UltraGround Penetrating Radar (UltraGPR) Inputs for Bauxite Geological Modelling with Accuracy Improvements

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Abstract

The Ultra-ground penetrating radar (UltraGPR) is a geophysical surveying technique based on transmitting pulsed electromagnetic (EM) energy into the subsurface and measuring the strength of the reflected energy. The reflected energy depends of petrophysical characteristics of each rock type with different porosity, permeability, humidity and crystallinity degree. For geological applications, in particular Amazonian lateritic bauxite deposits, the challenges were always the depth of penetration as well as the ability to discern bauxite from clays at significant depths, where traditional GPR would not penetrate. Therefore, this study aimed to evaluate the efficiency of UltraGPR methodology to determine lateritic horizon and the ore zone thickness and geometry, since these are probably the most challenge aspects to well understand in bauxite deposits and also considering the more recent technology innovations and developments. The study area is located at Paragominas Bauxite Province (PBP), northeastern of Pará State (Brazil). The UltraGPR data were processed from specific algorithms in a similar scheme to what has been applied to others lateritic deposits worldwide using custom low-pass frequency filters to subdue unwanted interference caused by the conductive clay overburden and thereby enhance the underlying bauxite layers. The data were interpreted and crosschecked with boreholes and then were incorporated in the 3D geological modelling workflow in Leapfrog Geo® environment. The results showed nearly perfect correlation with boreholes and a clearer geometry definition among lithological contacts, confirming that UltraGPR is a suitable method for bauxite exploration since it leads to improvements on geological models' accuracy. During mineral exploration in regional targets, the UltraGPR survey can be used to obtain a preliminary information regarding ore thickness and its potential, supporting the drilling plan and a more assertive and agile decision making. Similarly, mine planning and operation may benefit from better control and precision of geometry in the short-term models.

Keywords: Geological modelling, Paragominas Bauxite Province, UltraGPR, Geophysics.

1. Introduction

Ground Penetrating Radar (GPR) has a long history with the first commercial equipment release during the 1960's. Early works were done with standard military radar systems and radio echo sounders to map the thickness of ice sheets in the Arctic and Antarctic, pioneering research conducted by the British Antarctic Survey [1]. In the 1970's, work with GPR in non-polar environments began focus on civil engineering and mineral explorations for coal beds purposes [2] and as the strengths and limitations of the technique became more apparent, the possible applications dramatically broadened together with the technology advances involving the advent of the high-speed laptop computer and the ability to capture, digitize, and store large volumes of radar data in the early 1990's.

Today, modern GPR systems have fast data processors and data transfer circuitry, and are easily mounted within small boats, aboard sleds, or within backpacks. Typical commercial applications of GPR include engineering and environmental site evaluations, fracture mapping, stratigraphic mapping, void detection, forensic studies, glaciology and permafrost engineering, archaeological studies as well as mineral exploration [3, 4].

The operational concept of GPR is very simple. At a total weight of less than 4 kg, UltraGPR is highly transportable and easy to deploy in the most challenging terrain and environments. The entire GPR is designed to be enclosed within two small cylinders, a generator and receiver connected by a hose. No control unit, laptop and no fiber optics are used, it has been replaced by wireless protocols, including Bluetooth and Wi-Fi which transmitter the data to a palmtop (Figure 1a).

The UltraGPR is a geophysical surveying technique based on transmitting pulsed electromagnetic (EM) energy, usually 10 MHz – 1 GHz range, which radiates ultra-wideband radio waves into the subsurface. The radar receiver measures and digitizes the subtle voltage fluctuations in the antenna, storing the values for later processing on computer (Figure 1b). The reflected energy depends mainly on differences in electrical conductivity and permittivity that are a function of the water content, soil moisture and others petrophysical characteristics of each rock type such porosity, permeability and crystallinity degree. Due to physics of EM wave propagation in dielectrics environments (subsurface) the radar energy penetration is optimized in highly electrically resistive soils and rocks such sands and gavels in dry conditions and limited in saturated clays [5, 6].

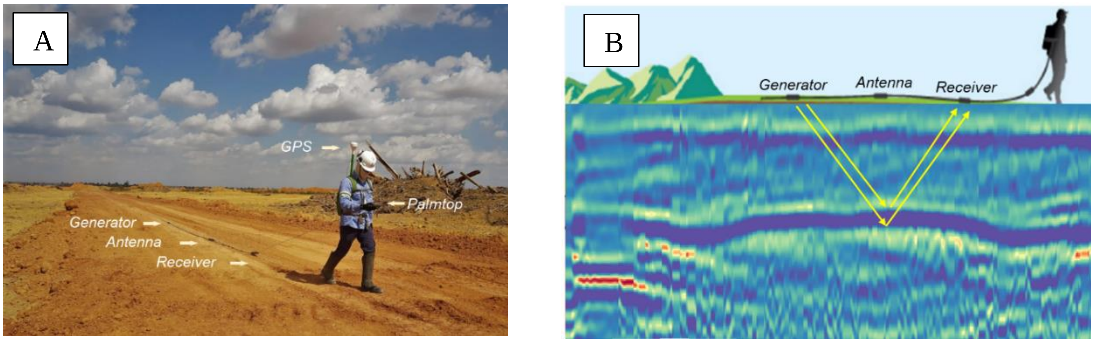

Figure 1. UltraGPR's components (a) and operational concepts (b).

