Revista Brasileira de Geofísica (2018) 36(4):427-438

ISSN 0102-261X
www.scielo.br/rbg

ELECTRICAL RESISTIVITY APPLIED TO OPTIMIZATION OF BLASTING DESIGN AT PRODUCTION BENCHES: A CASE STUDY AT ABÓBORAS MINE, QUADRILÁTERO FERRÍFERO, MINAS GERAIS – BRAZIL

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ABSTRACT. Quadrilátero Ferrífero is one of the main regions of iron ore production in the world. The action of the weathering processes promotes the conformation of compact rock immersed in friable material. The usual model of blasting applied in production benches, with blast drillholes distributed homogeneously, produces boulders of compact rock, which are impracticable to extract and grind, causing impacts on daily production of iron ore. Therefore, this work proposes a methodology capable of overcoming this problem caused by weathering, using the electrical resistivity method. The application of it was carried out at the Abóboras mine (VALE S.A.), and was able to differentiate two types of materials, interpreted as compact and friable itabirite. With the use of the electrical data, it was possible to generate a geophysical model that allowed to determine the position of the compact itabirite boulders. From this model, it was possible to optimize the blasting design, with higher concentration of detonation drillholes where the model indicated the compact rock. With the appropriate tests, it was observed a 75% decrease in the amount of boulders present in the fragmented material as compared to the usual model. Consequently, there was a significant increase in ore loading effectiveness, thus optimizing iron ore production.

Keywords: applied geophysics, iron ore, mining.

RESUMO. Quadrilátero Ferrífero é uma das principais regiões de produção de minério de ferro no mundo. A ação dos processos intempéricos promovem a conformação de rochas compactas imersas em material friável. O modelo usual de detonação e desmonte aplicado em frentes de lavra, com furos de detonação distribuídos de modo homogêneo, gera matacões de rocha compacta, o que inviabiliza sua extração e moagem e impacta na produção diária de minério de ferro. Desse modo, este trabalho propõe uma metodologia capaz de suplantar esse problema causado pelo intemperismo, através da utilização do método de eletrorresistividade. A aplicação do método foi realizada nas dependências da mina de Abóboras (VALE S.A.), e foi capaz de diferenciar dois tipos de materiais, interpretados como itabirito compacto e friável. Com o uso dos dados elétricos, foi possível gerar um modelo geofísico que possibilitou determinar a posição dos blocos de itabirito compacto. A partir desse modelo, houve uma otimização da malha de desmonte, com maior concentração de furos de detonação onde o modelo indicou rocha compacta. Com os devidos testes de detonação, foi observado diminuição dos matacões em 75% em relação à malha de desmonte usual. Como resultado, houve significativo aumento da efetividade do carregamento de minério, e consequente otimização da produção de minério de ferro.

Palavras-chave: geofísica aplicada, minério de ferro, mineração.

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INTRODUCTION

The Quadrilátero Ferrífero, in the state of Minas Gerais, Brazil, is one of the main regions of iron ore production in the world. The extracted ore comes from banded iron formation (BIF), called itabirite. In this region, the rocks are weathered, with the alteration level reaching, in most cases, depths of 50 meters or more (Dorr, 1969).

Because of that, the action of the weathering processes promotes the conformation of compact rock blocks immersed in friable material. The usual model of blasting applied in production benches, with blast drillholes distributed homogeneously, isn't able to reduce the size of the compact blocks. As a consequence, boulders of compact rocks, infeasible to extract and grind, remain immersed in the friable material (Fig. 1), which impacts on the daily production of iron ore.

Figure 1 – Compact itabirite blocks immersed in friable material after a blast in a production bench at Abóboras mine.

In order to develop a methodology capable of overcoming the problems caused by weathering in the blasting process, the use of shallow geophysics was proposed, aiming to determine the position of the boulders of compact rock. The application of the electrical resistivity method was carried out in the Abóboras mine area (unit belonging to VALE S.A.), in order to generate a subsurface model that corresponds to the reality of the mine.

Once finished the geophysical model, the final objective of this work was to assist in the location of the blasting drillholes, by increasing the density of drillholes when compact rocks were present and reducing the amount of them when there was friable material, in order to avoid the production of compact itabirite boulders and consequently, to maximize the production of iron ore at the Abóboras mine and reduce operation costs.

LOCATION

The Abóboras mine is located in the western portion of the Quadrilátero Ferrífero, between the municipalities of Rio Acima and Nova Lima, approximately 40 km from the state capital, Belo Horizonte, in Minas Gerais state, Brazil (Fig. 2).

Geological context

The Quadrilátero Ferrífero is located in the south-central region of the state of Minas Gerais, on the southern edge of the São Francisco Craton, as indicated in Figure 3A. Its geology, with rocks of varied ages, is the result of complex and superimposed geological processes, resulting from successive orogenies in the Archean and Proterozoic eons (Uhlein & Noce, 2012). Due to the orogens, the mountain ranges reflect large structures folded into synclines and anticlines (Alkmim & Marshak, 1998). The Abóboras mine is located on the eastern limb of the Moeda Syncline, which extends approximately 40 km in the N-S direction, in the western portion of the Quadrilátero Ferrífero (Fig. 3B).

According to Alkmim & Marshak (1998), the Quadrilátero Ferrífero is composed of four main geological units: Granite-Gnaiss Complex (Metamorphic Complexes), the Rio das Velhas Supergroup (both being Archean units), the Minas Supergroup and the Itacolomi Group (both Paleoproterozoic). A portion of the Espinhaço Supergroup (Paleo until Mesoproterozoic) occurs also in the region.

The Minas Supergroup contains the main lithological units where iron ore is extracted in the region. The ore comes from metamorphic iron formations, composed of itabirites, ferruginous dolomites and phyllites rich in hematite, from the Itabira Group (Rosière & Chemale Jr, 2000). The mining activity at the Abóboras mine occurs on the itabirites of the Cauê Formation, Minas Supergroup.

Due the action of the weathering processes in the region, the itabirite is intensely altered, forming thick soil horizons. In some cases, the consolidated rock is immersed in friable material, constituting a mixture of friable and compact itabirite. The aim of this study was to generate a subsurface geological model, based on electrical resistivity data, in order to differentiate these two lithotypes through their contrasting physical properties.

