The rediscovery of Rondon do Para, the last giant world-class bauxite deposit in an attractive geography

Hélcio José dos Prazeres Filho[1], Saulo Batista de Oliveira[2], Lúcio Molinari[3], Jones Belther[4]
1. Senior Exploration Geologist
2. Senior Resource Modelling Geologist
3. Mineral Exploration General Manager
4. Mineral Exploration Director

Votorantim Metais, Brazil
Corresponding author: jones.belther@vmetais.com.br

Abstract

Rondon do Pará deposit is located in Pará State, north Brazil. Also known as the Amazon Bauxite Province, it holds mineral resources greater than 3 billion tons of bauxite. Lateritization of sedimentary rocks is the genetic process of a thick gibbisitic bauxite layer. Several companies have explored the region for bauxite since the 1970's, defining Trombetas, Juriti and Paragominas deposits, currently under production. At the same time, Votorantim Metais/CBA (VM) defined a small bauxite resource in some mining permits. In 2006 VM returned to the province to re-evaluate its mining permits resources and additional potential. This work program entailed 90 000 m of drilling, analysis of > 40 000 samples and the execution of three pilot pits for bulk sampling. Exploration investment totaled US$ 35 million and all activities were developed according to industry best practices complying with JORC Code. The deposit resources add up to 1.6 billion tons of bauxite grading 42.6 % available alumina, 3.9 % of reactive silica and a stripping ratio of 7, with inexistent organic matter. A feasibility study was completed in 2013 of 9 million tons of washed bauxite per annum mine integrated to an alumina refinery with 3 million tons production capacity.

Keywords: Amazon Bauxite Province; Rondon do Pará deposit; Mineral Exploration; Feasibility Study.

1. Introduction

Votorantim Metais (VM), a subsidiary of Votorantim Group, is one of largest Brazilian metals & mining company producing zinc, copper, nickel, aluminum and with a mineral exploration program with focus in the Americas. The company has 17 production units in several regions of Brazil and the World.

The Alumina Rondon Project (ARP) is VM's largest investment in Brazil and it considers the development of a bauxite mine with an integrated alumina refinery located in Pará State, North Brazil, within the World's second largest bauxite/alumina production province. The ARP will have an annual production capacity of 9 million tons of washed bauxite and 3 million tons of alumina. These projected production capacity had its viability defined after a large investment in Mineral Exploration, executed by VM, that resulted in the rediscovery of the world-class Rondon do Pará deposit, that summed up to other VM bauxite deposits in the province, aggregated resources in the order of 1.6 billion tons of washed high quality bauxite.

This paper presents the main geological characteristics of Rondon do Pará deposit and summarize the exploration work and techniques used to estimate and classify resources. The results presented in this paper were obtained during 2006 - 2015 exploration works at mining rights of VM in *Amazon Bauxite Province* that host the largest bauxite deposits of the world.

2. Location of Rondon do Pará deposit

The Rondon do Pará deposit is located in the Northern Region of Brazil, in the Amazon, southeast portion of Pará State and is surrounded by Rondon do Pará, Dom Eliseu and Goianésia do Sul municipalities (Figure 1). This region is very favorable mining activity with community friendly to mining, developed infrastructure with paved federal highways, electric energy available and skilled human resources. Additionally, the deposit is located very close to an important railway project, the North-South (EF-151) that will connect the cities of Açailândia to Barcarena, about 450 km, where the Vila do Conde Port is located.

