GEOLOGY, MINING OPERATION AND SCHEDULING OF THE PARAGOMINAS BAUXITE MINE

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VALE, Paragominas, Pará, Brazil

Abstract

The Paragominas bauxite mine (VALE) is the first in the world integrating the mine process with beneficiation and transport of milled bauxite by mineral pipeline. The mine is located in the far north of Brazil, in the State of Pará, part of the eastern Amazon region. As from 2001, Vale has undertaken exploration and technical characterization of Bauxite over the whole of the Paragominas Bauxite District, culminating in the opening of the first VALE mine an the Miltônia Plateau, based on reserves equivalent to 300 MT of beneficiated product.

The geological profile of the deposits consists of seven layers: Topsoil and Clay Overburden (Belterra Clay) Nodular Bauxite, Ferruginous Laterite, Crystallized Bauxite, Crystallized/Amorphous Bauxite, Amorphous Bauxite and, at the base, argillaceous sediments of the Lower Cretaceous Ipixuna Formation.

Mine grade control and production monitoring is based on processing data obtained by logging and sampling boreholes made on a 100 X 100 meter grid and channels made on a 25 X 25 meter grid on the mine fronts.

The mining operation faces two major challenges: a high stripping ratio of 7.6 in volume and a high level of rainfall. The mining system, therefore, needs to optimise waste stripping and allow for ore selectivity. The system developed to achieve these results uses hydraulic excavators and bulldozers for waste stripping, and hydraulic excavators and trucks for ore production.

The mine scheduling developed to design, simulate and sequence the mine on both Paragominas plateaus are described. Several scenarios were analyzed in order to better understand the relationship between the design parameters and the geological resources. The use of specific software tools, the appropriate data format and checks, and the experience of the mine staff were key issues to produce the best results.

Keywords: Stripping mining, Bulldozer, Overburden, Open pit, Stripping ratio

1. Introduction

Location and Access

The Paragominas bauxite complex is located 220km south of Belém, Northern Brazil, and 70km southwest of Paragominas, the closest town (about 3°21' S, 48°05' W). Site access is from Belém, via the BR-010 Belém–Brasília highway, and also from the town of Paragominas. CVRD stated that local access roads are due to be asphalt-sealed prior to production start-up. Belém is the capital of the Pará State, with excellent aerial and river-borne communication (Figure 1).

Topography, Climate and Vegetation

The mine property is located in the *Amazonas* sedimentary basin, between the basins of the *Capim* and the *Gurupi* Rivers, and is characterized by a well-developed drainage system, forming low valleys that separate isolated plateaus. The Paragominas bauxite deposits are developed on a 10,000km^2 plateau, situated 50 m to 150 m above the drainage-incised valley floors. The average altitude does not exceed 150 m in the plateaus.

The climate is hot and humid. The average temperatures range from 20°C to 33°C and the natural humidity averages 90%. There are no well-defined seasons, only very wet and less wet periods, locally known as "*inverno*" (or winters, December to May) and "*verão*" (or summers, June to November). Annual precipitation reaches 2,200 mm, with monthly averages of 180 mm.

The original vegetation is the equatorial latifoliated forest, with transitions to a tropical forest, dominated by low and medium size plants, and locally with very high trees, among them the cedar (*Cedera odera*), "ipê roxo" (*Tabebuia barbata*), "angelim" (*Hymenolobium petraeum*), and "maçaranduba" (*Manikalra luberi*). Other common species include the "cipós" and various species of palm trees. However, much of the area has been deforested, and is currently used for agricultural purposes.

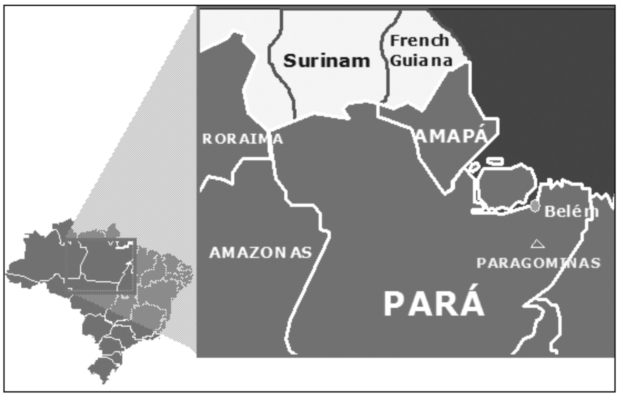


Figure 1. Paragominas Location Map Geological setting

Local Geology and Mineralization

The Miltônia 3 (M3) and Miltônia 5 (M5) gibbsitic bauxite deposits have formed by deep tropical weathering of the *Ipixuna* Formation. The bauxite layer forms a nearly continuous tabular body, less than 5 m thick, but extending 20km north–south, and as much as 8km east–west, beneath the plateau surface.