In general, clays are highly absorptive of radar energy, and standard GPR instrument signals cannot penetrate through more than 50 cm of clay. However, GPR has proven effective at imaging partially weathered rocks and the underlying parent bedrock to depths of over 30 m [7], a challenge for mineral exploration purposes in laterite regions that generally contain a high clay fraction. UltraGPR has been designed to be able to penetrate though up to 20 m of overburden clay by using real-time sampling receivers coupled with a ultra-wide band antenna system whereby data in the range of 10 MHz – 20 MHz can be used to map bauxite horizons through thick clay [3].

For geological applications, in particular Amazonian lateritic bauxite deposits, the challenges were always the depth of penetration as well as the ability to discern bauxite from clays at significant depths, where traditional GPR would not penetrate. Therefore, this study aimed to evaluate the efficiency of UltraGPR methodology to determine lateritic horizon and the ore zone thickness and geometry, since these are probably the most challenge aspects to well understand in bauxite deposits and also considering the more recent technology innovations and developments.

2. Methodology

2.1 Study Area

The study area is located at Paragominas Bauxite Province (PBP) central domain, northeast of the state of Pará, in the Eastern Amazon, Brazil. The PBP represents one of the most important, extensive, and dense groupings of bauxite deposits in Brazil, with a potential of more than 3 billion tons of metallurgical ore, about 70% of Brazilian bauxite reserves [8]. The PBP is characterized by a relief of plateaus covered by a thick layer of clays (Belterra clay) and ferroaluminous crusts. The formation of these deposits was originated by the lateritic alteration of siliciclastic deposits from the Cretaceous, in this case, sediments from the Itapecuru and the Ipixuna Formation, during the Paleogene [8] (Figure 2).

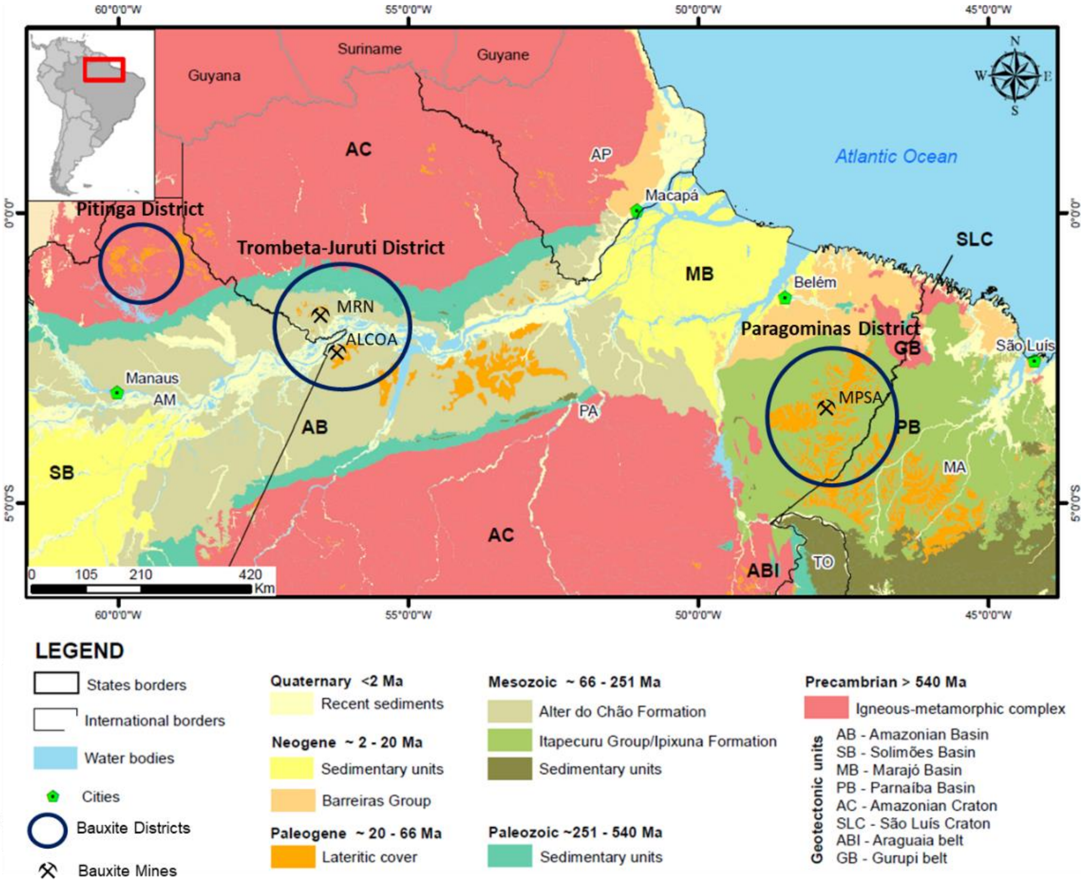

Figure 2. Simplified geological map of northern Brazil with the distribution of the main lithostratigraphic units and identification of the main bauxite districts.