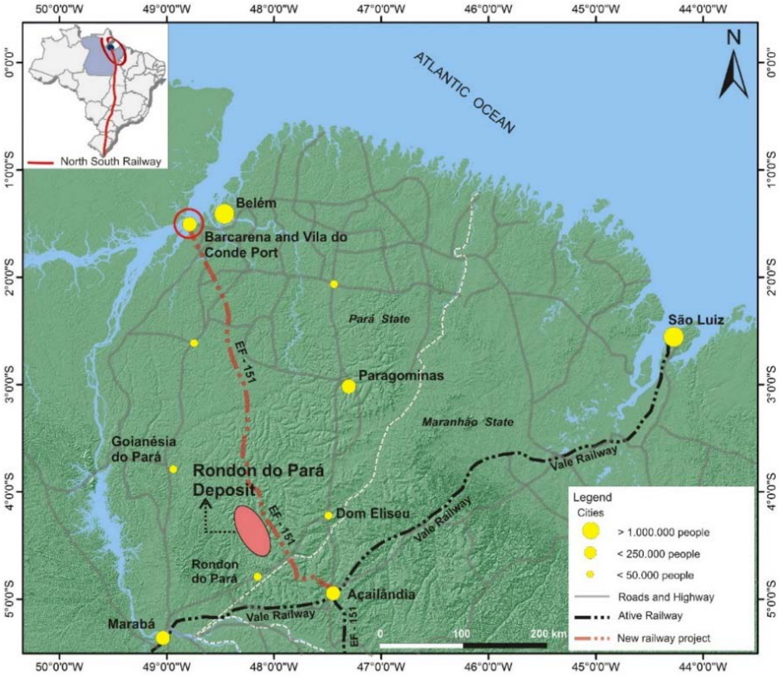

Figure 1. Location of Rondon do Pará deposit and near infrastructure.

3. Geological and geomorphological context

In this paper the term *Amazon Bauxite Province* is used to refer to a region that host all bauxite deposits located in northern Brazil that is formed during Paleogene under similar conditions, as the result of mainly sedimentary rocks exposed to laterization processes.

The bedrocks of these deposits are predominantly sedimentary in origin. The similarities among the bedrocks all over this province and this tectonic stability allowed us to compare and correlate the laterization profiles of all bauxite deposits in this province, such as: Juruti, Trombetas and Paragominas (Figure 2).

The geological underlying units of the *Amazon Bauxite Province* have the paleogeographical reference to the evolution of Amazon Basin and Grajaú Basin related to the opening of Equatorial South Atlantic Ocean during the late Jurassic/early Cretaceous. These geological units are formed by siliciclastic sediments, mainly constituted by clayey sandstone, intercalated with conglomerates of Alter do Chão Formation (Amazon Basin) and Ipixuna /Itapecuru Formations (Grajaú Basin), Figure 2 [1].

The bauxite deposits of *Amazon Bauxite Province* are found as large plateaus, some of then up to 500 km^2, 70 to 450 m above sea level, and with broad thalwegs (Figure 3). The origin of this landscape is associated with old peneplanation surface event that occurred between Eocene to Miocene epochs [2].

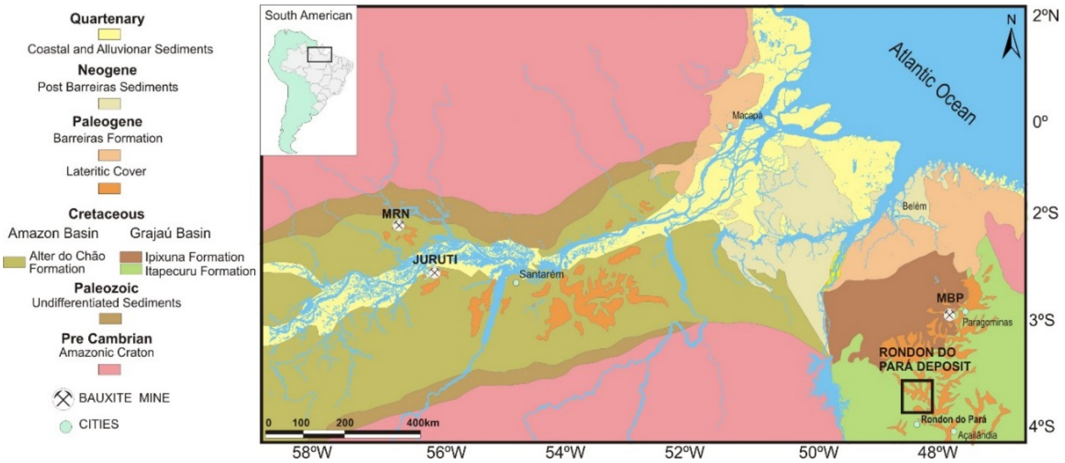

Figure 2. Regional geological map of the *Amazon Bauxite Province* [3]).

