two sites. A narrow straight magnetic negative line indicating a north-south fracture connects the two areas.

they are remobilized into fractures. Examples: Vila Nova River and Baixão, at the Cupixi River.

High-grade oxide manganese

The better manganese ores are made of high-grade surface concentrations of oxides of manganese and iron, produced by enrichments, during weathering, of manganeseiferous marbles of the Serra do Navio Formation. Example: Serra do Navio mines. The possibility of identification of another sequence like that of Serra do Navio seems remote at this stage.

Low-grade oxide manganese

Low-grade surface concentrations of oxides of manganese, iron and silicates could be mineable. They are produced by secondary enrichments, by weathering, of gondites and manganese-rich schists. They occur in the Serra do Navio Formation and at the base of the Serra da Canga Formation. Examples: Serra do Veado, Serra Grande and others.

Carbonate manganese

Primary beds of manganeseiferous marbles constitute a barely touched ore. They occur in the Serra do Navio Formation, at Serra do Navio.

Base metals

Appear as hydrothermal deposits of copper, lead, zinc, plus gold and silver, in metasediments of the Vila Nova Group. No one was found yet, but their presence was indicated by a few already identified and not examined geochemical soil and stream sediment geochemical anomalies.

Chromite

Chromite-rich layers constitute a product of magmatic segregation, appearing at the base of ultramafic layers of layered mafic-ultramafic complexes. Example: Bacuri Complex.

Platinum group elements

They appear as sulfides, segregated and concentrated in ultramafic layers of layered mafic-ultramafic complexes. No one was found yet.

Tantalite, cassiterite

Found in pegmatites intruded in the metasediments of the Serra da Canga Formation, near syntectonic granitic intrusives.

Gold, tantalite, cassiterite

Secondary concentrations found in alluvial deposits downstream of their primary deposits.

Titanium

Concentrations of ilmenite and anatase occur in pyroxenites of alkaline intrusives. Other alkaline intrusives, observed at the Jari River Basin. Examples: Maraconá and Maicuru. Alkaline intrusions observed at the Jari River might have carbonatites, eventually with phosphates and other economic minerals.

The good cover of aerogeophysical information by CPRM should be used to identify geological districts and structures and to locate mineralization responsive to magnetic and scintillometry surveys. Relatively flat surfaces covered by thick canga and associated to magnetic and scintillometric thorium anomalies are favorite targets for mafic-ultramafic layered sequences. Metasediments locally folded to north due to an adjacent fault seem to constitute good targets for hydrothermal mineralization, better yet if iron formations are involved.

Due to the intensive weathering, the area is quite poor in outcrops, with only the more weathering resistant rocks outcropping. In this environment, geochemical exploration techniques are mandatory for the identification of concentrations of nickel, platinoids, base metals as copper, zinc and lead, and other elements. We feel that is very important to call here the attention to differences observed between soil samplings in the dry and in the wet (rainy) seasons. During the dry season, water ascends from the water table to the surface, bringing metals in solution, and dropping them near the surface when it evaporates or is absorbed by the vegetation. During the wet season, the portions of those metals that were not yet fixed in stable minerals are carried back to the base of the zone of weathering. Over a same area, higher values could be observed with samples collected during dry seasons in comparison with similar samples collected during wet seasons.

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