

Final open pit design for Monte Raso phosphate mine

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ABSTRACT: A fundamental aspect in the development of any open-pit mining project is the determination of the mineable reserves and the respective design of the ultimate pit limits. The design of the ultimate pit is of prime importance for practical open pit mining as is evident from the worldwide attention it has been receiving in the past decades. All major mining software offer some version of pit limits design packages among their services. The Monte Raso property (MR mine) is a phosphate prospect located in the central state of Goiás, in Brazil. The drillhole information and the topographic map have been kindly provided by a Brazilian phosphate mining company. As the true location of the prospect is not important in this case study authors have modified it to the vicinity of a real phosphate mine in order to provide a realistic geological information from published sources. In this fictitious account, the names of the structural features have been retained. In this paper, at first, the Vulcan software, applied over the data of MR phosphate deposit, will be introduced. The modeling of the ore deposit was done using a geological database of 41 diamond core samples. Finally, the ultimate pit limits of the deposit were determined and the design of the ultimate pit presented.

Keywords: Design, Mining, open pit, phosphate

I. INTRODUCTION

The mineral resources are nonrenewable in the human scale of time and their exploitation should be made thoughtfully objectifying the maximal recovery of the mineral reserves. The mining of an open pit is a complex operation that extends for many years and involves a huge capital and risks. Before *start up* is fundamental to classify the ores of the mineral deposit (ore types, ore grades, ore amount and ore spatial distribution) and establish as these ores should be mined to get profit. A fundamental aspect in the development of any open pit mining project is the determination of the mineral reserves to be exploited through the design of the called ultimate pit limits [1], [2], [3], [4]. Currently, the different types of algorithms used to optimize the mine open pit can be divided in two categories [5]:

Heuristics: the experience demonstrates that their results in terms of mine open pit optimization are satisfactory although without a mathematical demonstration to assure their validity. This is the case of the methods of the Flotation Cone, Korobov, and Function of parameterization of François-Bongarçon.

Rigorous: When the optimization has a complete mathematical demonstration. The most characteristic and famous is the method of Lerchs & Grossmann [6].

II. The Monte RASO Phosphate Deposit

The Monte Raso phosphate deposit exploration was made by the Mineração Boa Esperança S.A - MBESA [7]. The phosphate reserves, for which a basic project for definition of the final open pit limits was developed in this paper, is a unreal reserve, but it is not impossible. The structure of this reserve was based on a real reserve and the grades are resulting of the multiplication of the grades of the original deposit by a certain unknown factor. The justification for this procedure is based on confidentiality needs and in the convenience of joining, in a same ore reserve, most of the problems that generally happen in a mine project. The phosphate reserves of Monte Raso are located in the state of Goiás, approximately at 200 km (NW) of Brasília and 250 km of Goiânia. (Fig.1).

The older geologic formations of this region have a correlation with the Precambrian era. The geology of the deposit of Monte Raso is stratigraphically positioned in Paraobepa formation of Bambuí geological Group. The phosphate rocks are located in the top of the Paraobepa formation in conformity with a layer of weathered slate with high grade of magnesium (WM). On the other hand, the phosphate mineralization is covered by a layer of calcium-chlorite-schists. The phosphate layers were submitted to a light geological weathering characteristic of the Bambuí group and Paraobepa formation. In the determination of the typology of the phosphate ores of the reserve of Monte Raso the grades of P_2O_5 , CaO and $Al_2O_3 + Fe_2O_3$ were considered and were included samples off all of the 41 survey holes. The method used for ore characterization is denominated Cluster Analysis. In this methodology the objective is the formation of homogeneous groups of ores based in chemical and/or mineralogical composition of the samples. As conclusion of this studies three elementary types of ore were established: the weathered slate superior (WSS), weathered slate medium (WSM) and the weathered slate inferior (deep) (WSI). The wavellitic crust (WC), the black slate (BS) and the horizon slate with magnesium (WM), although they constitute different groups, were not classified as ore. The conclusion is that the primary ore of the deposit is a weathered slate (WS) with an average grade of 10% of P_2O_5 [8].



Figure 1 - Location map of the Monte Raso Phosphate Reserve (MR mine).

