Integration of refraction and resistivity to study an iron ore deposit, Serra Norte, Carajás – PA

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Abstract

This work comprises the acquisition, processing and interpretation of 2D shallow seismic refraction (P-wave) and resistivity profile located in the iron ore deposit of N4WS, Carajás Mineral Province, Brazil. The geophysical methods were used to identify the limits of the iron ore deposit, and thus evaluate the potentiality of these geophysical methods in that geological context. The geophysical results were compared with boreholes. Despite some regions do not show good correlation, the overall comparison between the geophysical results and the borehole profiles was satisfactory, and this information can be used to generate a preliminary geological model and also to indicate most favorable locations for boreholes.

Introduction

The Carajás Mineral Province (CMP) hosts one of the most important deposits of iron ore in the world, and is being explored since 1985. The annual production of iron ore is about 110 million tons, and the percentage by weight of iron oxide is on average 69 % (ASSIS, 2013).

The study of iron deposits in Carajás is mostly done by boreholes, and regionally using airborne geophysics (ASSIS, 2013). Airborne geophysics plays an important role in this context, mostly due to the existence of a thick lateritic layer that prevents direct geological analysis. However, these methods do not have sufficient resolution to define local depth variations, and the use of boreholes is needed for a more detailed characterization of the ore body. This approach is very common for the characterization of mineral deposits in Brazil.

In order to obtain detailed information of a deposit, a dense grid of boreholes is needed (e. g. 100m apart in N4WS). Generally, this practice increases significantly the costs in the research phase, and requires considerable time, especially in areas of difficult access. As an alternative to the exclusive use of boreholes, geophysical methods have been used worldwide since the 1970s (GREEN, 1974). Among the main advantages of geophysical methods, is the fact that these are not invasive, and also its low cost when compared with direct surveys. However, among the disadvantages there is the ambiguity of the results, which can be resolved by integrating different geophysical methods, or, using direct information.

In this work we use the shallow seismic refraction (P-wave) and resistivity to identify the interface between the iron ore and other lithologies in a line located in the iron ore body of N4WS, Serra Norte, PMC (Figure 1). The objective was to create a geophysical model integrating the results of these two methods, and compare them with the available borehole information in order to evaluate the potential of these methods in that geological context.

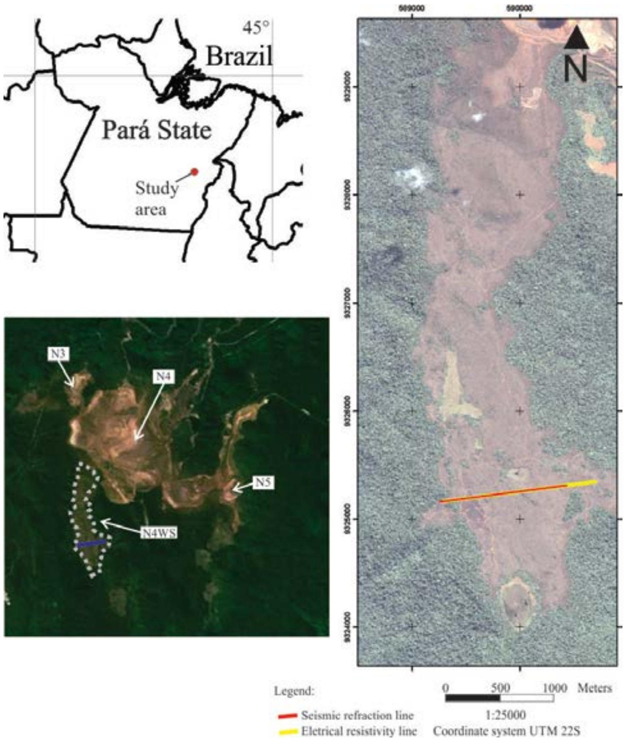


Figure 1 – Right: Location of study area within Brazil, in Pará State and the iron ore body of N4WS alongside the bodies of N3, N4 and N5, in the Serra Norte region. Right: Geophysical lines of seismic refraction (red) and electrical resistivity (yellow), in the body of N4WS.