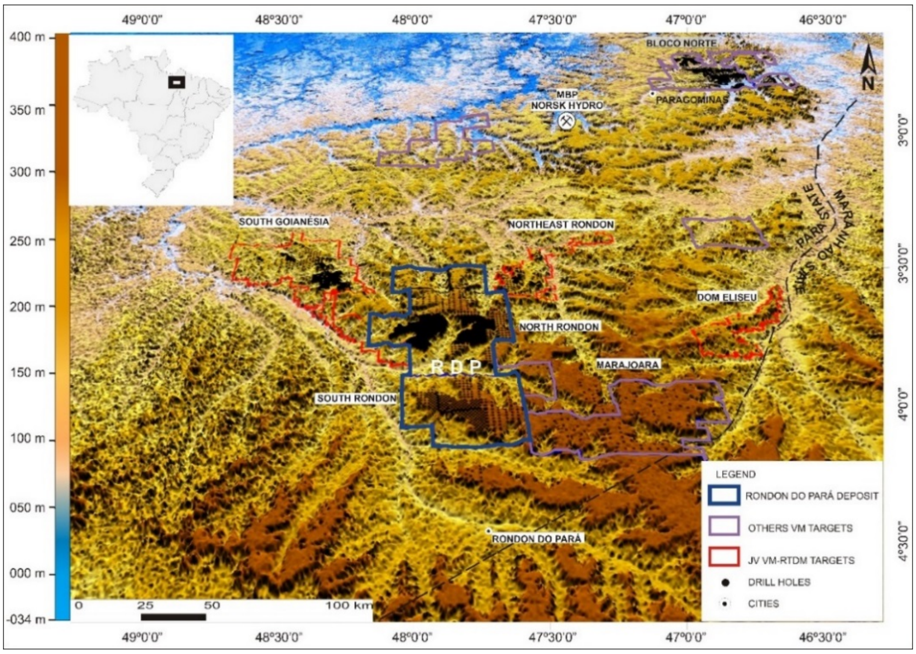

Figure 3. SRTM 3D View showing the location of Rondon do Pará Deposit (RPB) and other targets of Votorantim Metais in the south portion of Amazon Bauxite Province.

4. Geology of Rondon do Pará Deposit (RDP)

The RPD is formed by the North Rondon and South Rondon plateaus that aggregate over 100.000 ha. Other surrounding plateaus, such as Marajoara, North Block, South Goianésia, Northest Rondon and Dom Eliseu complete VM's properties in the Amazon Bauxite Province (Figure 3).

The bauxite profile is composed of six main lithotypes belonging to the Mature Lateritic Unit, characterized by clear textural, compositional and color differences, and with well-defined contacts between them (Figure 4). A brief description of these units is provided below (from bottom to top): A) The first lithotype from base to top of lateritic profile is the bottom clay (AG), which has a gradual transition from the fine-grained kaolinitic sandstone bedrock of

Itapecuru Formation. This layer include typical saprolitic and mottled zone ending in the main bauxite zone; B) The Lower Bauxite horizon (BX-BI) is formed of a massive bauxite layer of reddish color with abundant, millimeter-sized gibbsite crystals and iron oxides, averaging 1.8 m and exceptionally reaching up to 4.0 m thick; C) The third lithotype is Ferruginous Bauxite (BG) that represents a transition layer between the main bauxite and the top iron crust. This layer with 1.0 m thick on average is composed of hematite crystals coated by goethite with gibbsitic cement; D) The following lithotype, called Ferruginous Laterite (LT) is composed of goethite and hematite pisolites in a massive texture and lies below the fifth lithotype, the Nodular Bauxite (BX-BS), a layer texturally different from the other bauxite horizons, being composed of heterogeneous gibbsite nodules, formed by amorphous bauxite immersed in a kaolinitic matrix.

The contact with the overlying clayey cover, called Belterra clay (AG-BT), is discordant and occurs with frequent ferruginous pisolites found among gibbsite nodules. This geological formation covers the lateritic profile and has 10 m to 15 m of thickness, it is constituted by a homogeneous sequence of kaolinitic clays, which does not exhibit any apparent bedding.