METHODOLOGY

For the geophysical investigation, the methods of ground penetrating radar (GPR), electrical resistivity and induced polarization were tested. The electrical resistivity method,

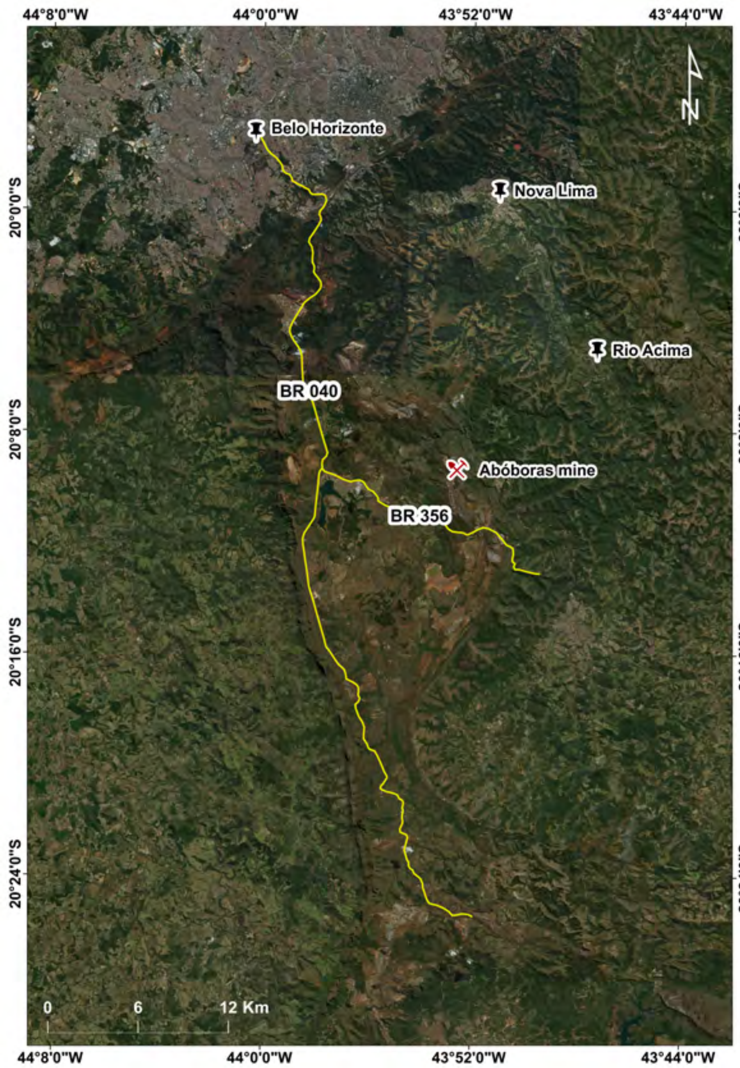

Figure 2 – SPOT satellite image indicating the location of the Abóboras mine, between the municipalities of Rio Acima and Nova Lima, as well as its main accesses: BR-040 and BR-356.

acquired through electrical profile was the one that presented greater contrasts of physical properties in subsurface materials, and, thereby, was selected for this study.

Electrical Resistivity

The electrical resistivity method uses the injection of an artificial electric current introduced into the ground through two current electrodes (named A and B) with the purpose of measuring the potential generated in two potential electrodes (named M and N) in the vicinity of the current flow (Loke et al., 2013), as displayed in Figure 4. This method allows to identify regions in subsurface that present higher or lower resistivity values.

To determine the resistivity, it is necessary to calculate the potential difference (ΔV) between the M and N electrodes mentioned above. For this, the resulting potential of the electric field in the electrodes M and N (V_M and V_N) is calculated using the following Ohm formulas, Eqs. (1) and (2), assuming a homogeneous and isotropic medium:

$$V_M = \frac{I\rho}{2\pi}\left(\frac{1}{AM} - \frac{1}{BM}\right), \qquad (1)$$

and

$$V_N = \frac{I\rho}{2\pi}\left(\frac{1}{AN} - \frac{1}{BN}\right), \qquad (2)$$

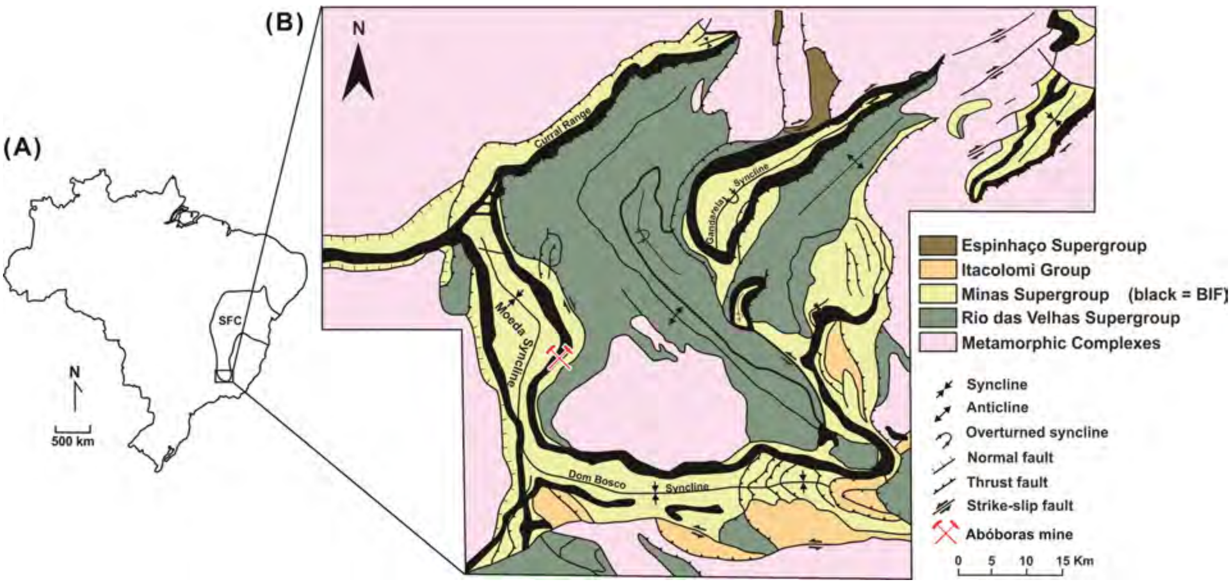

Figure 3 – Simplified geological map of the Quadrilátero Ferrífero (Dorr, 1969), modified by Alkmim & Marshak (1998). (A) The location of the Quadrilátero Ferrífero on the southern edge of the São Francisco Craton (SFC). (B) The location of the Abóboras mine in the Quadrilátero Ferrífero, established on the eastern limb of the Moeda Syncline. The Quadrilátero Ferrífero is composed of four main geological units: Metamorphic Complex in pink, the Rio das Velhas Supergroup in green, the Minas Supergroup in yellow with the BIF in black and the Itacolomi Group in orange. In brown, Espinhaço Supergroup.