Geology of the study area

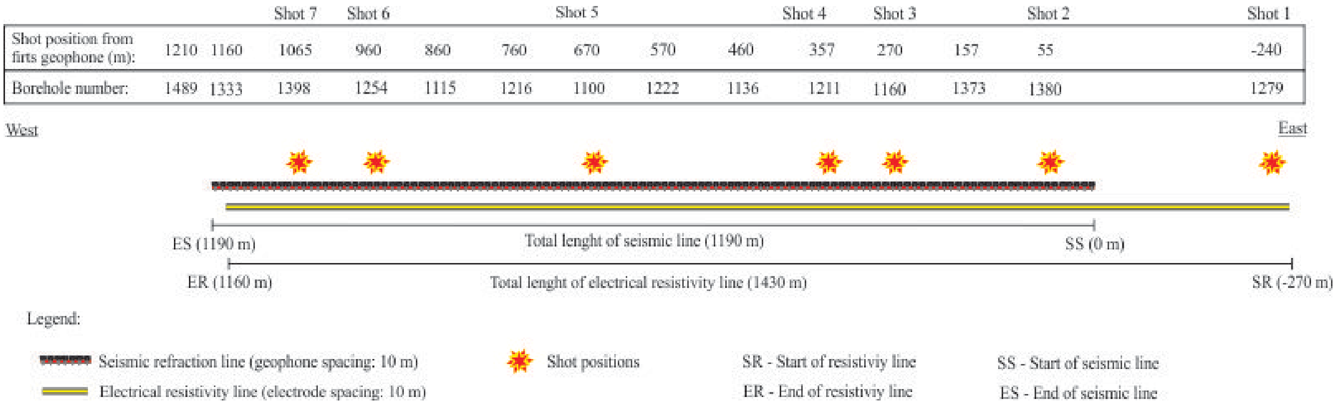
Along the acquired geophysical profiles, there are 14 geologic boreholes made by Vale SA during research stage of the body. The boreholes have different depths varying between 100 and 550 m. The lithologies present in the study area include mafic rock (MS), jaspilite (JP), two different horizons of altered mafic rocks (MSD for less altered rock and MD for more altered rock), the iron ore layer of weathered hematite (HF) and two layers of laterite, a chemical laterite (CQ), and lateritic hematite (CM).

The mafic rocks (MS) are basalts that represent the basement unit, and are the rocks found at greater depths. The altered mafic rocks form a saprolite layer with two different degrees of alteration, the more preserved rocks (MSD), and the more altered horizon (MD). The jaspilite (JP) are rocks of chemical sedimentation that represents the protore of the iron ore deposits. The weathered hematite (HF) represents the iron ore. The uppermost layer is formed by two types of laterite, chemical laterite (QC), associated with the decomposition of mafic rocks, and a lateritic hematite (CM), formed by the exposure of the weathered hematite (ASSIS, 2013). More details about the geology of the study area can be found in Macambira (2003).

Methodology

The acquisition of both geophysical methods, where obtained in coincident lines from east to west (Figure 2). For the seismic refraction were utilized five 24 channels seismographs (Geode, Geometrics), totalizing 120 channels spaced 10 meters apart. The line had 1190 meters. Seven explosive shots were used as seismic source. Due to difficulties related to logistics and security, the shafts of the geological boreholes were used to detonate the explosives. Thus, the shot positions were uneven spaced, with fixed positions: -230, 55, 357, 670, 960 and 1065, in meters, related to the first geofone. The data were processed and modeled with the program SEISIMAGER 2D (OYO Corporation).

The resistivity line was acquired with the multi-electrode resistivity SYSCAL PRO 72 (Iris Instruments), using 72 steel electrodes spaced 10 meters. The acquisition was performed using three sections in the roll-on scheme. The total profile had 1430 meters, and the selected electrode array was the pole-pole, due to the higher investigation depths that it provides. The acquisition protocol enabled the imaging of 32 levels, with 4031 points of investigation, reaching a depth about 300 meters. The data were processed with the software RES2DINV (GEOTOMO, 2010).