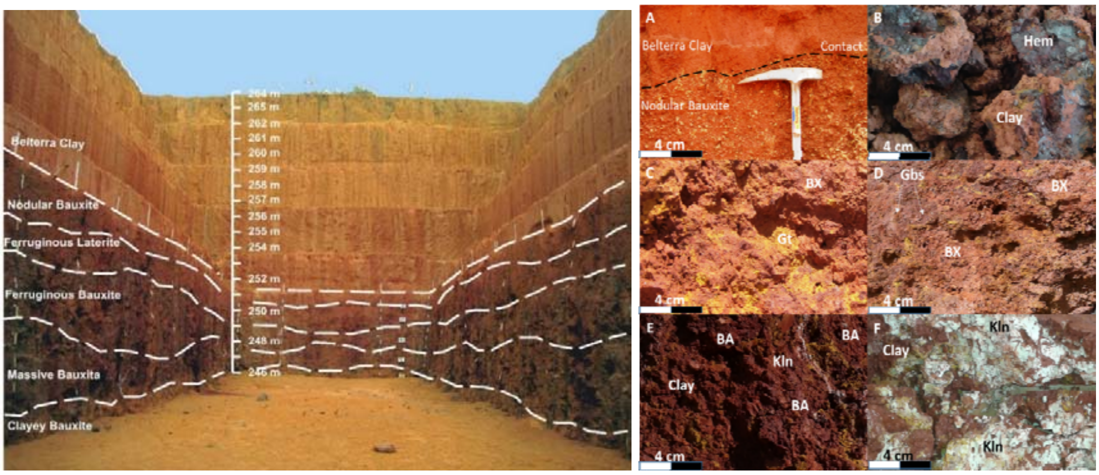

Figure 4. Lateritic profile of RPD and its horizons exposed in the pilot mine of North Rondon Plateau. A) Contact between Belterra clay and Nodular Bauxite; B) Ferruginous Laterite; C) Ferrouginous Bauxite; D) Massive Bauxite; E) Clayey Bauxite; F) Botton Clay. Hem-Hematite, Gt-Goethite, Gbs-Gibbisite, Kln-Kaolinite, BX-Bauxite, BA-Clayey Bauxite.

The genetic model for the formation of the lateritic has been proposed by Kotschoubey and Truckenbrodt (1981) [4], quoted by Votorantim (2013): A) Initial lateritization of the saprolite; B) Formation and partial reprocessing of the ferro-aluminous crust; C) First (and main) gibbsitization phase of the crust, formation of the massive bauxite layer and ferrouginous bauxite; D) Second reprocessing phase of the crust: formation of the ferruginous, pebbly surface layer and E) second bauxitization phase of the upper crust.

5. Mineral exploration of Rondon do Pará Deposit (RPD)

5.1 History

Votorantim Metais through Companhia Brasileira de Alumínio (CBA) obtained the first exploration permits in 1974, and conducted exploration until 1980. This activity was then halted until 2005. Between 2006 and 2009, VM-CBA conducted an exploration program with 24.500 m of drilling in the proximity of Paragominas (North Block), after which the focus was moved to Rondon do Pará.

From 2009 until 2015 Votorantim Metais drilled over 80 956 meters and analysed more than 40 000 samples at targets near Rondon do Pará town. The drilling grid was infilled from 800 m x 800 m to 400 m x 400 m and further to 200 m x 200 m in certain portions to improve the mineral resource classification. This program was responsible for the delineation of RPD and other satellite deposits, as well as, the discovery of other potential areas.

Presently the RPD is a part of Alumina Rondon Project, which projects the construction of an industrial complex, integrating a bauxite mining and an alumina refinery. The Project completed a full feasibility study, obtained the previous license and is working on obtaining the installation and operation licenses and is ready for construction once capital is made available. Bauxite resources considered in the feasibility study totals 642 million tons with grades of 42.6 % of free Al_2O_3 and 3.9 % of reactive SiO_2, total resource inventory considering the surrounding plateaus sum up to 1.6 billion tons of bauxite with similar grades.

5.2 Drilling

In total, 60,814 m have been drilled from 2010 to date in the RPD, totaling 3.316 holes (Table 1). Additional 44.642 m were distributed on other VM targets. The drilling grid started with drill spacing of 800 m x 800 m. Infill-drilling was later conducted in selected areas up to 200 m x 200 m drill spacing in the areas of the deposit considered for the first 20 years of operation.

Table 1. Drilling summary of RPD.