The geological profile found in drill holes, pits and trenches indicates that differences in composition, mineralogy, and texture have arisen from differences in the original sedimentary protolith, as well as from the position within the weathering profile.

The main factors in the bauxite formation were as follows:

- geologic factors: geologic stability over a long period,

- petrographic factors: the presence of the porous and aluminum-rich *Barreira*s formation rocks,
- climatic factors: a tropical climate, with abundant precipitation,
- morphological factors: the depth of the phreatic layer, the presence of old elevated surfaces (plateaus).

Prolonged weathering and oxidation of aluminum-rich sediments allowed the formation of gibbsite, an aluminum hydroxide, which can occur in a microcrystalline, porcelain-like form (amorphous bauxite), or as fine-grained euhedral crystals that occasionally reach 1 mm in size.

Minerals within the deposit display either 'detrital' or 'secondary' character. Minerals that are 'detrital' were originally deposited as part of the host water-borne sediment (e.g., quartz and anastase); those that are 'secondary' are weathering products of kaolinite and feldspar.

2. Exploration

Drilling

Drilling at the Paragominas bauxite district started in July 2002. The drilling was made using triple-barrel air-flush drills. Core drilling at the Miltônia 3 was initiated on a 1,600 m x 1,600 m grid, and progressed to a 200 m x 200 m centered grid (a 200 m square with a central hole). In some areas, the grid was even more detailed, 100 m x 100 m and 25 m x 25 m. The Miltônia 5 grid went from 800 m x 800 m to 200 m x 200 m with center holes. Table I lists the drilling meterages per plateau.

Core Logging

Drill core in the PVC pipe was transported to a logging facility, where the entire hole was laid out and logged. Measures of core recoveries were made by inserting a measuring tape in each end of the PVC pipe and then were compared to the recovered length of the drilled length.

The PVC pipe was then cut longitudinally with a saw; the core was placed into the underlying tray with a minimum amount of disruption, and was then photographed with a digital camera (one picture per drill hole).

Logging intervals were measured to the nearest centimeter. The logs were general, mainly describing the rock type and color. The distinction between ore and waste units was quite clear in the drill core.

Table I. Drill Hole Meterages by Deposit

Deposit	Year	No.Holes	Meterage (m)	Grid
Miltônia 3		9	131	1,600 m x 1,600 m
		43	567	800 m x 800 m
	2002-	741	10,223	400 m x 400 m
	2005	1,087	14,724	200 m x 200 m
		580	8,466	200 m x 200 m Centered
		28	457	100 m x 100 m
		128	2,159	25 m x 25 m
Subtotal		2,616	36,727	-
Miltônia 5		91	1,174	800 m x 800 m
	2004-	561	7,638	400 m x 400 m
	2005	735	10,695	200 m x 200 m
		112	1,252	200 m x 200 m Centered
Subtotal		1,499	20,759	-

The following lithology types were logged: CAP, *capeamento* (overburden); BN, *bauxita nodular* (nodular bauxite); BC, *bauxita cristalizada* (crystallized bauxite); LF, *laterita ferruginosa* (ferruginous laterite); BM, *bauxita maciça* (massive bauxite), BA, *bauxita amorfa* (amorphous bauxite), ARV, *argila variegada* (mottled clays), with mixed or transition zones, like BNC, BCM and BCBA. These attributes were hand-entered by a technician into the in-house database management system.

Sampling, Sample Preparation and Assaying

After logging, the core was split in two, with hammer and chisel when needed. Sample intervals were marked off in nominal 0.5 m intervals. However, main geological contacts were honored; maximum and minimum sample lengths were usually 0.75 m and 0.30 m, respectively, although sometimes those figures were exceeded. All material was placed in large, 300 μm thick plastic bags, with the drill hole number and sample number on the outside and the inside. Out of every 20 samples, one sample was weighed to compare it with the weight obtained later by the laboratory.