Source: CPRM - Brazilian Geological Service

III. THE VULCAN PROGRAM

The Vulcan program is a dynamic graphic system with the most modern three-dimensional technique (3D) to accomplish the exploration and to model the geology, project of mines, production of mines, topography, extraction of resources, geostatistics, surfaces in general, environmental rehabilitation, planning of open pit and underground mines [9] [10]. This program uses the algorithm of Lerchs & Grossmann as optimization method for open pit mines. The program VULCAN allows the construction, visualization and manipulation of models of blocks, providing an optimization of the space representation of the geometry of the ore body starting from the definition of the size of the initial block or root (or secondary blocks, if it is necessary) and the variables of the model. The number of variables that can be inserted in the model is satisfactory including those that store the revenue generated in each block, the number of samples used to esteem the grades, the average distance of the samples to the block, the number of holes used in the estimate and the variance of the estimate of each block. The program VULCAN facilitates the estimate of referred grades of the blocks, the definition of the geologic reserves and the drawing of the final limits of the pit. Several geologic scenarios can be modeled (as metallic deposits of good stratigraphic conformity, deposits of coal and complex disseminated deposits or veins). The program incorporate geostatistical tools and of analysis of data and estimate of the reserves. One of the modules of the program allows the interface with programs and algorithms of optimization as Lerchs&Grossmann and the program Whittle 3D.

IV. OPEN PIT MINE DESIGN METHODOLOGY

The open pit mine design methodology starts by construction of databases containing the general data of the mine exploration, visualization of the surveys, geologic modeling and, based in the topographic map of the Monte Raso region (Figure 2), generation of the topographical surface (Fig.3). The next steps are implementation of the model of blocks, evaluation of reserves and project of the final limits of the pit [11] [12]. For modeling the ore body are used, frequently, regular blocks and a great collection of regular blocks to represent the overall mineral body.

According to Hustrulid, W. and Kuchta, M. [11] the steps that were generally used to create a block model for a mine to evaluate the mineral reserves are listed below :

- a) Create a file containing the collar coordinates of the exploration drill holes, the hole directions and the assay values along the hole lengths.
- b) Create a surface topography and plot the locations of the drill holes.
- c) Plot vertical sections through lines of drill holes in order to examine probable pit location.
- d) Choose the size and position of the blocks and the model grid. The thickness (B_z) of the blocks is usually set to planned bench height. The block width (B_x) and (B_y) height dimensions are chosen arbitrarily (normally equal to one another) but a rule of thumb is that the block size (in plan) should not be less than one-fourth the average drill hole spacing. The location of the grid can be decided upon by examining the plan and section maps and locating the block grid such the potential pit area (including a provision for pit slopes) is covered. Create a composite file from the drill hole file. In order to estimate block values, the assay samples must be regularized to form composites defined over core sections of equal length. It is common in open pit mining to choose the composite lengths to be equal to the bench height, or a submultiple of the bench height, and to calculate the composites such that their centers fall at the midpoints of the blocks.

- e) Assign the block grades. After preparing the necessary data files and deciding on the size and location of the block model, a grade must be assigned to each block. In this simulation, the geostatistical methods was used for assigning block values.
- f) Create horizontal plan maps and vertical section maps through the block model to be used for planning purposes.

Assign economic values to the blocks. From the block grades and estimated mining costs, an economic value for each block is assigned. In the specific case of a mine after mineral grades for each block have been calculated, the economic block values were assigned using a benefit function (BF) presented in equation 1.

$$BF = \gamma \times v \times (\% \text{ mineral}) \times (\text{mineral recovery}) \times (\text{price of mineral product}) - \text{costs of (refine + milling + processing + administration + mining + haulage)} \quad (\text{Eq.1})$$

being γ the density of “*in situ*” material, v the block volume and (% mineral) the block grade. The equation 1 is a general mathematical expression to determine the net value of each block of a block model according to economic parameters. This function determines the net value of each block of the block model by calculating the difference between the revenue based on the mineral contained and the costs for mineral production. The economic parameters for the benefit function used in the simulations are presented in Table 1 and were evaluated taking in to account data of the Brazilian production of phosphate rock. This figures were calculated based in information of the references [13] and [14].

Table 1 – Mine economic parameters of the exploitation in US \$ per ton

General mineral recovery (mining and processing)	0.7
Cost of mining & processing	- 54
Price of mineral product	+ 62.0

- g) Calculate the final pit limits. From the economic block values, the pit limit shell may be calculated using one of the several available optimization techniques. It was used a slope bench angle of 60°. In this simulation a L&G algorithm included in the Vulcan software was used.
- h) Locate in the ultimate pit the blocks of waste and the blocks of ore by restricting the entire block model using the surface topography (Fig.3) and the ultimate pit limits calculated in the item g). A select tridimensional vision of the resulted open pit restricted by topography and ultimate pit limits is presented in the Fig.6.