where I is the intensity of the electric current introduced underground, ρ the resistivity that the medium offers to the propagation of this current and AM, BM, AN, BN the distance between these electrodes. The potential difference measured in the equipment will be as in Eq. (3):

$$\Delta V_{MN} = V_M - V_N. \tag{3}$$

And, therefore, can be written in the form of Eq. (4):

$$\Delta V_{MN} = \frac{I\rho}{2\pi}\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right). \tag{4}$$

However, the reality in the Abóboras mine corresponds to a heterogeneous environment, composed of compact and friable rocks, resulting in variations of ΔV due to the changes of ρ in the subsurface. Therefore, the measure of ΔV represents a weighted average of all true resistivity values in a volume of subsurface material. Thus, by performing the relevant calculations, it an apparent resistivity, ρ_a is obtained, which can be calculated using the Eq. (5):

$$\rho_a = K\frac{\Delta V}{I}, \tag{5}$$

where K corresponds to the geometric factor, which was defined according to the electrode array used (Koefoed, 1979) and can be written as in Eq. (6).

$$K = 2\pi\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)^{-1}. \tag{6}$$

At the beginning of the data acquisition, a test area was selected for the calibration of the method. The test site was a bench, with known geology, where it was possible to carry out direct observations of compact and friable itabirite (Fig. 7A). In this bank, 14 sections of electrical resistivity were acquired (Fig. 7B). This stage, besides the determination of the best arrays for the electrodes, provided valuable information about the geophysical response of the two lithotypes (compact and friable itabirites) in relation to the electrical resistivity method and validated the capacity of it to help to distinguish such lithologies.

After the acquisition of the resistivity data, they were processed and interpreted in order to generate a geophysical model compatible with the subsurface reality of the mine. After the modeling, there was a drilling campaign in order to validate the model generated.

Planning and data acquisition

For the present study, 40 resistivity profiles (L01 - L40) were acquired, with 2 meter spacing between lines, and 1 meter between the electrodes. In total, 4,345 meters of electrical data were acquired. The location of the acquired profiles (L01 to L40), with NW-SE orientation, can be observed in Figure 5.

In the initial phases of the project, tests were carried out using different electrode arrays at the Abóboras mine in order

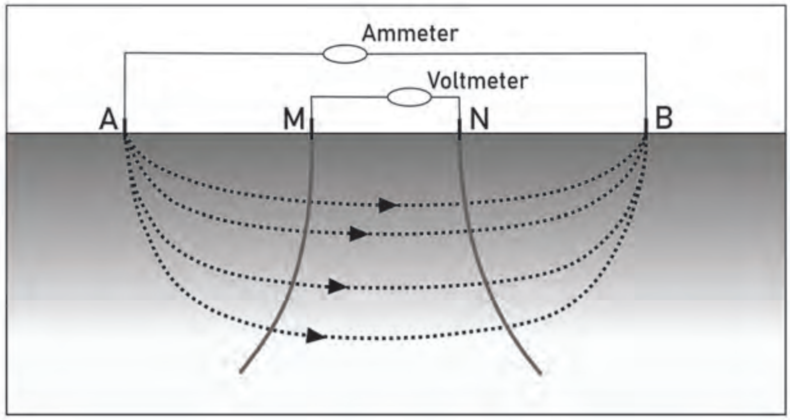

Figure 4 – Schematic drawing, illustrating the operation of the electrical resistivity method, wherein the pair of electrodes AB corresponds to the current circuit and the pair of electrodes MN corresponds to the potential circuit, modified from Braga (2006)

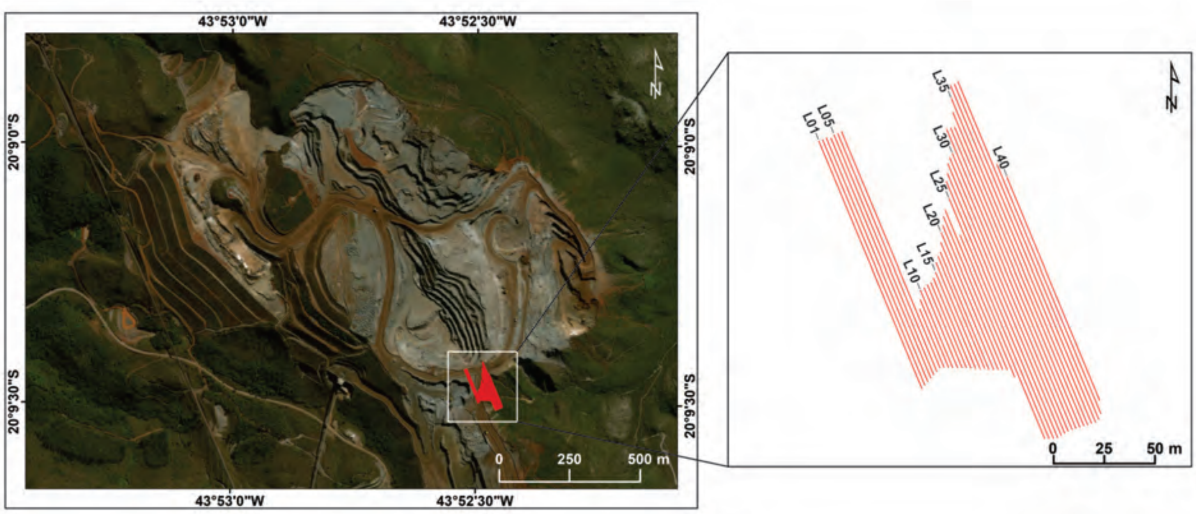

Figure 5 – Location of the resistivity profiles (L01 - L40) acquired at the Abóboras mine.

to find the best methodology for the acquisition of the electrical profiles. The arrangement chosen for the data acquisition was the Dipole-Dipole array, because it presented better signal-to-noise ratio and a satisfactory rate between depth of investigation *versus* lateral resolution. In other words, the study of the lateral variation of the physical parameters could be carried out in several levels of depth, obtaining a characterization of the medium, in subsurface, both horizontally and vertically.