Only samples from the bauxite section were submitted to the laboratory, although one or two samples from the overlying and underlying material were also included. The crude sample and the +20 mesh fraction were assayed in the lab. The assay suite includes ICP determinations for Total Al_2O_3, Total SiO_2, Fe_2O_3 and TiO_2; and Loss on Ignition (LOI). In addition, a Parr sodium hydroxide bomb was used to measure Available Al_2O_3 (by titration with $ZnSO_4$) and Reactive SiO_2 (by ICP).

Quality Assurance and Quality Control

People from CVRD had detailed written procedures for every operation, from drilling and sampling to sample preparation and assaying, including recommendations to minimize errors. A quality control procedure was implemented during the Miltônia 3 and Miltônia 5 exploration programs. The program included the following control operations and control samples:

- mass control after crushing (5%)
- sieve tests after pulverization (5%)
- coarse duplicates (5%): conducted after splitting the original sample, before the granulometric separation (sent blind to the laboratory)
- pulp duplicates (5%): conducted after pulverization (blind to the laboratory)
- check samples (5%): submitted for external analysis to a secondary laboratory.

3. Resource Estimation

Geological Model

The geological modeling was prepared using two different general mining software packages. Two methodologies were used for building Miltônia 3 and Miltônia 5 models where eight lithological units were interpreted and modeled.

For Miltônia 3, a Gridded Seam Model was used. The methodology consists of defining the lithological contact points in the drill hole database, then interpolation of the seam thickness, and finally corrections of the surfaces that auto intersect. Surfaces were created and then a block model was defined.

For Miltônia 5, a traditional method of vertical section interpretation was used. Sections north–south and east–west were interpreted where drill holes exist. A manual interpretation of the lithological units was done, by "*snapping*" the line point to an existing drill hole intersection, thereby building a straight line between two drill hole points. This contact line is then smoothed using a GMP command tool that will create intermediate points along the string segments and interpolate a curve, or smoothed line in between the existing points, honoring the contact information. The strings, north–south and east–west, are then used for building three-dimensional surfaces. Where lenses of material occur in between the seams, a three-dimensional solid modeling technique was put in place.

Models were extrapolated laterally up to 400 m from the last existing drill hole, just to impose a limit for the block model.

Resource Model Validations

A statistical validation was done comparing averages from the composites and estimated blocks. The comparison considered separate blocks that were estimated in each run, compared to the average of the total number of composites available. The graphs showed a very good correlation of the average from estimated blocks in the first run and the composites, being within less than 3% for all variables. This difference is higher for blocks estimated during second and third runs.

Swath plots were also used as another grade estimation / validation tool. Slices of 500 m along north–south and east–west directions and 10 m in the vertical axis were generated. The averages of the blocks and composites within these slices were then compared in a graph where the number of composites used for estimation was also considered.

Based upon examination of drill core, test pits, and trenches, CVRD planners calculate that losses of the BCM (ore) horizon during mining will be minimal. The contact with underlying BCBA from crystalline bauxite (BCM) is gradational and of only slightly inferior quality to the main ore horizon. Therefore, it is calculated that 20 cm of BCBA below the BCM will be incorporated into run-of mine ore. Given that the BMC horizon averages about a meter thick, the dilution is equivalent to about a 13% increase in tonnes, with only a slight effect on the ore quality parameters. This twenty centimeters of dilution was considered for the block model used at mine planning, and the built ore blocks include the dilution obtained from the BCBA blocks.

4. Resource Classification

The resource classification of each block was based on the anisotropic distance between the block centroid and the nearest sample used to estimate the block, see Table II. The distance cutoff was selected by reference to the BCM thickness variogram, since this variable was considered to have the greatest impact on the reliability of the *in situ* resource estimate and presents the shortest range of variograms when compared to other variables.

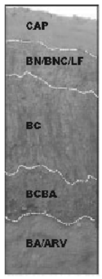
The distance cut-off corresponds to one half of the distance at which the first spherical component of the BCM thickness variogram reaches a level of 98% of the first structure sill, termed D98/2. Measured resources comprise blocks with a BCM thickness value estimated in the first pass and in which the anisotropic distance to the nearest sample was less than D98/2. Indicated resources comprise blocks interpolated in the second pass. Inferred resources comprise all remaining blocks and are estimated in the third run.