Usually a pattern of ore dissimilarity is reached subdividing the mineral deposit in areas that are geologically homogeneous. The attribution of the blocks grades (Table 2) usually is made by a procedure of deterministic interpolation as, for example, the methods of the inverse of the distance or kriging. Besides, the experience demonstrates that, frequently, about 95% of the elementary blocks of the block model don't have any value and not even contains any sample value. The estimate of the blocks of the pit and consequently, the geologic reserves of phosphate of Monte Raso were made using a geostatistical method. The block model built for evaluation of the geologic reserves of Monte Raso presented a total of 403.117 blocks with tridimensional dimensions established for each block of 10 x10 x 10 meters.

It is important to reminder that the task to attribute or to esteem values of costs for the blocks in an open mine is not easy. This fact has a huge influence on costs and time in terms of evaluation of the model.

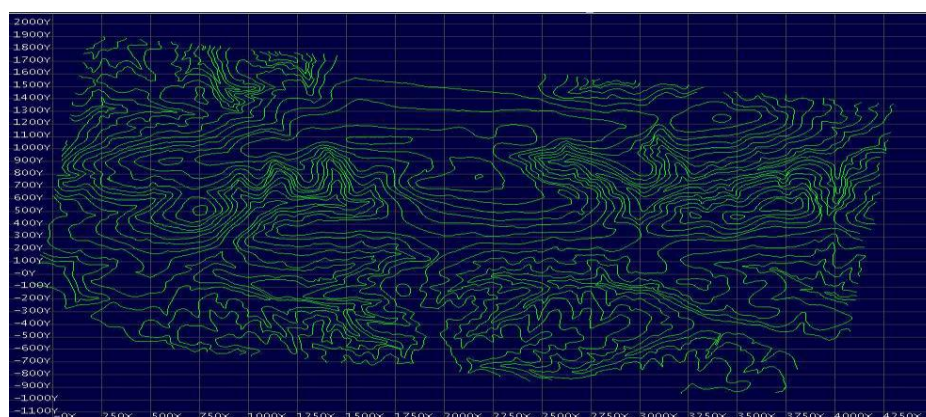


Figure 2 - General aspect of the topographic map of Monte Raso region (without scale).

Source: Pereira, 2000

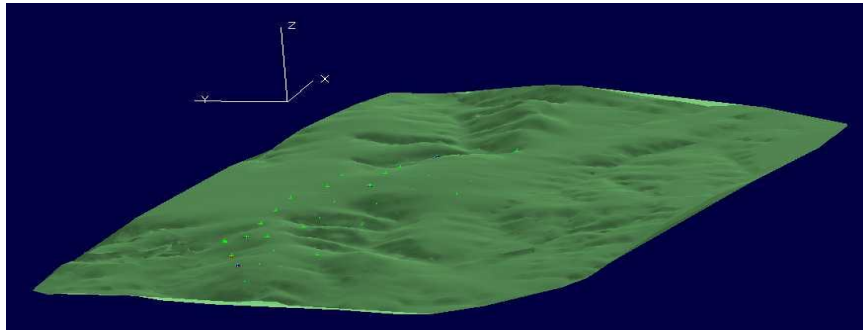


Figure 3 - General aspect of the surface map of Monte Raso region including drill holes (green dots) (without scale)

Source: Pereira, 2000

Table 2 - Statistical analysis of the data for Monte Raso reserve

Products	%P ₂ O ₅	%CaO	%Fe&Al
Arithmetic average	6,5	8,7	5,3
Standard variation	3,6	4,8	2,8
Variance	12,8	22,8	7,7
Median	6,0	8,3	4,6

In the definition of geologic reserves any limitation or restriction of cutoff was applied. It results in a subtotal of 41.082 blocks (in a total collection of 403.117 blocks of the whole block model). The table 3 presents the grades and mass calculated for each lithology as mentioned in the section II . It is important to highlight that the average grades for P₂O₅ and CaO were pondered by mass. The general average grade of phosphate is 7,3 % of P₂O₅ for a total geologic reserve of 50 million tons and a volume of 31 million of cubic meters, considering a average density of 1,60 ton/m³. The weathered slate lithology (WSS, WSM) and the deep weathered slate (WSI) are the ones that presented higher grades of P₂O₅, being, therefore, the lithologies that represent the ore body to be mined.