The Paragominas Province central domain is constituted by many bauxite deposits including Miltonia 5 (M5) and Miltonia 3 (M3) plateaus, where the Hydro Paragominas has a mining operation since 2012. The Hydro Paragominas mine is located in the municipality of Paragominas, in the northeast of the state of Pará, 356 km from its capital, Belém do Pará and 70 km from Paragominas city center.

The lateritic profile generally comprises five main lithotypes characterized by clear textural, compositional, and color differences and well-defined contacts. A brief description of these units is provided below (from bottom to top): A) The first lithotype from base to top of lateritic profile is the bottom clay (ARV), which has a gradual transition from the fine-grained kaolinitic sandstone bedrock of Itapecuru/Ipixuna formations. This layer includes typical saprolitic and mottled zone ending in the main bauxite zone; B) Lower Bauxite horizon is formed of a massive bauxite layer of reddish color with abundant, millimeter-sized gibbsite crystals and iron oxides, it is subdivided in Crystallized Bauxite with "Amorphous" Bauxite (BCBA) and Crystallized Bauxite (BC); D) Ferruginous Laterite (LF) is composed of goethite and hematite pisolites in a massive texture; E) Nodular Bauxite (BN), being composed of heterogeneous gibbsite nodules, formed by amorphous bauxite immersed in a kaolinitic matrix; F) Belterra clay (CAP) , discordant and occurs with frequent ferruginous pisolites found among gibbsite nodules. This geological formation covers the lateritic profile and has 5 to 20 meters of thickness, being constituted by a homogeneous sequence of kaolinitic clays.

2.2 Data Acquisition and Processing

Approximately 32.6 linear km of data were acquired, spanning 64 individual profiles divided into two plateau areas (Miltônia 5 (M5), a mineral exploration target and Miltonia 3 (M3), where the mining operations of Hydro Paragominas are concentrated (Figure 3). The two surveyed area cover approximately 136 hectares.

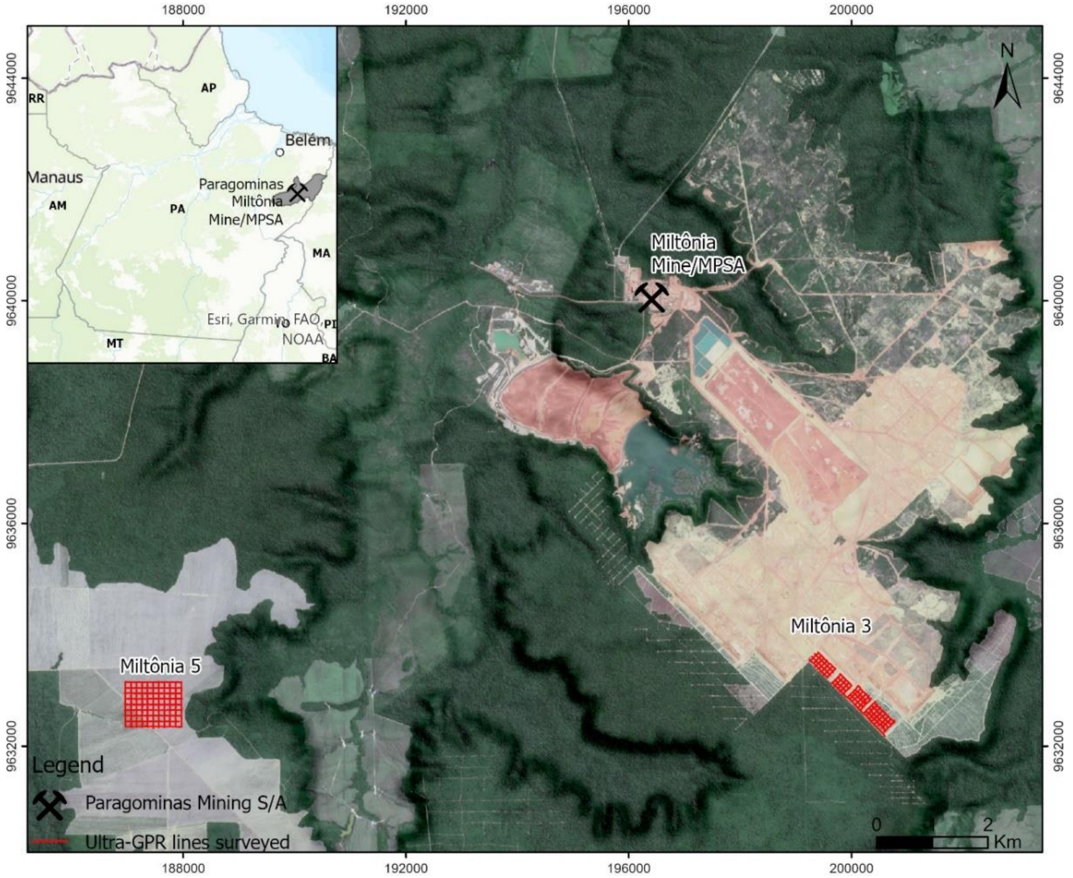

Figure 3. Map showing the location of the UltraGPR survey profiles.