Table II. Resources Statement

		Product		
Plateau	Category	Tonnage (Dry Mt)	Al_Av (%)	Si_React (%)
	Measured	161.90	49.39	3.49
Miltônia 3	Indicated	59.50	48.80	3.77
	Measured & Indicated	221.40	49.23	3.57
	Measured	130.60	45.69	4.48
Miltônia 5	Indicated	48.00	42.14	5.39
	Measured & Indicated	178.60	44.73	4.73
	Measured	292.60	47.74	3.93
	Indicated	107.50	45.87	4.48
Total	Measured & Indicated	400.10	47.23	4.08
Inferred		18.10	44.60	5.48

5. Mine Geology

The geological profile of the Miltônia deposit has eight horizons (Figure 2), with lateral variation in thickness to characterize the following lenticular horizons: Clay Overburden (CAP), Nodular Bauxite (BN), Crystallized Nodular Bauxite (BNC), Ferruginous Laterite (LF), Crystallized Bauxite (BC), Crystallized/Amorphous Bauxite (BCBA), Amorphous Bauxite (BA), and Variegated Clay (ARV). According to Kotshoubey *et al.* (2006) the oldest rocks of the District pertain to the Itapecuru Group (south and central portions) and the Ipixuna Formation (north portions) belonging to the Upper Cretaceous, according to Santos Jr. and Rosseti (2002).



Miltônia 3: Typical Geological Profile

Layer		Thickness in meters Average	Range	Classification
CAP	Clay	11	0 - 17	Overburden
BN/BNC	Nodular Bauxite	1,3	0,3 - 2,1	Marginal Ore
LF	Ferruginous Laterite	0,6	0 - 2,1	Waste
BC	Crystallized Bauxite	1,5	0,5 - 4,5	Ore
BCBA	Crystallized/ Amorphous Bauxite	1,0	0,5 - 2,5	Marginal Ore
BA	Amorphous Bauxite	0,3		Waste
ARV	Mottled Clay	-	-	Deposit floor

Figure 2. Typical Lateritic profile at the Miltônia Plateau

The Nodular Bauxite is characterized by nodules which increase in size towards the base. This material forms quite discontinuous bodies. At the top, there are millimetres to centimetre sized bauxitic nodules, coloured from yellow to lilac, associated with ferruginous pseudo-pisolites. At the base the nodule become concretions, with a diminishing quantity of pseudo-pisolites and increased degree of crystallization of the gibbsite.

With increasing depth, the nodular bauxite grades into Crystallized Nodular Bauxite, constituted by nodules and/or concretions of reddish colour, with a relative absence of ferruginous pseudo-pisolites. This material sits discordantly on the Ferruginous Laterite level. Together, the thicknesses of Nodular and Crystallized Nodular can be up to 2 meters.

The Ferruginous Laterite is predominantly in the form of pseudo-pisolites or nodules, at the top and in concretions at the base. Sometimes, this horizon contains medium to coarse grained crystalline bauxite, associated with ferruginous concretions. Thickness of this layer varies from a few centimetres to 2 meters.

The Crystallized Bauxite horizon is that which has the best lateral continuity. It consists of reddish coloured bauxite in the form of blocks or concretions. Frequently, the top is enriched in iron, due to contact with the Ferruginous Laterite, but iron grades decrease towards the base. The contact with the underlying horizon, Crystallized/Amorphous Bauxite is represented by a very irregular transition. The average thickness of the horizon is about 1.5 meters.

The Crystallized/Amorphous Bauxite occurs as nodules and concretions, having yellow to lilac coloured micro to macro-crystalline gibbsite, which is associated (or not) with light grey to light brown porcelaneous (micro or crypto-crystalline) gibbsite. The contact with the Amorphous Bauxite is characterized by an increase in the clay matrix material found between nodules and strong indications of kaolinization, appearing as variegated clay. The average thickness of this horizon is about 1 metre.