Year	Nr. of holes	Air Core Driling Total (m)	Nr. of Core Samples
2010	1.046	19.527	9.160
2011	1.262	23.140	12.327
2012	591	10.637	6.003
2015	417	7.510	4.048
Totals	**3.316**	**60.814**	**31.538**

Drilling started with auger through the Belterra Clay without recovering samples. After that, the drilling continued with 4" air-core drilling as soon as the bauxite horizon was intersected. The drilled material was recovered using a 4" diameter and 1.45 m long PVC tube that was placed inside the core barrel. The average recovery was estimated at 95 %.

5.3 Chemical Analysis

Sample preparation was conducted by Intertek laboratory, simulating a processing plant. ALS in Lima-Peru was responsible for assaying. Samples were assayed for Al_2O_3, Fe_2O_3, SiO_2, MnO and TiO_2 by X-ray fluorescence (XRF), and the loss on ignition (LOI) was determined by a thermo-gravimetrical method (TGA). In addition, Al_2O_3avl and RxSiO_2 were determined using high-temperature, caustic pressure leaching, and inductively-coupled plasma-atomic emission spectrometry (ICP-AES) for readings.

Mineralogical analysis was conducted using X-Ray Diffraction (XRD) in a bulk bauxite sample to determine semi-quantitative phase concentrations in CSIRO, Waterford in Australia, University of São Paulo in São Paulo Brazil and State University of São Paulo, Rio Claro in Brazil. Total Organic Carbon (TOC) also was analyzed in CSRIO laboratories.

5.4 Density

Bulk density was determined and cross-validated by four methods: caliper, water displacement on core segments, Jolly (water-displacement on large segments), and *in situ*. The average densities obtained by these methods are presented in Table 2. VM used the average result of 1.7 g/cm^3 for resources estimation.

Table 2. Average Bulk Density by the Calliper Method, validated by others methods.

Lithology	Nr. of Samples	Bulk Density (g/cm^3)
Ferruginous bauxite,	2 757	1.72
Massive bauxite, BI	3 338	1.69

5.5 Qa/Qc results

A quality assurance and quality control (QA/QC) program included the insertion of more than 3.000 samples in the assay batches to measure the precision using coarse duplicates, blind pulp duplicates (from previously assayed batches), coarse blanks, pulp duplicates. For the accuracy it was used two certificated standard reference material (SRM) representative of two main ore types of the RPD. The overall precision error coefficient of variation (CV %) of the samples does not exceed 10 %.

5.6 Pilot Mines

Three pilot mine were prepared in order to get access to the bauxite horizons and to obtain bulk samples (ca. 3 thousand tons). VM geologists took advantage of the access to the mineralized material to map and sample in extreme detail, (Figure 5). Both mapping and sampling were carefully conducted and have given support to feasibility studies.

Figure 5. Aerial and in situ photographs of pilot mine located in North Rondon Plateau during the excavations in 2012.

5.7 Results

Figure 6 shows the main results of mineral exploration conducted in RPD. For the evaluation of the RPD three parameters are considered: a) thickness of Belterra Clay cover; b) thickness and continuity of ore body; c) grade of total available alumina (Al_2O_3), total iron in the form of

Fe_2O_3, total reactive silica ($RxSiO_2$); and d) washed bauxite recovery (WR). Total organic carbon contained average concentrations of 0.06 %.

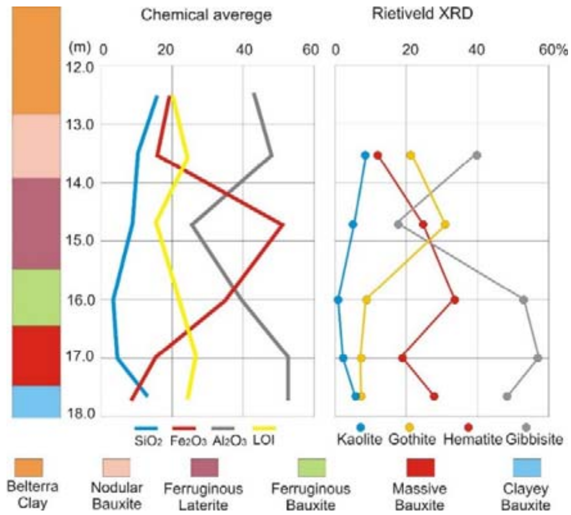

Figure 6. Chemical average composition and Rietiveld/RXD analysis of Rondon do Pará laterite profile. Zircon, tourmaline, rutile, quartzo, anatase are trace mineral < 2 %.