The data were collected through terrestrial walks and along lines with SE-NW orientation, parallel to the mining advance limits, and SW-NE, orthogonal to them. The lines have an interval of 70.71m, with geometry adhering to the preferential drilling grids of 200 x 200m, with drillholes in a central position. The amounts of survey areas and lines are shown in Figure 4, 56 hectares and 14,33 km in M3 (Figure 4a), 80 hectares and 18,26 km in M5 (Figure 4b).

In anticipation of the need for penetration power through the likely electrically conductive overburden, a low-frequency UltraGPR (20 MHz) was used for the task of penetrating through 15 m of overburden in the study area.

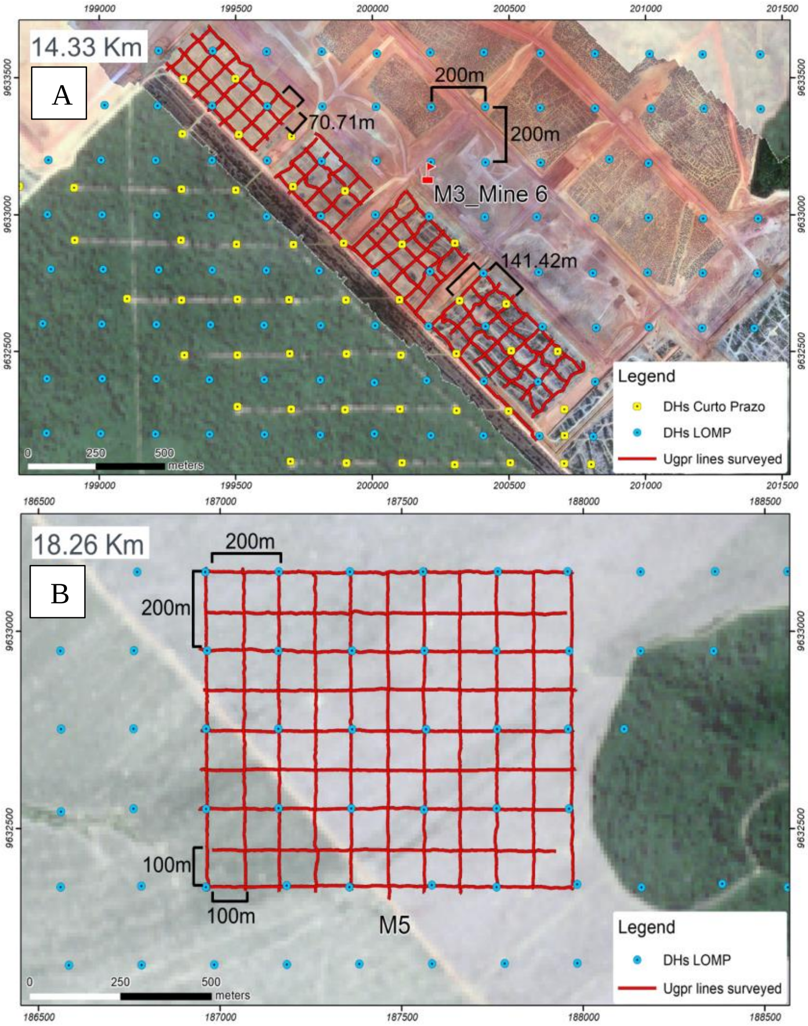

Figure 4. Survey areas in M3 (a) and M5 (b) plateaus.

The X and Y points used are from the GPS of the equipment, but the Z data (elevation) belongs to a topographic wireframe generated from drillhole coordinates and elevation. Equipment data is tied to XYZ information collected in conjunction with a field GPS, coupled to the system. Both data (investigative pulse and XYZ coordinate) are integrated into a wireless device via Bluetooth, with the ideal processing and data storage capacity for the process. This data is integrated and shown in real time (raw, untreated information) on the device screen using the patented software of Groundradar Consulting Inc.

During the field data acquisition, geopositioned data were collected in the UTM (Universal Transverse Mercator) metric system, using the WGS84 (World Geodetic System 1984) datum, which were transferred from the collection equipment to a computer at the end of each day. The data was exported in an ASCII text format (*.txt or *.csv) and organized according to a pattern defined according to the structure required for processing and then it was reprojected to the South American Datum (SAD69), thus making it compatible with the standard coordinate system used by Hydro S/A. During this stage, the quality control of the data was carried out, in order to identify any failures and/or non-conformities that may compromise their integrity.

The UltraGPR data were processed in a similar scheme to what has been applied to others lateritic deposits worldwide. The process used amplitude gain functions and custom low-pass frequency filters to subdue unwanted interference caused by the conductive clay overburden and thereby enhance the underlying bauxite layers.

Ground penetrating radar is not a suitable geophysical method for regions of high clay content, such as the overburden material at Paragominas. However, the real-time sampling capabilities of UltraGPR can allow enough energy to penetrate through the overburden to image the bauxite. In conductive clay environments, the amount of radar energy which is absorbed by the clay is very high. All radar systems emit energy both into the ground as well as into the air. In normal, or good, radar environments (e.g. sands and gravels), the strength of the reflections from underground are many times greater than signals which are emitted into the air.