The Amorphous Bauxite is characteristically formed of elongated nodules and blocks of micro-crystalline gibbsite, of yellowy colour set in a clay matrix, which is typically variegated. This horizon is the part of the bauxitic zone with the highest silica content.

The Variegated Clay, or kaolinized sapprolite, characterized by multicoloured kaolinitic clay, is the basal limit of the Laterite profile.

The graph on Figure 3 shows that there are two zones of alumina enrichment in the bauxite/Laterite profile found at Miltônia. These are denominated Upper and Lower Enrichment Zones by the authors of this paper. They correspond to the BNC and BC horizons, respectively.

Despite the gradational contact between BN and BNC, the BNC exhibits strong alumina enrichment, with consequently strong suppression of iron content. Silica is slighthy depressed coming to grades of less than 5.5%. The LF acts like as inversion zone for iron grades, while silica is slightly enriched here.

The top of the BC is marked by the presence of ferruginous blocks and nodules, usually forming concretions less than 20 centimetres thick. This explains why iron oxide grades are about 15% in this portion, dropping off below. Visually, the gradational contact between BC and BCBA is marked by a change in texture of the reddish concretions with clearly crystalline bauxite. The nodules become yellow and lilac; the crystals are less well defined and frequently show evidence of degradation. Chemically, this contact is marked opposite trends in the silica and iron curves.

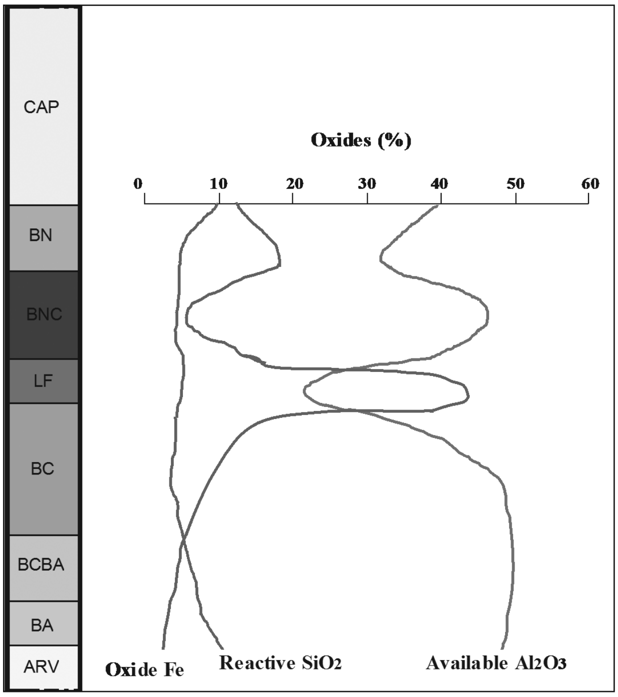


Figure 3. Progression of Available Alumina, Reactive Silica and Iron Oxide in the Typical Miltônia Profile

The lower horizons are marked by successive enrichment of reactive silica concomitant with suppression of iron and available alumina.

The variation in mineralogy is relatively small over Miltônia. The principal mineral constituents are gibbsite, kaolinite, quartz, hematite, anatase, goethite and, in lesser quantities, micas, zircon, tourmaline, ilmenite, pyrophyllite, and locally a little boehmite.

Characteristics of the Ore

The Crystallized Bauxite and the upper portion of the Crystallized/Amorphous Bauxite are the principal components of the ore, because of the high grades of available alumina and lower quantities of reactive silica found here. This combination also has an almost constant presence over the entire plateau and affords the best thickness for mining. The Upper Enrichment Zone offers a subordinate option in places where grades and thickness are adequate and the intervening Ferruginous Laterite is not too thick to be included without upsetting overall grades, or it is thick enough to be separated with efficient use of the mining equipment.

6. Mining Methodology

The mining sequence consists of deforestation, waste stripping, and ore scarification, bauxite mining (loading and hauling), waste fill (from subsequent strip) and reforestation. The geometry of the operation is characterized by the continuous flat tabular bauxite deposit, on average 1.59 m thick for Miltônia 3 (M3) and 1.22 for Miltônia 5 (M5), under overburden that averages 11.45 m on M3 and 10.18 m on M5.