The value of the apparent resistivity (ohm.m) was calculated taking into account the geometric factor (K), which was defined according to the array used (Koefoed, 1979). The equipment used in the geophysical acquisition were two SAS 4000 units of the manufacturer ABEM, with 64-channel configuration, composed of control unit and selector unit (Fig. 6). The software used for data processing was the Res2DInv (GEOTOMO Software, 2003).

RESULTS

The resistivity profiles acquired reached 7 to 15 meters depth and were consistent in the differentiation of high and low resistivity anomalies. Through the test performed prior to the acquisition of the data (Fig.7A), in order to determine the response of the geological environment to the applied geophysical method, it was observed that the compact material had a resistive response to the method as compared to the friable material, which exhibits a

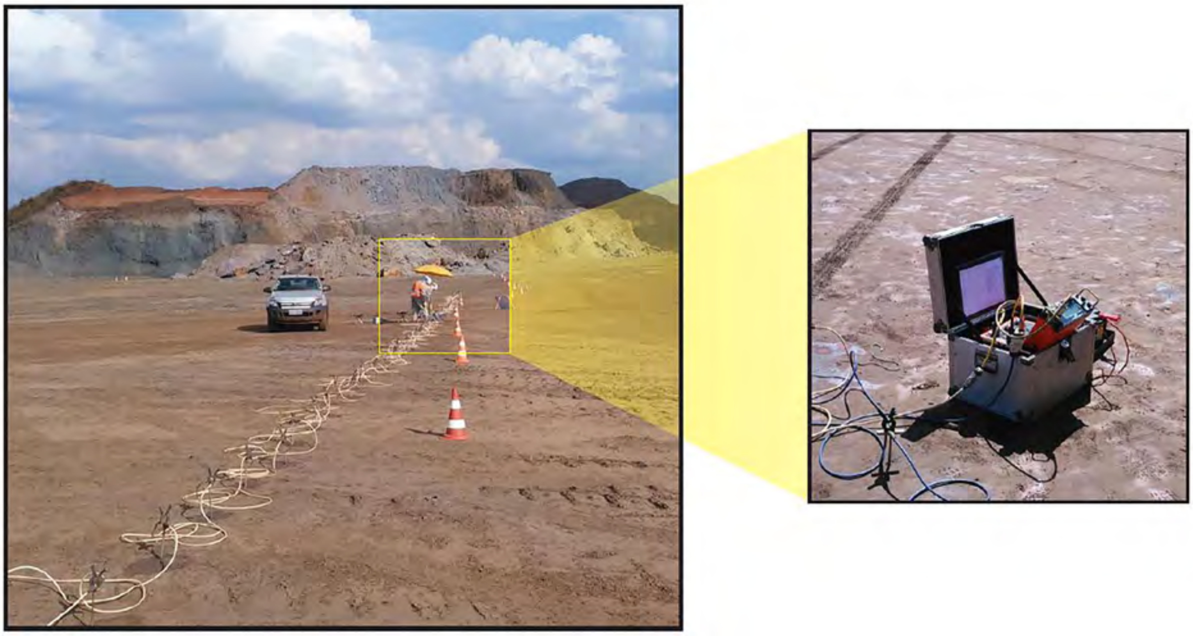

Figure 6 – Acquisition of electrical data at the Abóboras mine. On the right, the equipment used: SAS 4000 from ABEM.

more conductive behavior (Fig.7B). Therefore, at the test bench, it was possible to associate the compact itabirite to zones of high resistivity (ZHR: > 40,900 ohm.m) and friable itabirite to zones of low resistivity (ZLR: < 2,400 ohm.m). The zones of intermediate resistivity (ZIR: 2,400 - 40,900 ohm.m) were also considered as friable itabirite, according to the results of the performed tests. The same range of resistivity values was applied to the resistivity profiles L08 to L40.

With the analysis of these profiles, it was possible to differentiate them into two large groups because of the arrangement and concentration of ZHR and ZLR. The first group (L08 - L17) is characterized by the predominance of ZIR, with the appearance of well-defined high resistivity anomalies, deep below the surface, near the beginning of the sections, as observed in Figure 8.

In the second group of sections (L18 - L40), with exception of the upper part of the profiles, which presents lower values of resistivity, there is a predominance of ZHR, with resistive anomalies that make up all profiles, as observed in Figure 9.

The L01 to L07 profiles, acquired during a rainy period, presented interferences in the obtained resistivity values and, for that reason, they had distinct normalizations in relation to the lines L08 to L40, which were acquired after the rainy season. The ZHRs in this group were defined from values higher than 40,000 ohm.m, while ZLRs were defined as values lower than 2,700 ohm.m. This group of sections presents the upper portion characterized by ZLR and the other regions by ZIR, except for the presence of a strong resistive and persistent anomaly along the intermediate portion of the sections. This anomaly extends from near the surface to the basal regions of the profiles, as can be observed in Figure 10.

DISCUSSION

The electrical resistivity method is capable of detecting contrasts of electrical properties, conditioned by differences in the physical and chemical properties of the material, such as porosity, permeability, presence of interstitial fluids, composition of the rock and concentration of fine grains (Boadu & Owusu-Nimo, 2010; Loke et al., 2013).

The two lithotypes present in the Abóboras mine, compact itabirite and friable itabirite, present differences in these parameters, and the choice of the electrical resistivity method is therefore appropriate.

Among these properties, porosity presents a significant dissimilarity between the two materials in question, which can be directly observed at the mine benches. It would be expected that the compact material presented lower values of resistivity in relation to the friable material, as discussed in Boadu &