However, in conductive environments such as Paragominas, the energy going into the ground is absorbed so much that the energy which goes into the air is much greater. The result of this is that any tree, truck, person, or protruding rock can create a very strong reflection on the radar, but any underground layer will be a very weak reflection. Given that it is not practical to shield the radar antennas at these frequencies (the shields would be very large), the data collected is often overwhelmed by above-ground (e.g. tree) reflections. This is shown in the sample Paragominas raw data in Figure 5a.

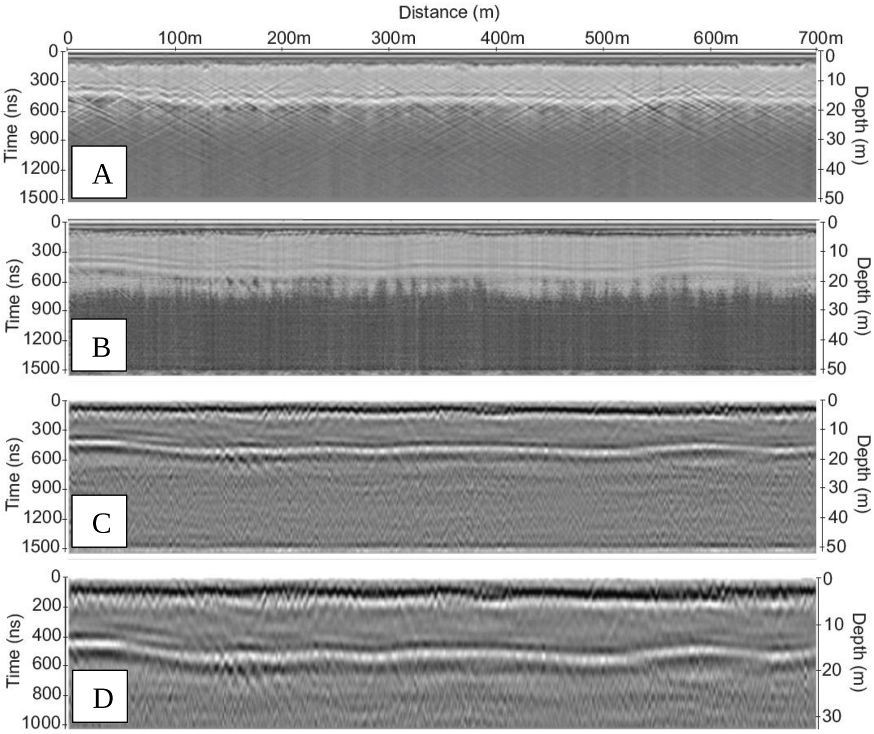

Figure 5. (a) Raw data from Miltonia 5 after geo-referencing and gains; (b) Data after 2D FFT; (c) Data after dewowing; (d) Final data profile.

In this raw section, it is possible to see the bauxite layer. However, the "X" patterns from the above-ground reflections can obscure the data. In order to remove those reflections, a 2D fast Fourier transform (FFT) is applied as well as a Butterworth low pass filter, as shown in Figure 5b. In order to remove the low frequency "wow" effect, a dewow filter is applied to the data (Figure 5c). Finally, the lower portions of the profile are removed to improve the interpretability of the bauxite layer (Figure 5d). The "X" or "Λ" patterns still visible on the profile section are the remnants of the unwanted above-ground interference reflections from trees. These patterns are to be ignored when analyzing the data.

2.3 Data Interpretation and Validation

The interpretation of the processed data is ostensibly a simple task of drawing lines at the top and base of the bauxite layer. However, interpretation is a more time-consuming task because it is critical to ensure that all interpreted layers match perfectly the tie-lines to ensure a smooth final surface. To achieve this, the Groundradar Studio software was used, a tool developed by Groundradar Consulting Inc., as shown in Figure 6.

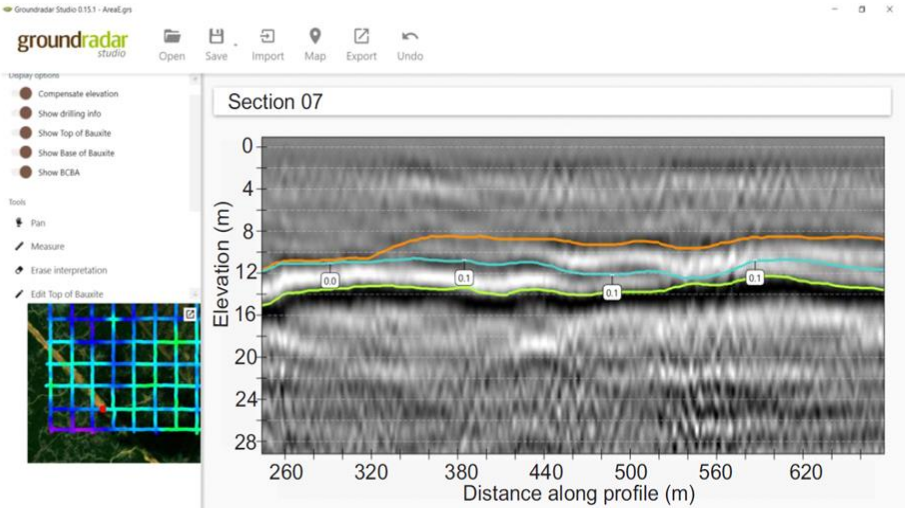

Figure 6. Groundradar Studio being used to interpret UltraGPR data from Paragominas.