The mining operation has two major conditions to consider: a high stripping ratio (7.6 in volume) and a high rainfall, thus it is necessary to have a mining system that minimizes the cost of waste stripping and aids selectivity. The appropriate system comprises hydraulic excavators and bulldozers for waste stripping, and hydraulic excavators with trucks for ore production. These are supported by auxiliary equipment. Figures 4 and 5 show the steps of the mining methodology.

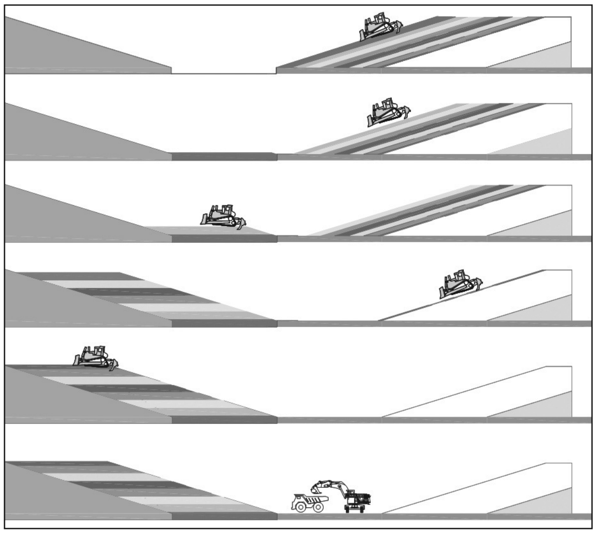


Figure 4. Mining methodology up to 8m of overburden

The methodology uses a hydraulic excavator (Liebherr 994) when the productivity of the bulldozer (D11R) decreases. This happens when great distances and steeper up-slopes leave an optimal working height for the excavator.

Depending on the overburden thickness, there are two different ways to remove the waste material. Areas with up to 8m are totally removed by bulldozer Cat D11R (Figure 4) and the other areas are excavated by bulldozers and hydraulic excavators (Figure 5). In both cases the bulldozer scarifies the ore, which is mined using backhoe excavators of 4.5m^3 to load trucks of 35 metric tons.

In areas with more than 8m of overburden, the bulldozer (Cat D11R) does the pre-stripping Figure 5: (I). Afterwards, the excavator (15 m^3) digs the approximately 5m of overburdenleft on the strip, Figure 5: (III). The remaining material is dug and re-handled as showed in Figure 5 (II).

The mining schedule was constructed from block models, delimiting reserves by the maximum proximity to the plateau border (40m) allowed for environmental preservation.

The uniformity of bauxite quality throughout the deposit, and sourcing of run-of-mine (ROM) bauxite from a minimum of three faces at any time assures a homogeneous supply of material from the mine.

The mining schedule considered both plateaus, Miltônia 3 and Miltônia 5; the sequence for them shows that during the first four years only Miltônia 3 will be in production. During year 5, production will start in Miltônia 5. At which point the plant will reach the maximum capacity. Also the detailed investment profile was determinate for the Life of Mine Plan, which includes equipment acquisition and replacement; and installations; etc.

One of the main issues for fleet calculations is productivity, especially of the CAT D11 bulldozer, because this equipment has a large influence on the mine cash cost.