Table 3 - Results of the geologic reserves of MR.

Lithology	%P ₂ O ₅	%CaO	Mass (ton)	Volume (m ³)
WSS	3,3	3,2	1.323.400	827.125
WSM	8,2	10,6	35.804.601	22.377.875
WSI	5,3	7,9	10.924.400	6.827.750
BS	3,4	7,0	972.750	486.375
WCc	1,5	0,7	620.500	310.250
Total	7,3	9,6	49.645.651	30.829.375

The options to define the final pit limits of the MR mine were done by a specific module of the Vulcan program. Several simulations bearing in mind the obtainment of better pit were made considering economic factors and mainly the profit; the key objective of a mining industry. The resultant final pit was which one that presented the higher profit considering the whole ore body to be mined. Taking into account the economic aspects the ore body to be mined was divided in several horizontal layers (levels) or mine benches. Starting from the bottom of the ore body the first level or mine bench where the profit was positive (profit > 0) was determined. The open pit was so built taking this level as a level of reference. The other mine levels or benches were so projected and designed in the surface (Fig. 3) direction (down / top) using the geometrical parameters of the pit listed in the Table 4 (See below). It results in a subtotal of 36.026 blocks (in a total collection of 403.117 blocks of the whole block model). The first level or mine bench is in the elevation of 805m in relation off the sea level. Starting from the level 805 m, foot of the first bench, the other levels of the open pit were built. The values of the geometrical parameters of the open pit are shown in the table 4 [15]:

Table 4 - Geometrical parameters of the MR mine

Parameters	Value
Width of the berms (m)	5
Height of the bench (m)	10
Angle of the face of the slope (degree)	60°
Width of the road (m)	12
Maximal inclination of the road	10

V. RESULTS

The pit to be selected must be the one that provides the maximal recovery of the reserve to be mined, that is, the reserve that if exploited will generate maximal profit. The benefit function used to select the pit should consider the objectives of long term, taking in to account the value of the money, submitted to an interest rate along the time [16]. The final pit selected for the reserve of MR was the one that provided the highest profit and it has (13) mine benches with height of ten (10) meters, that is, benches 805 m, 815 m, 825 m, 835 m, 845 m, 855 m, 865 m, 875 m, 885 m, 895 m, 900 m, 905 m, 915 m and 925 m. (Figure 6). Were made simulations for cutoffs of 6%, 7%, 8% and 9% of P_2O_5 being obtained evaluations of the amount of ore and waste, waste/ore ratio and profit. The Fig.4 presents the variation of the ore tonnage in function of the cutoff off % P_2O_5 [14].

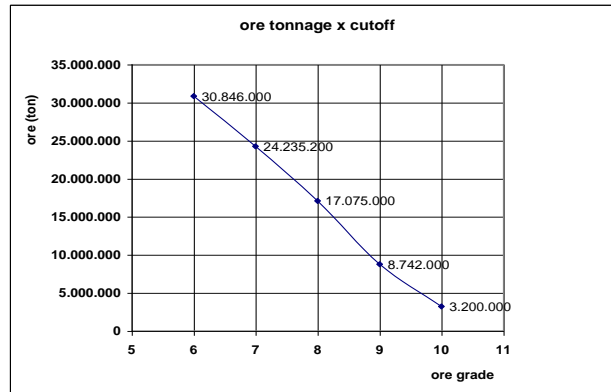


Fig.4 - Analysis of sensibility (ore grade x cutoff of P_2O_5)

The determination of the general waste/ore ratio, and also waste/ore ratio along the years, is of fundamental importance for the mining planning. The waste/ore ratio for the MR mine is not different of the reality that is found in an usual open pit mine. By analysis of the results could be concluded that the best pit is the one designed with a cutoff of 6,0% of P_2O_5 resulting in a mineable reserve of 30.846.000 tons of ore, an average ore grade of 8,5% of P_2O_5 , a general waste/ore ratio of 0,39 and a gross profit (not discounted cash flow) of US\$ 5.023.909.166. It is important to point out that this value didn't take into account the interest rates or the investments that will be applied during the life of the mine.