The data were interpreted and crosschecked with boreholes and considered the signal reflection pattern as strength, texture and contrast between layers. For a simple exercise to define the top and base contacts of the bauxite-rich lateritic layer, it was preferred to simplify the drilling logs in: Top Clay (overburden) in blue color, Ferruginous laterite in red, Bauxite Layers (all lithological codes of bauxite) in pink and Bottom Clay (ARV code) in black. This example can be seen in Figure 7, where the drill hole is arranged in the section. The hole collar was normalized to 0 so that it represents position in the space in the same way as the surface of the section in question.

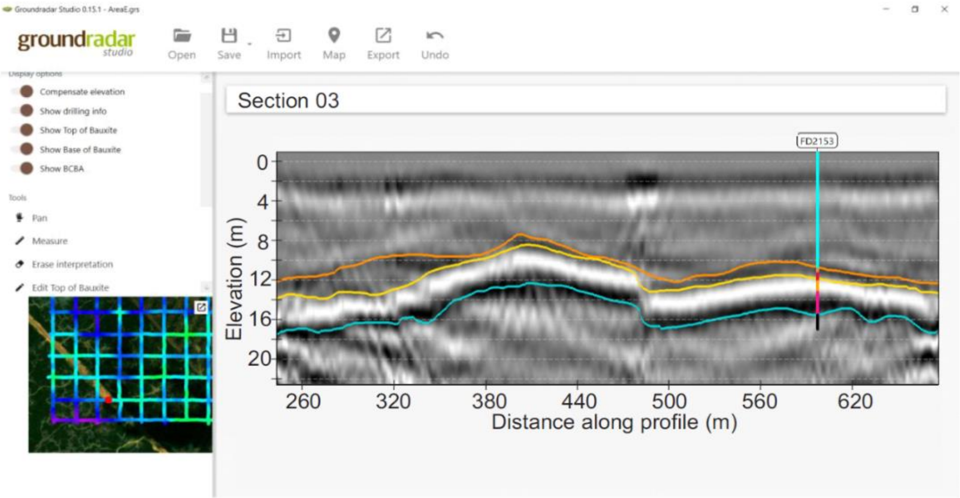

Figure 7. Sample of drill hole correlation.

The collection and digital processing of the data resulted in the following products:

- 3D vector data (xyz) in ASCII (American Standard Code for Information Interchange) format (.txt or .csv), i.e. point clouds, which were used to represent the intersection of reflection surfaces and the different layers of the lateritic profile, to be used in geological modeling;

- The sections were generated in GeoTIFF format (or similar georeferenced), which will reflect the real (terrain) and normalized topography;

- Section images (black and white, color images) were exported in pdf formats;

- Isopach maps showing the depth to the top and bottom of bauxite generated from Kriging interpolation to create surfaces from UltraGPR interpretations. The surfaces can be output as grid files for graphical display, or as 3D DXF (Drawing Exchange Format) surfaces for import into the mine models.

The workflow since data collect until 3D modelling is resumed in the image below (Figure 8):

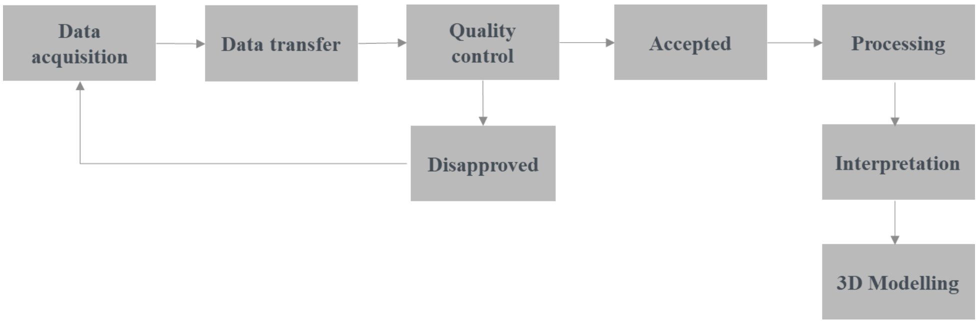

Figure 8. UltraGPR workflow for acquisition and applications.

In order to validate the results, geological mapping campaigns were programmed on mining fronts in parallel sections and coincident with the geophysical profiles (Figure 9a). The geological contacts between the different layers were identified and surveyed with a high-precision Trimble R8 GNSS (Global Navigation Satellite System) receiver (Figure 9b) and then all the data were incorporated in the 3D geological modelling workflow in Leapfrog Geo® environment.