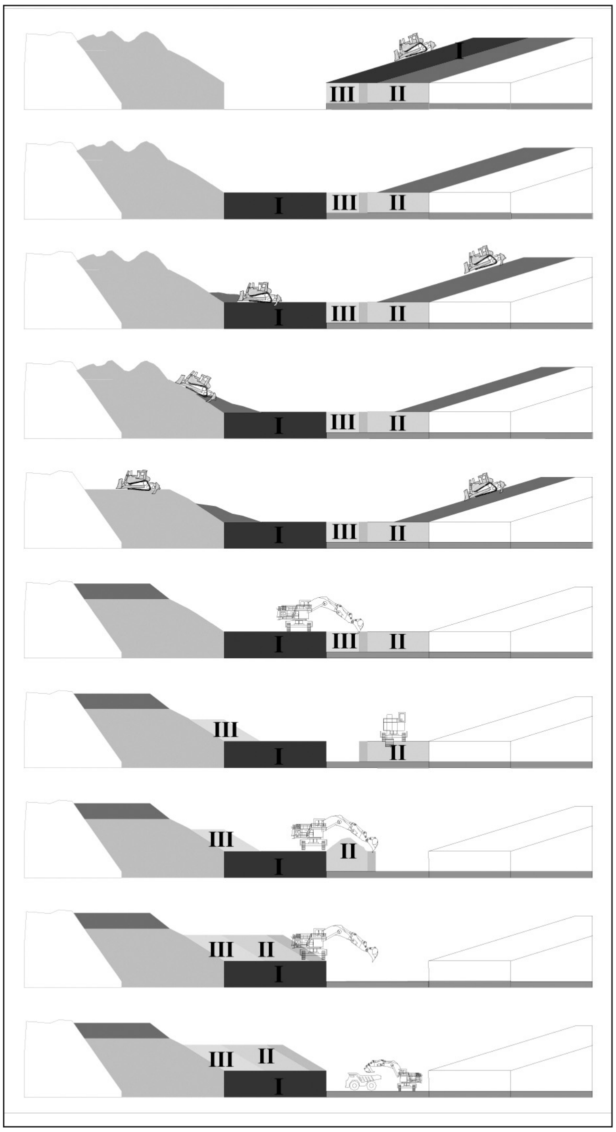


Figure 5. Mining methodology above 8m of overburden

7. Production Schedule

A simple way to calculate this productivity is to use the supplier manual. After selecting the appropriate blade according to the material (mainly clay), the next step is to estimate the dozing production by the following formula:

Production (Lm^3/hr) (LCY/hr) = Maximum production x Correction factors

The bulldozer production curves give maximum uncorrected production for universal, semi-universal, and straight blades and are based on several conditions. Figure 6 shows a typical productivity chart.

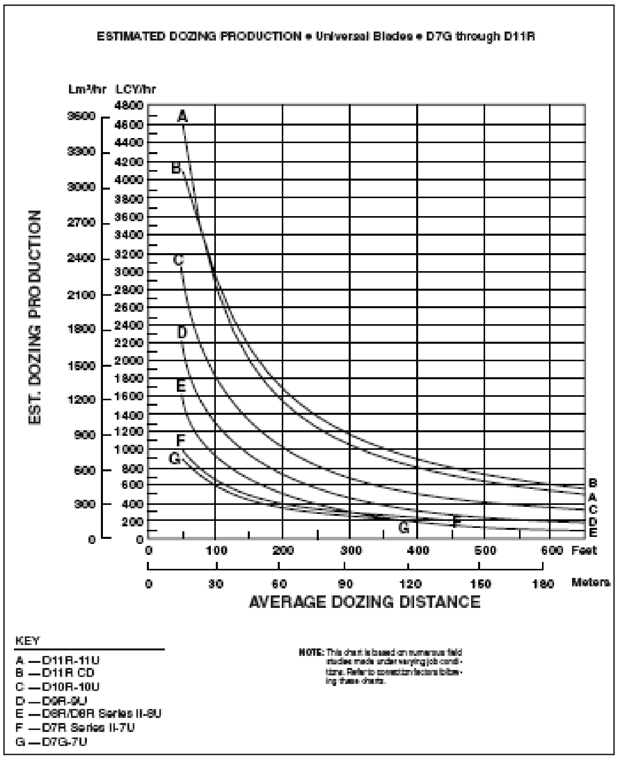


Figure 6. Bulldozer productivity

The main factors for estimating the productivity are: the operator skills (0.5-1.0), type of material (0.6-1.2), Slot Dozing (1.2), side by side dozing (1.15-1.25), job efficiency (.67-.83). The grade factor has a big influence on the productivity and can be calculated from Figure 7.