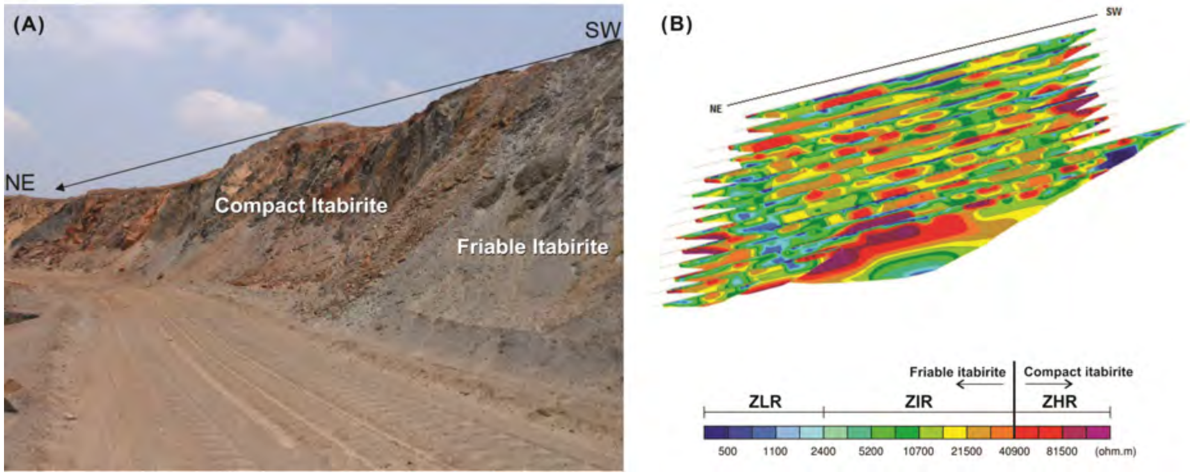

Figure 7 – (A) The test bench at the Abóboras mine where it was possible to observe directly the lithotypes investigated and, therefore, perform the tests to determine their response to the geophysical methods used. (B) Results of the electrical resistivity profiles acquired on the test bench. Warm colors represent high resistivity and cold colors represent low resistivity.

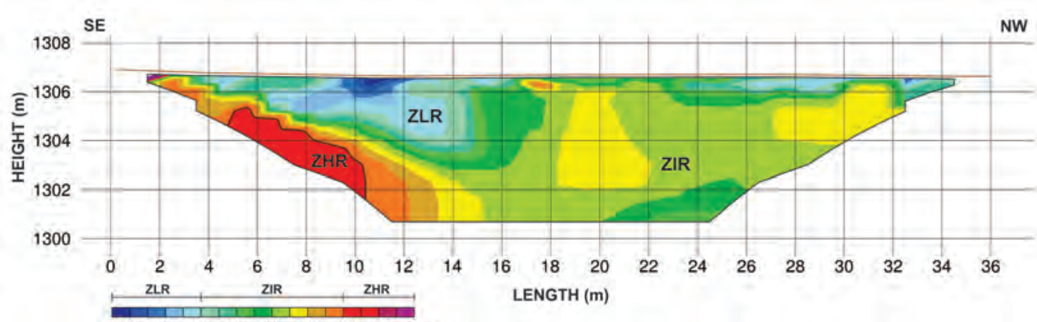

Figure 8 – Line L09, with prominent high resistivity anomalies below the surface, near the beginning of the sections, similar to the lines L08 - L17.

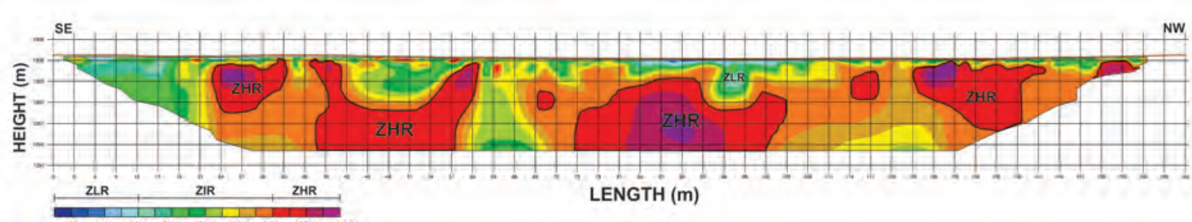

Figure 9 – Line L32, where ZHR predominates, with the exception of the upper part of the profile. This line is similar to the lines L18 - L40.

Owusu-Nimo (2010). However, the presented results showed the opposite, suggesting that the porosity is not the determining physical factor for the electrical results in the case of Abóboras mine. Because the data acquisition was carried out during the rainy season in the state of Minas Gerais, it is plausible to assume that the presence of fluids may have played a decisive role in the geophysical response of the substrate. The friable material, because of its greater porosity and permeability, would absorb a greater amount of fluids from meteoric water, causing an increased presence of interstitial fluids in its matrix. Such a process could explain the resistive signature of the compact rock in relation to the surrounding friable material.

In addition, the absence of lateritic crust in the bench where the data were acquired may have been an accelerator of fluid percolation in the rock mass. As discussed in (Nogueira et al., 2016), lateritic iron has impermeable characteristics. In this way,

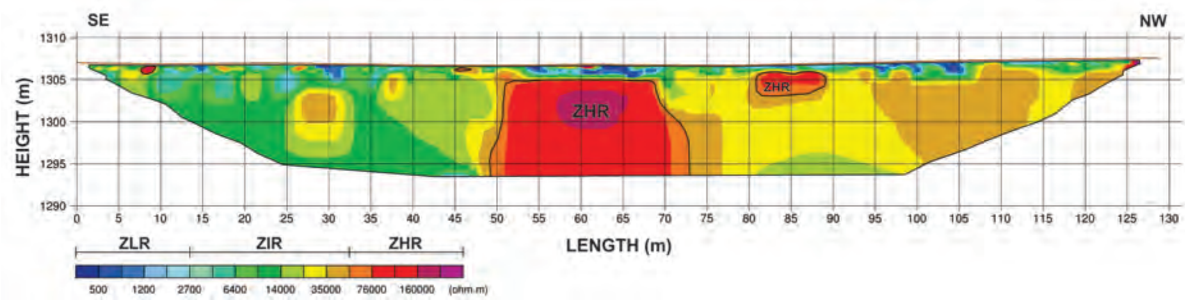

Figure 10 – Line L03, in which ZLR prevails, with the exception of the central portion, where there is a high resistivity anomaly.

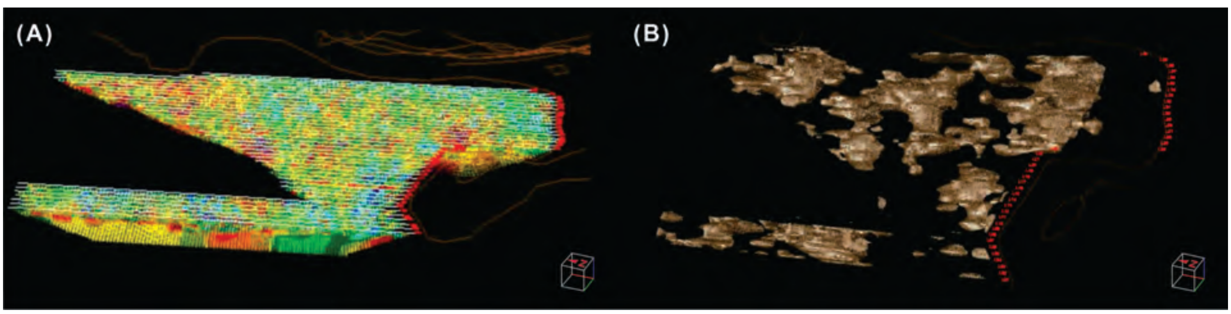

Figure 11 – (A) Juxtaposition of the electrical resistivity sections. (B) Three-dimensional geophysical model, where the location and volume of compact rock bodies are indicated.

its presence would make it difficult the fluid penetration to the substrate. As this material was not present in the bench, due to the advance of the mine, the exposure of the ground facilitated the percolation of meteoric water.