			Shot 7	Shot 6			Shot 5			Shot 4	Shot 3		Shot 2	Shot 1
Shot position from firts geophone (m):	1210	1160	1065	960	860	760	670	570	460	357	270	157	55	-240
Borehole number:	1489	1333	1398	1254	1115	1216	1100	1222	1136	1211	1160	1373	1380	1279

Figure 2 – Geophysical acquisition scheme. The seismic line (red) used 120 channels spaced 10 meters, forming a line of 1190 meters and used 7 shot points. The resistivity line (yellow) had a length of 1430 meters with electrode spaced 10 meters. The reference position is the beginning of the seismic line (SS).

Results

A two layer model was generated as result of the seismic refraction (Figure 3). For the first layer, the mean velocity found was 1858 m/s. For the second layer, the mean velocity was 5413 m/s. The calculated thickness for the first layer varies from 75 to 200 meters. The RMS adjust error during the modelling was 10,58%. Due to uneven spacing and distribution of the shot positions, and poor explosive location (inside the boreholes), the most constrained region of the model is the center-east location (from 0 to 900 m).

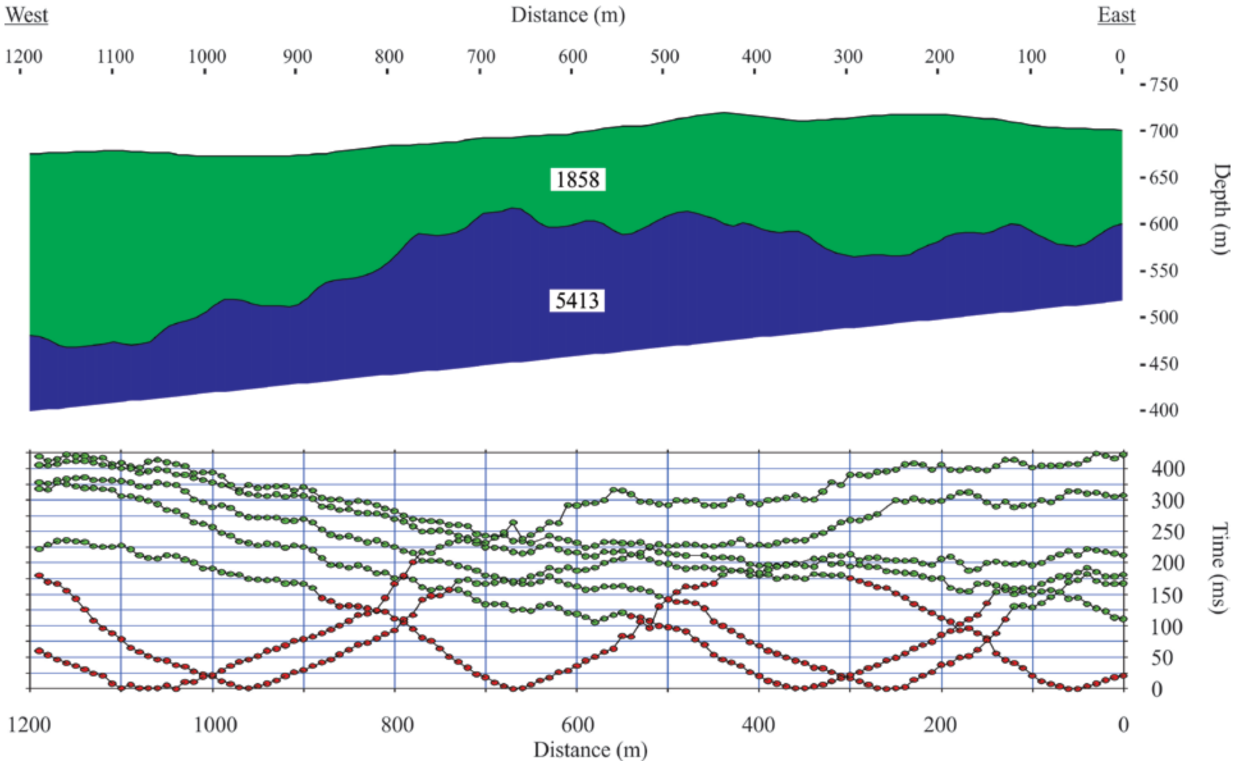
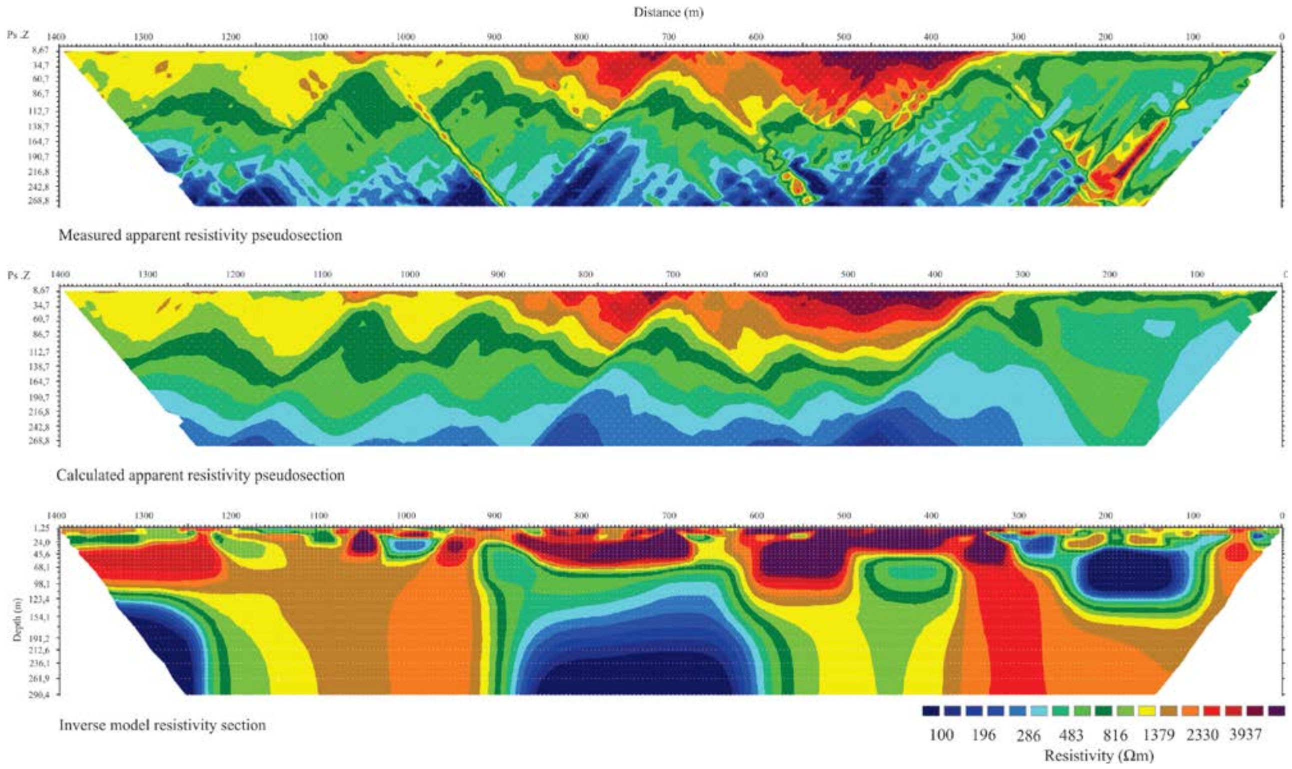