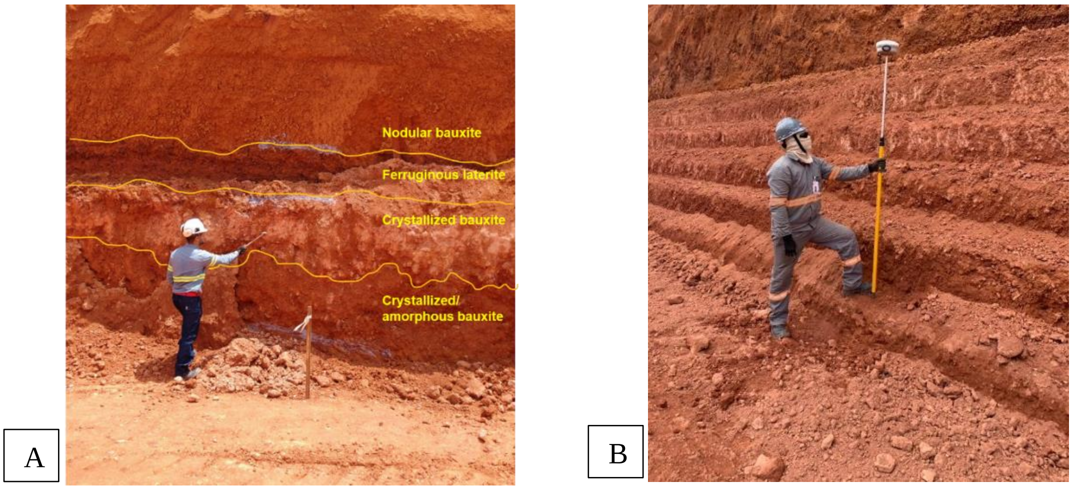

Figure 9. Geological mapping on mining fronts in parallel sections and coincident with the geophysical profiles (a) and geological contacts high-precision topographic survey to validate geophysical sections (b).

3. Results

In all sections it may be noted that the average depth reached from the surface will be approximately 20-25 m where the dispersion of the radar signal reaches its full peak. The geological environment is very conductive, consisting of clays and materials with high iron content, thus facilitating the dispersion of the signal in the environment, instead of its reflection. However, it was possible to map to the desired depth in the region to reach medium depths up to twenty and few meters.

The images below represent the sections M5-01 (Figure 10), arranged E-W, and M3-01 (Figure 11) arranged NW-SE and illustrate the reflection surfaces found in the investigated environment. The lateritic layer rich in bauxite or iron oxide/hydroxide has a greater electroconductive response than the top and bottom clay layers, and therefore stands out in the image as a raised texture. These images go through noise treatment and wave filter, in which only long waves were analyzed and short waves were ignored or removed. In this way, we can better visualize structures and reflection surfaces that are more intense and with a more marked response, at the cost of sacrificing short waves and thus losing detail in the image. This type of analysis is used to highlight entire layers at low resolution, making it easier to understand the main lithological change.

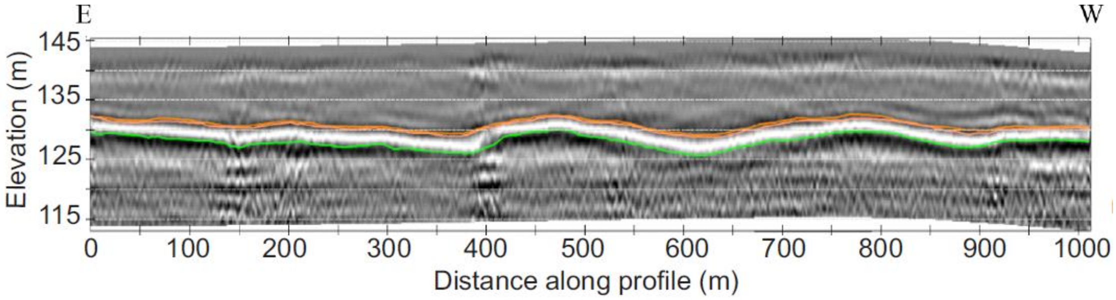

Figure 10. M5-01 section, oriented E-W direction, 5x vertical exaggeration.

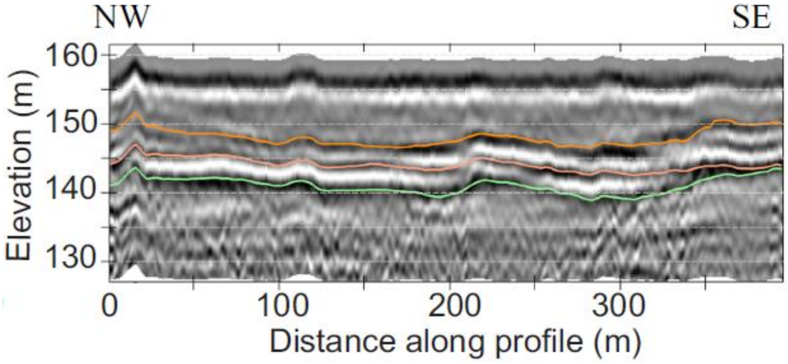

Figure 11. M3-01 section, oriented NW-SE direction, 5x vertical exaggeration.

The radar reflection strength is related to geology and it is noted that the radar reflection strength of the bauxite layer varies greatly across the project area. The relative strength of a reflector can be a function of several factors. In the case of bauxite, the hardness of the layer could cause an increase in radar reflection strength.