GEOPHYSICAL MODEL

The integration of the resistivity data, with the proper classification of the detected anomalies, allowed to determine the position of the compact and friable itabirite, presenting the volume of the rocky bodies and their georeferenced coordinates. Based on the electrical data 3D interpolation (Fig. 11A), a three-dimensional geophysical model was developed (Fig. 11B) from the electrical profiles, using the *Voxler* 3D software (Golden Software, 2015).

In the *Voxler* 3D, through polynomial calculations, a data grid was created and then a tri-linear interpolation, in order to quantify the values to be allocated in each calculated vector. Based upon those calculations it was possible to obtain the coordinates of each anomalous point and to generate the associated geological model. The interpolator used was the *Inverse Distance to a Power*, which provided the best model considering the characteristics already known of the compact itabirite blocks of the Abóboras mine. This method consists of a weighted average interpolator which can provide both accurate and smoothed estimates. During interpolation, weights are assigned, whose influence on the data decreases with increasing distance of the knot of the array (Davis, 1986).

From the body generated by the interpolated correlation of the electrical profiles (Fig. 11A), it was possible to confirm the cut-off values used to differentiate the compact itabirite from the friable itabirite. Anomalies modeled with resistivity values greater than 40,000 ohm.m, for the sections L01 to L07, and higher than 40,900 ohm.m, for the sections L08 to L40, were associated with compact itabirite and are represented in Figure 11B as brown colored bodies. These bodies, in the final model, have a total volume of 23,218.15 m^3 within an area of approximately 8,900 m^2.

The generated model was validated through ten exploratory drillholes, eight of these displayed in Figure 12. Only one hole obtained an unsatisfactory result in relation to the interpretation of the geophysical model.

The Figure 13B shows the correlation between the electrical data, represented by the electrical line L21, and the lithological types obtained through drillholes. It's possible to observe that where there are zones of high resistivity ($>$ 40,900 ohm.m) at L21, the drillholes indicate compact material. Whereas, where

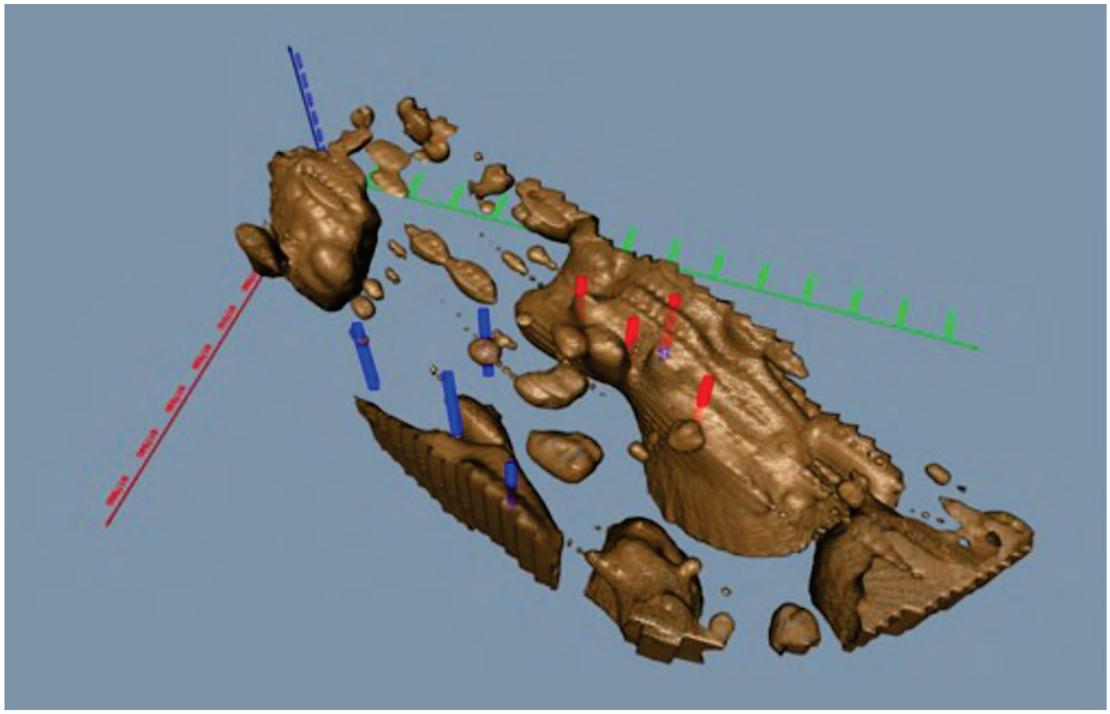

Figure 12 – Geophysical 3D model generated using the geophysical data, indicating the location of exploratory drillholes. The drillholes represented in red have reached the compact itabirite, while the drillholes represented in blue have reached only the friable itabirite.

the resistivity zones are low or intermediate ($<$ 40,900 ohm.m), the drillholes indicate friable itabirite, which corroborates to the veracity of the geophysical model.

The Figure 13A shows the comparison between the geological model of the Abóboras mine, based on drillholes, and the 3D model, based on the electrical resistivity data. It is possible to notice the higher resolution of the 3D model based on the geophysical data in the determination of the blocks of compact itabirite, since in this model, the electric lines have a data acquisition spacing of 2 m, while the drillholes are done in a more spaced network, of 150 m by 150 m. In that way, the higher spatial density of the data acquisition on the electrical sections, confers to the model based on the geophysical data a greater fidelity to the reality in relation to the model based on the drillholes in respect of the determination of the positioning of the compact itabirite blocks.

The Figure 16 shows a significant improvement in the fragmentation of the exploded material, with the absence of boulders at the waste pile generated by the new blasting design. Consequently, there was an increase in ore loading effectiveness by 12%, and there was no need for secondary detonations or discard of blocks in the waste pile.