Figure 3 – Seismic refraction result with two layer model (Above). Time-term curves of the two layer model (Below). The mean velocity of the first layer was 1858 m/s, and the second layer was 5413 m/s.

The resistivity section (Figure 4) were obtained with four iterations, with a RMS adjust error of 20.1%. The maximum depth observed in the pseudo-section was 268.8 meters. For the apparent resistivity section, obtained from the pseudo-sections, the depth was 290.4 meters. The first 100 meters of the profile is composed of areas with high and low resistivity values. In the central portion, we observed a large continuous area with the highest resistivity found (>3937 ohm.m). In these depths, this zone contrasts with adjacent areas, characterized by smaller size anomalies with alternating high and low resistivity.

Below 100 meters of depth, larger regions of low and high resistivity occur. The regions of low resistivity observed in these depths are the largest and most intense of the entire profile (<286 ohm m). The intermixed regions of higher resistivity have values between 380 and 3000 ohm.m.



Measured apparent resistivity pseudosection

Calculated apparent resistivity pseudosection

Inverse model resistivity section

Figure 4 – Measured and calculated apparent resistivity pseudo sections (Above and center), and the inversion result (below).

Discussion and Conclusions

We compared the geophysical models with the geological boreholes, and proposed an interpretation model (Figure 5). In the Figure 5a, the interface found with seismic refraction is represented by the dark dashed line, and the layers velocities are highlighted. In the interpretative model (Figure 5b), the main vertical interface was drawn using mainly the seismic interface.

Lima et al., (2013) conducted a petrophysical study in some lithologies presented in another iron ore deposit, also in the CMP. Their results indicated P-wave velocities between 2818 and 2965 m/s for altered rock and about 6000 m/s for regions of preserved rocks. Although the velocities in the seismic model are lower than the petrophysical velocities, the two results are correlated. The differences are due to the fact that the seismic refraction calculates average velocities for each layer, and the presence of cavities and rock alteration can reduce the seismic velocity. Thus, based on the work of Lima et al., (2013), we can relate the first seismic layer with the lithologies CM (lateritic hematite), HF (weathered hematite), MD and MSD (saprolites of mafic rocks) and CQ (chemical laterite), associated with the more altered rocks. Also, the second layer can be related to the lithologies JP (jaspilite) and MS (mafic rocks), which represents the preserved rocks.

The seismic method did not identify the exact location of the interfaces presented in the boreholes. This probably occurs because the seismic refraction method is not sensitive to regions of high geological complexity, especially with lateral variations (Green, 1974, Burger et al., 2006). And also, the geological boreholes were defined based on geochemical analysis, which may not reflect physical changes in rock, such as in a transitional region.

The upper layer of the resistivity model (first 25m) was divided into two regions with respect to the resistivity range. In the center of the profile, high resistivity values (>2330 ohm m) are correlated with lateritic hematite (CM lithology). Laterally in the profile, intermediate to low resistivity values (<800 ohm.m) are correlated with chemical laterite (CQ lithology).