The content distribution of SiO_2 decrease toward the top of profile while Al_2O_3 and Fe_2O_3 increase. This general chemical element distribution is quite similar to other laterite profiles. The lateritic evolution becomes very clear by the strong negative correlation Fe_2O_3–Al_2O_3, also SiO_2–Fe_2O_3 and SiO_2–Al_2O_3, reinforcing the leaching of SiO_2 and enrichment of Al_2O_3 and Fe_2O_3, which occur on different forms, being Fe mobile and concentrated in the iron crust.

However, the main difference between RPD and other Amazon deposits consists in the existence of ferruginous bauxite layer, which shows a distinguishable geochemistry and is rare in other deposits. This transition zone has intermediate Al_2O_3 and Fe_2O_3 values between ferruginous laterite and massive bauxite. Its composition indicates the presence of gibbsite in a matrix with small nodules of iron oxy-hydroxides seen macroscopically and the almost absence of kaolinite and quartz, with the lowest SiO_2 values.

6. Mineral Resources

6.1 Database

After the data validation that includes: a) Collar coordinate topography survey ; b) Data entry (logging records and assay data) in the database, by comparing them with original documents; c) Geological interpretation of cross-sections; and, d) QC data. Samples were then taken from the core honouring the identified lithology. Longer intervals were split into nominal 0.5 meter sample lengths. All assays are based on the washed portion of the sample. That means that the fine clays have been washed from the sample prior to assaying.

6.2 Ore definition

The sample attributes that are of interest for the resource are: total available alumina (Al2O3), total iron Fe_2O_3, total reactive silica ($RxSiO_2$) and total recovered fraction (WR). The resources are reported considering only the ferruginous bauxite and massive bauxite as ore. (Table 3).

6.3 Estimation

The resource was estimated using a standard block model that encompassed the area of interest. The block model incorporated 100 by100 by 0.5m blocks with allowable sub-blocks down to 10 m by 10 m by 0.25 m. The sub-blocks were used to accommodate the resolution of the lithology model. The four variables showed in Table 5 were estimated into each block.

Table 3. Chemical Limits Used to Define Ore Type.

Lithology	Al_2O_3_avl	$RxSiO_2$	WR%	Fe_2O_3%
Ferruginous Bauxite	> 27	< 8	> 35	> 27
Massive Bauxite	> 27	< 8	> 35	< 27

The block grades were then estimated using ordinary kriging using only samples that matched the block coding (hard boundaries). However, the method is applied after geometry of the bauxite seam is flattened using top flattening approach.

6.4 Resource classification

The two ore types, ferruginous bauxite and the massive bauxite were classified together based on the application of three basic criteria: a) drill hole spacing; b) distance and number of samples used in the estimate; and, c) relative errors from the simulation of thickness [5]. The resource was also limited by physical and environmental constraints. Only resources inside the property limits were considered. The area set aside for the process plant has been eliminated. Legally, no mining can take place within 30 m of the edge of the plateau. This area has also been removed of the resource. All three criteria mentioned must be achieved for measured category. Similarly, all three criteria must be met for indicated category. The remaining resource is considered inferred

The minimum spacing of 200 m adopted for measured category was validated through a specific study within two distinct areas of the deposit with drill-hole lines spaced at 10 m. For the same areas the tonnage was calculated based on detailed 10 m spaced and then compared to 200 m spaced one. The results showed maximum variations of 10% between the two drill-hole spacing for the two tested areas, proving that the tightening of drill-hole spacing had no significant variation in the tonnage obtained (Table 4).

Table 4. Results of drilling spacing study for resources classification.

		STUDY AREA 1	
Ore Type	10x10m drilling spacing	200x200m drilling spacing	Diferences (%)
Massive Bauxite	60 972	69 368	12
Ferruginous Bauxite	61 961	45 682	-36
TOTAL	**122 933**	**115,050**	**-7**
		STUDY AREA 2	
Massive Bauxite	48 121	64 227	25
Ferruginous Bauxite	80 293	78 382	-2
TOTAL	**128 414**	**142 609**	**10**

Table 5 and Figure 7 show the consolidated resources of RPD and other VM target in the south portion of *Amazon Bauxite Province*. It is also important to see the evolution of resources since the reactivation of bauxite exploration by VM.