BLASTING DESIGN BASED ON THE GEOPHYSICAL DATA

Applying the usual blasting design to the substrate of the Abóboras mine, with drillholes distributed homogeneously (3 x 7 m or 4 x 8 m), with a depth of 10 m and powder factor of 150 to 200 g/t, there is production of compact itabirite blocks, impossible to extract and grind, and consequently, causing a decrease in ore production at the mine.

From the generation of the geophysical model, a new blasting design was developed. The new design maintained the original spacing used for friable rock, 4 m x 7 m, but more drillholes were introduced where the geophysical model indicated compact itabirite, as shown in Figure 14. These drillholes were charged with higher density explosive having a powder factor of 320 g/t. At these points the blasting array was modified, and consequently, the timing sequence of the blasting had to be adjusted.

Five blasting tests were performed in the area where the geophysical data were acquired. Two tests were performed only by changing the blasting array, reducing the network spacing; two other tests were based on the geophysical model; and only one followed the mine's usual blasting design. The granulometric analysis of the fragments generated in these tests is presented in

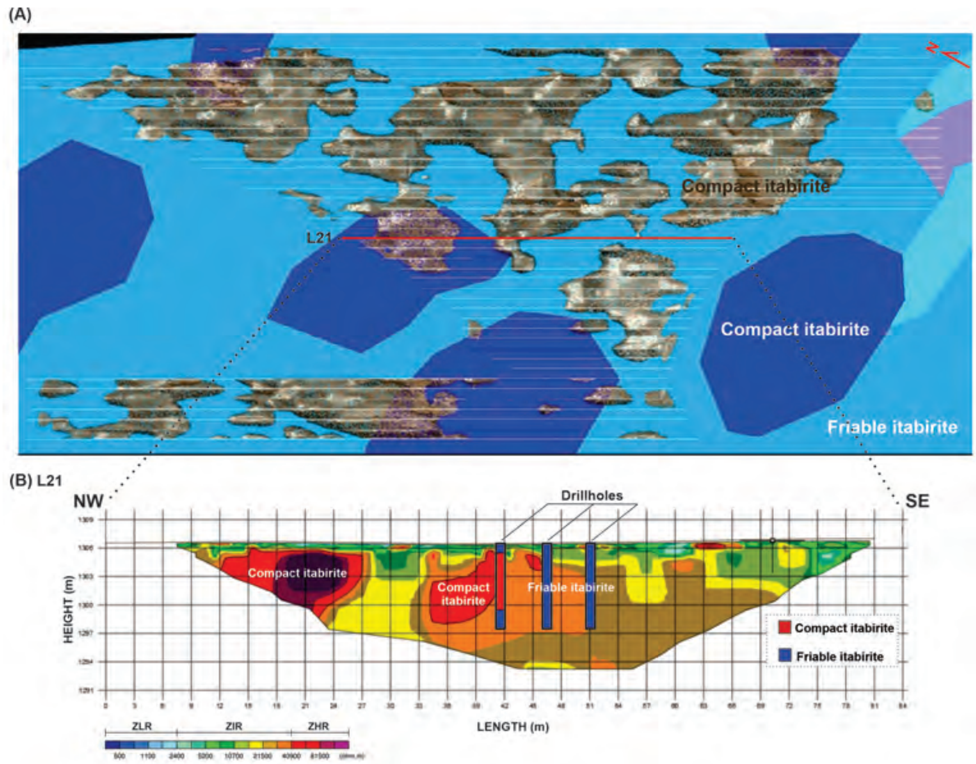

Figure 13 – (A) Comparison between the two models from the Abóboras mine. The geological model, based on drillholes, is represented by shades of blue, where the compact itabirite corresponds to the darker blue and the friable itabirite is equivalent to the lighter blue. The geophysical model, based on the electrical resistivity data, represents the blocks of compact itabirite in brown. (B) Comparison between the results obtained by the electrical resistivity method (L21) and the lithological types obtained through drillholes. The overlap of both data indicates that there is a correlation between the ZHR (> 40,900 ohm.m) with the compact itabirite. While zones with resistivity < 40,900 ohm.m can be correlated with the friable material.

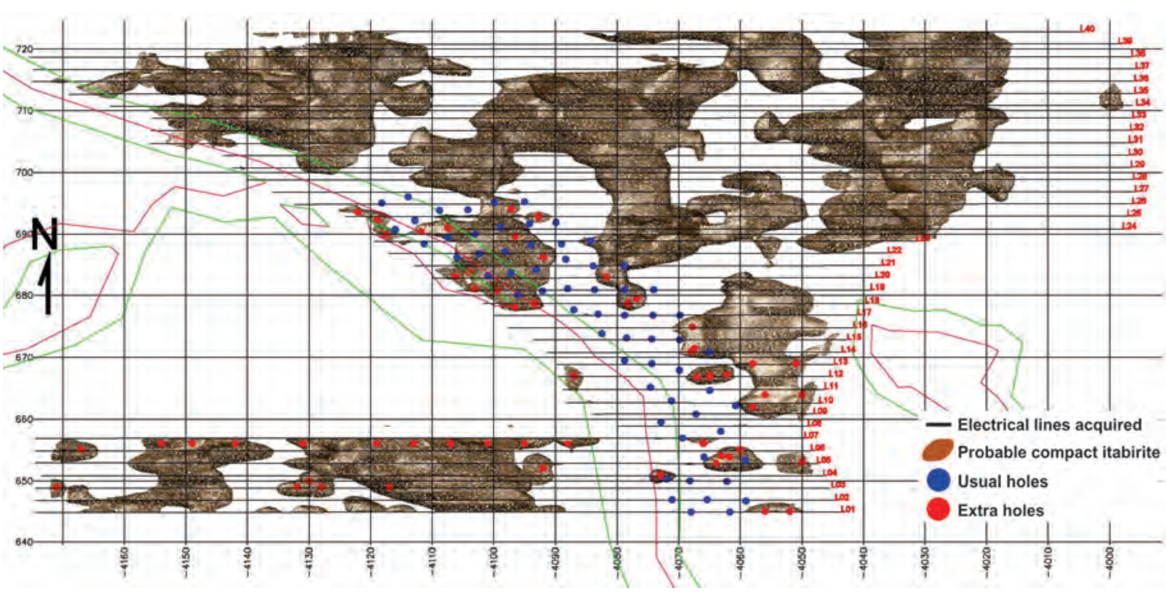

Figure 14 – 3D model at the Abóboras mine, in which the blue dots correspond to the regular blasting array and the red dots correspond to the extra drillholes, allocated according to the location of the compact itabirite blocks given by the geophysical model.