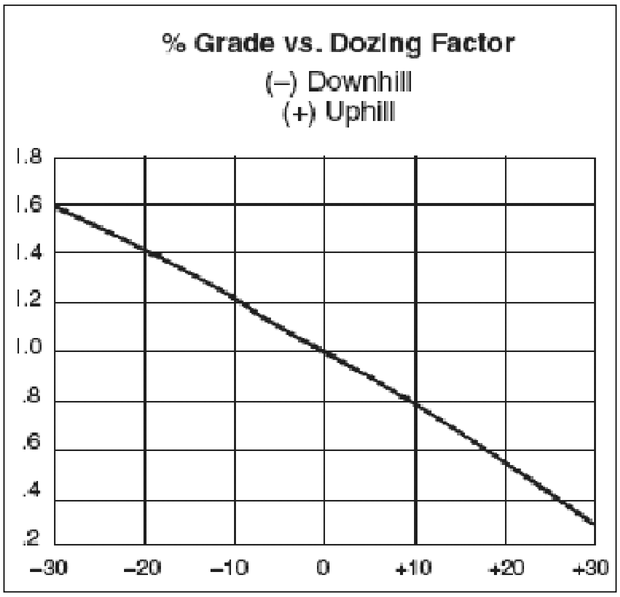


Figure 7. Grade factor

Another method of estimating the dozer productivity is to use the supplier dozer simulator (DOZSIM). The first step is to define a geometry that is compatible with the geology of the deposit. Figure 8 shows the parameters used to simulate the correct geometry.

The operation parameters are entered to the system in order to calculate the productivity. Since the estimations are quick, it is possible to evaluate the impact on the results of changing the different parameters.

The productivity obtained by both methods were simulated and compared with the estimates calculated using the Performance Manual. Figure 9 shows the simulation of the situation where the overburden are less then 8m. For areas, where the strip ratios were high, the simulated results did not get as close to those estimated using the Manual. Further tests and studies must be made with the dealer.

Another aspect that can be examined using the simulator is estimating productivity for different types of bulldozer (CD), different sizes of strips, different strip ratios and different contributions by the hydraulic excavators.

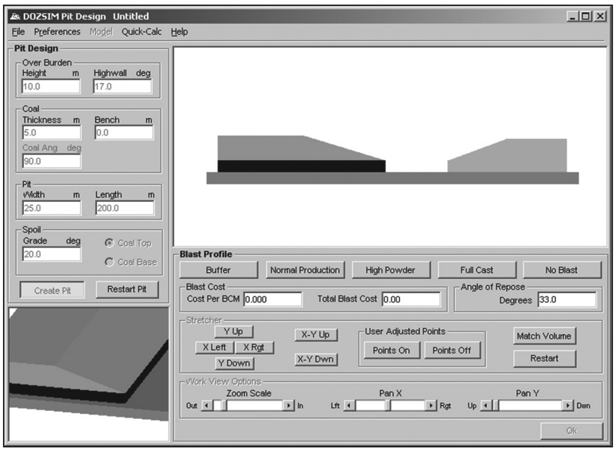


Figure 8. Design of the geometry

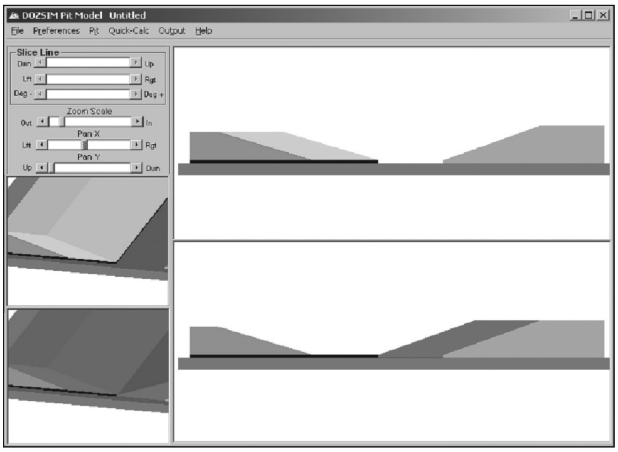


Figure 9. Use of the simulator DOZSIM

The influence of the resource classification, ore mining, washing and transportation costs and the price of the bauxite were also simulated and estimated. This type of study could help to indicate where VALE must invest in drilling, and evaluate the impact that efforts to reduce costs have on the final results.

8. Conclusions

The mining methodology is highly dependent on the thickness of the waste and ore of the deposit, the effective productivity of the dozer and the hydraulic excavator and their respective costs. Studies to compare the mining costs with other stripping methods (dragline, bucket wheel, etc.) are very important and under constant review.

The use of a specific software tool for scheduling, the appropriate data format and the experience of the staff developing the mine sequence, together with field checks are critical to producing the best results.

The key indexes and results obtained in current mining operations consolidate the methodology applied, in terms of estimating the equipment fleet required and the grade variation throughout the life of the mine.

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