Table 5. Consolidated resources of RPD (plateaus North Rondon and South Rondon).

Plateau	Resource	Washed Bauxite millions tons dry base	Avalaible Alumina	Reactive Silica	Wash Recovery	Ratio Alumina / Silic
North Rondon	Measured	103,9	40,80	2,54	68,27	16
	Indicated	121,4	43,67	3,98	69,17	11
	Measured+Indicated	**225,3**	**42,35**	**3,32**	**68,74**	**13**
	Infered	149,6	43,59	4,83	69,85	9
	Total	**374,9**	**42,84**	**3,92**	**69,19**	**11**
South Rondon	Infered	267,8	42,32	3,95	71,37	11
Total North Rondon + South Rondon		**642,7**	**42,62**	**3,93**	**70,10**	**11**

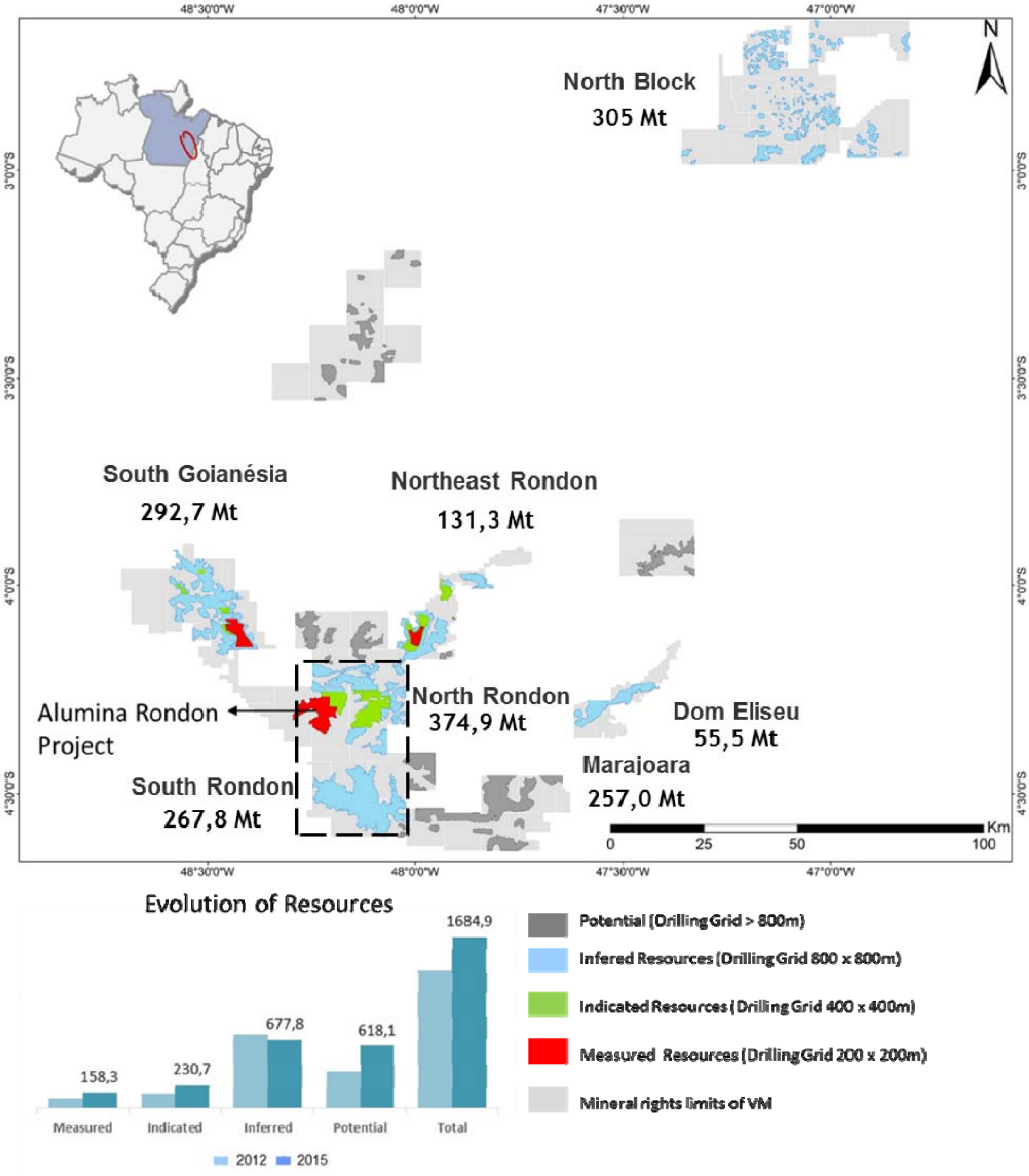

Figure 7. Consolidated resources of RPD, black dashed square (North Rondon and South Rondon plateaus) and others VM targets in south part of Amazon Bauxite Province.

7. Conclusions

1. The Rondon do Pará Deposit is the last giant bauxite deposit discovered in the last decade, placing the Amazon region as very important bauxite province in the World and still with a high potential for new discoveries. The total resources inventory including other VM targets sum up to 1.6 billion tons of high quality bauxite.

2. Regional and local geology, as well as the mineralization and its controlling factors, are sufficiently well understood, and their interpretation serve as a basis for the mineral resource estimation.

3. Geologically the Rondon do Pará Deposit profile can be well correlated to those ones from Paragominas, Trombetas and Juruti with lots of similarities in their lateritic profiles, clay cover, origin and age of bedrocks.

4. Among all Amazonian bauxite deposits, the Rondon do Pará Deposit figures with a distinctive lateritic profile hosting a Ferruginous Bauxite horizon that is a very important contribution for ore quality due to its low reactive silica content and good alumina grades. This horizon adds resources to the project and together with the massive bauxite horizon improves economic viability, incrementing ore thickness and lowering the waste/ore ratio.