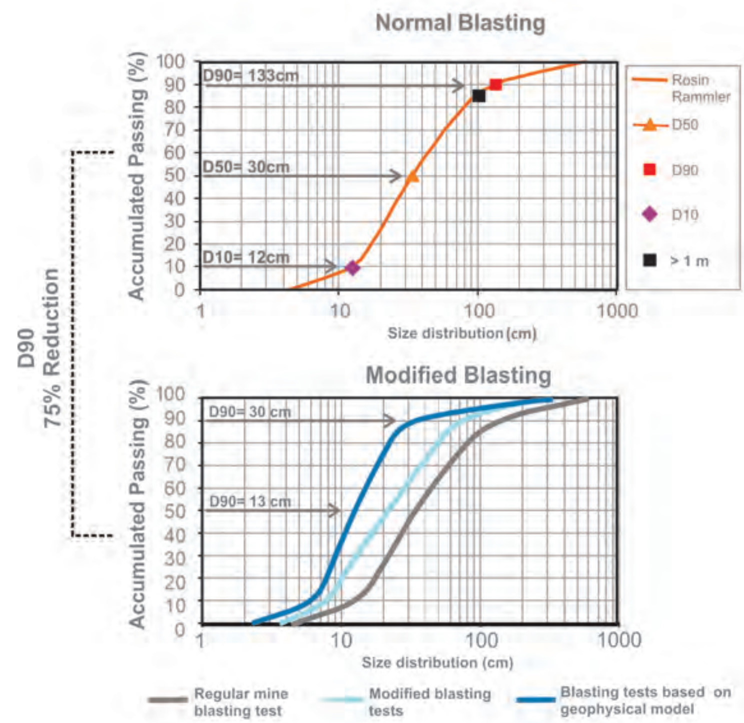

Figure 15 – Granulometric curves generated from the analysis of the fragments produced by the blasting tests. In the first graph, the orange curve represents the particle size distribution of the fragments generated by the usual blasting model. The second graph shows the comparison between the granulometric curves of the three blasting designs that were tested. In it, the gray curve represents the fragments generated by using the homogeneous blasting design, whereas the blue curves represent the fragments produced from modifications in the blasting array, showing the 75% reduction on the quantity of fragments larger than 1.33 m achieved by using the geophysical model.

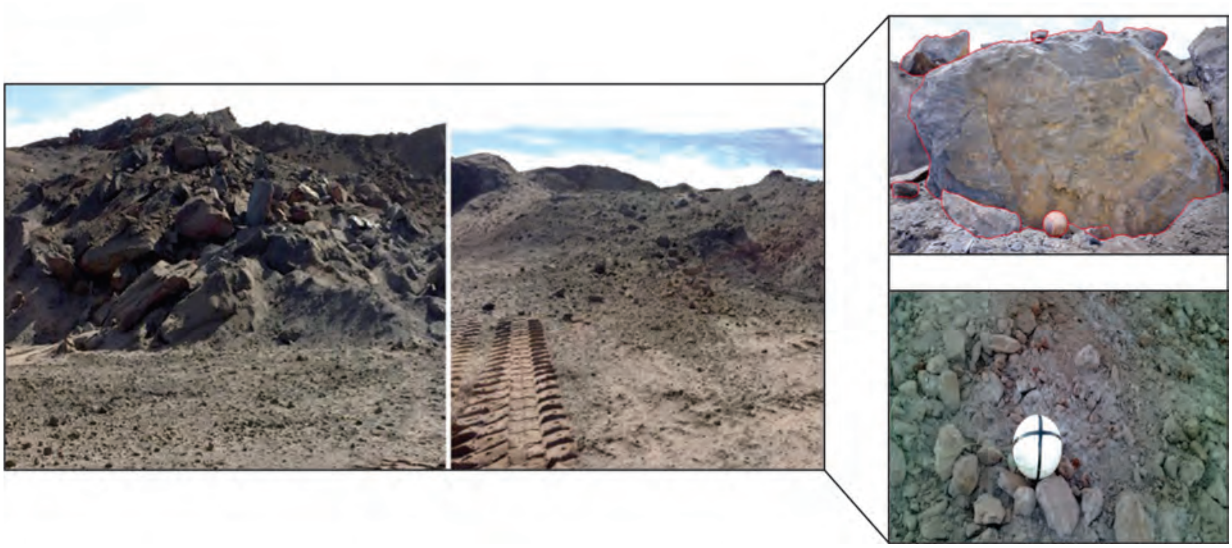

Figure 16 – Photographs illustrating the improvement in the fragmentation of the material produced by the fragmentation at the Abóboras mine.

Figure 15. Using the usual detonation design, approximately 10% of the total fragments generated by the blast were larger than 1.33 m in size. With the modifications made, the first two tests obtained a proportional reduction of 46% in the amount of fragments with size over 1 m, while for the two tests based on the geophysical studies, the reduction was 75%.

CONCLUSION

It could be verified that through the interpretation of the resistivity profiles it was possible to differentiate at least two types of material. The material with more resistive values was associated with compact itabirite, and the other material, less resistive, was associated with friable itabirite.

With the integration of the resistivity data it was possible to generate a geophysical model for the Abóboras mine, which allowed to determine the position of the geological features of interest and to present the volume of the compact blocks and their georeferenced coordinates.

The modeling corroborated the binary lithological differentiation of the mine, suggesting compact itabirite blocks immersed in friable itabirite. Subsequently, there was a validation of the model through drillholes, proving that the geophysical interpretations were compatible with the reality of the mine.

The objective of this work was reached when the blasting design was modified using as base the generated geophysical model. With the highest concentration of blast drillholes where the model indicated the presence of compact rock, it was observed a 75% decrease in the number of the boulders as compared the usual blasting model. As a consequence, there was a significant increase in ore fragmentation effectiveness, besides, there was no need for secondary detonation or disposal of blocks in the waste pile, thus saving on operating costs and optimizing the production of iron ore at the Abóboras mine.

ACKNOWLEDGEMENTS

The authors would like to thank VALE S.A. for permission to publish this research.

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Recebido em 8 maio, 2018 / Aceito em 4 outubro, 2018

Received on May 8, 2018 / Accepted on October 4, 2018