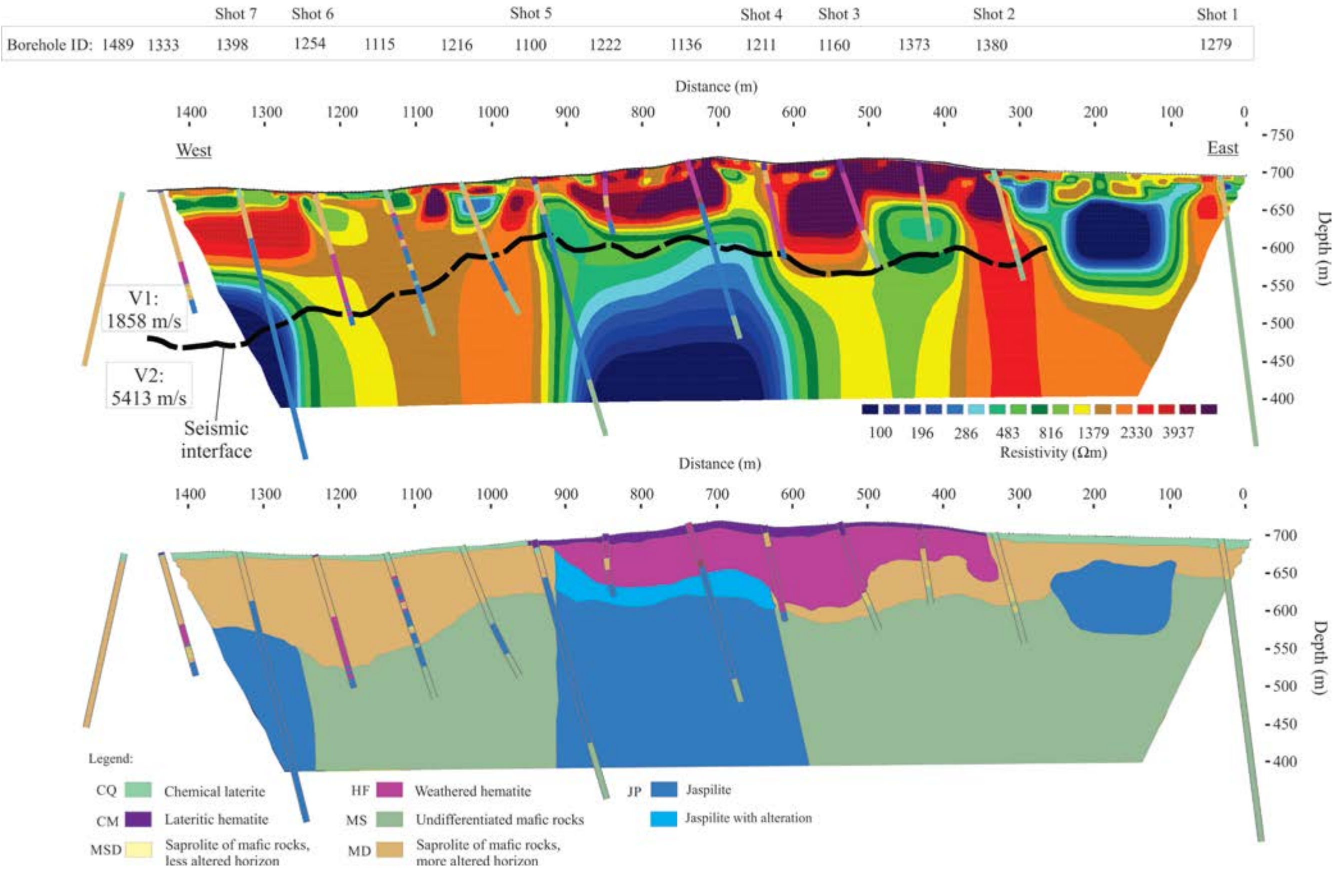


Figure 5 – a) Comparison of seismic (dashed dark interface) and resistivity results, with the geological boreholes. The positions of the seismic shots are also displayed. b) Interpretive model integrating the geophysical results of seismic refraction and resistivity.

Between depths of 25 and 100m, a region with high vertical resistivity contrast occurs, wherein the resistivity value ranges from 100 to >3937 ohm.m. The central part with resistivity values >3937 ohm.m, is associated with iron ore (HF). The eastern and western regions of this zone show resistivity values ranging between 100 and 2330 ohm.m. In the eastern portion, the anomaly of low resistivity (100 ohm.m), suggests the presence of jaspilite. This anomaly coincides with one of the faults mapped in the area, however, we do not believe that the presence of the fault would cause such unique signature low resistivity. Besides, there are no boreholes in this area to confirm this hypothesis.

In the western portion, resistivity values between 816-2330 ohm.m are correlated with decomposed and semi-decomposed mafic rocks (lithologies MD and MSD, respectively).

About the regions related with jaspilite (resistivity <483 ohm.m), these regions show decrease values of resistivity with increasing depth. So that, the rock becomes more conductive as is more cohesive. This behavior is expected to jaspilite, as described in Owen et al., (2005).

There is correlation between the intervals of higher resistivity and the occurrence of iron ore. However, the occurrence of HF in the borehole 1254 was not identified. Probably, this region is a restricted occurrence of HF, which is confirmed by adjacent surveys (1398 and 1115).

The high resistivity values for iron ore in the region can be explained by the increased porosity originated from leaching of silica, which is part of the process of enrichment of iron ore (MACAMBIRA, 2003). These pores could be filled with air and have low interconnectivity, which would cause the resistive signature. Furthermore, the upper layer of lateritic hematite may be acting as a sealant, preventing the entry of water, which would decrease the resistivity.

Comparing the geophysical models and the boreholes, we observe that more altered rocks are also more resistive and are associated with the first seismic layer (with lower velocity) where more altered lithologies (CQ, CM, HF, MD and MSD) are present. The second seismic layer (higher velocity) is associated with less resistive zones, dominated by the more preserved lithologies (JP and MS).

The sinuous pattern found at the interface between the iron ore and jaspilite suggests correlation with the model of supergenic enrichment model, proposed for iron rocks of the Carajás region (MACAMBIRA, 2003). However, more studies are needed in the region to assert this correlation.

Acknowledgments

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