5. The mineralogy of RPD is mainly constituted by gibbsite, hematite, goethite, with minor content of kaolinite and traces of resistate minerals (zircon, tourmaline, rutile and anatase). Very low grades of TOC (total organic carbon) were obtained.

6. The geological contacts, textures and disposition of lateritic horizons in Rondon do Pará profile allows us to correlate its geologic evolution with the other well-known Amazonian deposits recognizing two later superimposed bauxitization events over the previous laterization stage during Paleogene to Miocene.

7. VM Mineral Exploration team followed strictly defined work protocols for all exploration activities. Topography survey, down-hole survey, geological mapping, drilling, logging and sampling, QA\QC controls and mineral resources estimation were compliant to the industry best practices currently used in exploration programs worldwide.

8. References

1. D.F. Rossetti, Late Cenozoic sedimentary evolution in northeastern Pará, Brazil, within the context of sea level changes. Journal of South American Earth Sciences, (2001) v. 14, n. 1, pp 77-89.
2. M.L, Costa; G.S, Cruz; H.D.F, Almeida; and H, Poellmann. On the geology, mineralogy and geochemistry of the bauxite-bearing regolith in the lower Amazon basin: Evidence of genetic relationships, Journal of Geochemical Exploration (2014)v. 146, pp 58-74.
3. L.A, Bizzi; C, Schobbenhaus; R.M, Vidotti,., J.H, Gonçalves. Geologia, tectônica e recursos minerais do Brasil: texto, mapas & SIG. Serviço Geológico do Brasil. CPRM, Ed. UnB, Brasília, (2003), 692 p.
4. B. Kotschoubey. and W, Truckenbrodt,.Evolução poligenética das bauxitas do distrito de Paragominas-Açailândia, Estados do Pará e Maranhão. Brazilian Journal of Geology, (1981) v. 11, n. 3, pp 193-202.
5. S. B, Oliveira; J. B, Boisvert; and C.V, Deutsch. Assessment of thickness uncertainty using geostatistical simulation in the Rondon do Para Bauxite Deposit, Brazil, 37th International Symposium "Application of Computers and Operations Research in the Mineral Industry" 23rd - 27th May 2015, Westmark Fairbanks Hotel & Conference Center, Fairbanks, AK, (2015) 13 pages.