VI. Conclusions

The main conclusions of the case study are [15]:

- The estimate of the ores by sections (Fig.5) and of the parameters of the blocks for the geostatistic method using the ordinary kriging of blocks was quite reliable, facilitating the construction of a concise block model for the MR pit.
- The general average grade was estimated in 7,3% of P_2O_5 and 9,6% of CaO for a total geologic reserve of 50 million tons and 31 million of cubic meters of P_2O_5 , considering an average density of 1,60 ton/m³.
- The lithology of medium weathered slate (WSM) and deep weathered slate (WSI) presented higher grades of P_2O_5 , being, therefore, the lithologies that represent the ore body to be mined.
- The basics geometrical parameters of the MR are:
 - angle of final slope of the face of the benches of 60 degrees;
 - height of the mine benches of 10 meters;
 - minimum width of the berms of 5 meters;
 - width of the ramps and main roads of transport of 12 meters;
 - ramp or road gradient of 10%.
- The final pit selected for MR was the one that presented higher profit. This pit has thirteen (13) mine benches with height of ten (10) meters (Fig. 6).
- By analysis of the results could be concluded that the best pit is the one that took in consideration the cutoff of 6,0% of P_2O_5 with a mineable reserve of 30.846.000 tons of ore with average ore grade of 8,5% of P_2O_5 , for a waste/ore ratio of 0,39 and a gross profit (not discounted) of US\$ 5.023.909.166. It is important to point out that this value doesn't take into account the interest rates or the investments that will be applied during the life of the mine.

In an earlier investigation made by Costa[8], for the same case study, the ore reserve was evaluated in 109 million tons, with a average grade of 8,5% in P_2O_5 , corresponding to a cutoff of 6%. This great difference can be explained, partially, by the overestimate of the reserves due of the non-use, at that time, of a tool as the computers, that allowed more reliability in the evaluation of the mineable reserves.

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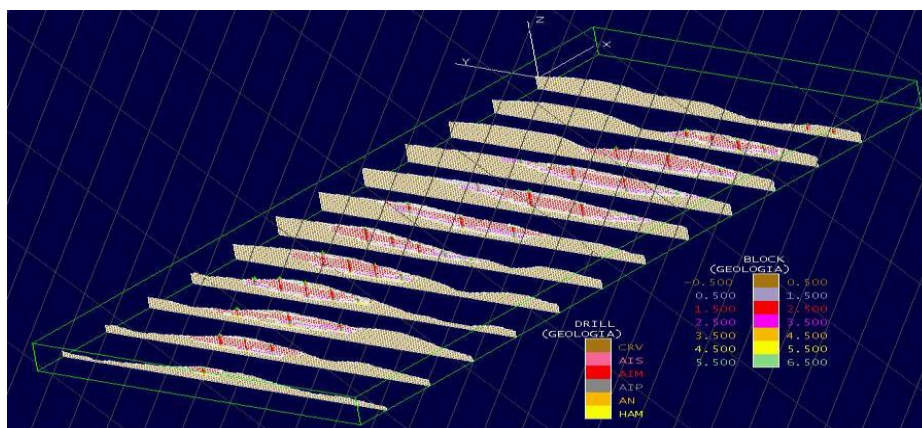


Fig. 5 - Estimate of the ore body by vertical sections for the of the Monte Raso region considering the topography of the region and the data of the mining exploration (drill holes). (Without scale)

Source: Pereira, 2000

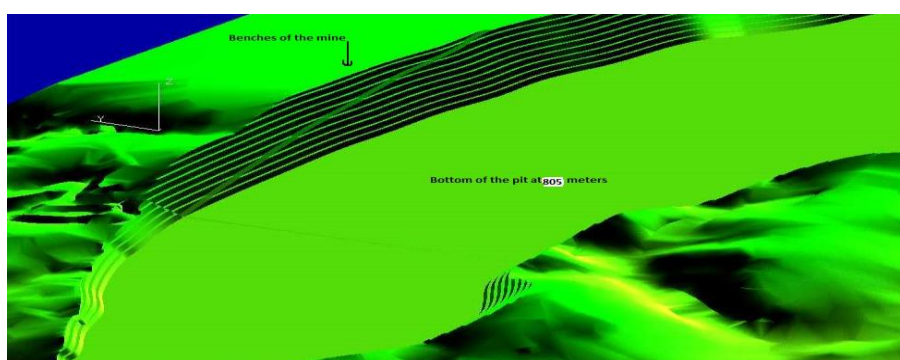


Fig. 6 - Partial view of the MR final open pit including the bottom of the pit at the level 805 m (without scale).

Source: Pereira, 2000

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