The results showed nearly perfect correlation with boreholes and a clearer geometry definition among lithological contacts. Both the bauxite top and bottom were well marked by a high contrast. Therefore, interstitial layers within the bauxite were more difficult and it was not possible to make a clear distinction between the crystallized bauxite (BC) and crystallized/amorphous bauxite (BCBA) layers (Figures 12 and 13). Colors randomly applied from a bluish spectrum, where the closer to blue the higher the conductivity values, and the closer to green the lower (and therefore more resistive) the conductivity values. Different speeds and dielectric values are illustrated by coloring.

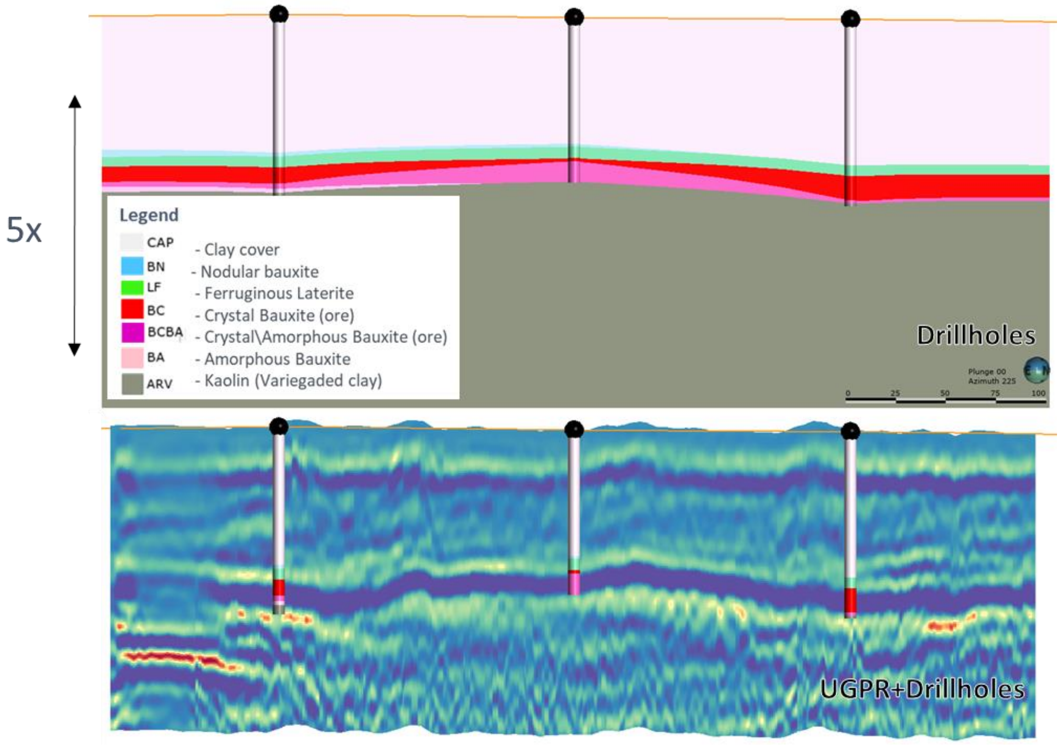

Figure 12. Comparison between the previous geological model built by drillholes information and geophysical section in M3.

The contrast seen in the first meters of clayey overburden is associated with differences in humidity and greater presence of organic matter in the soil.

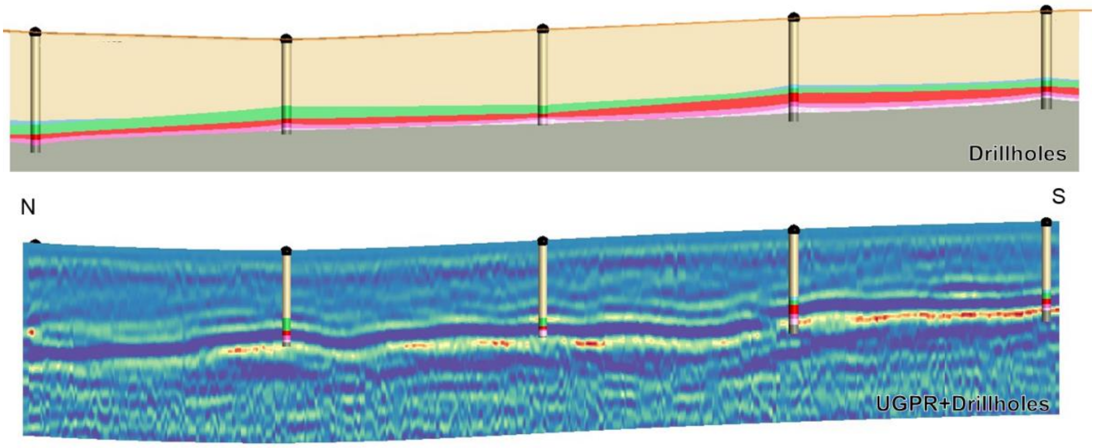

Figure 13. Comparison between the previous geological model built by drillholes information and geophysical section in M5.

The geological mapping on mining fronts in parallel sections and coincident with the geophysical profiles was essential for the interpretation and final validation of the geophysical signal. The Figure 14 shows the perfect correlation between the geometry of the ore, modeled from the drillholes and geophysics, and the mined ore, even allowing the identification of areas where ore loss and contamination have occurred.

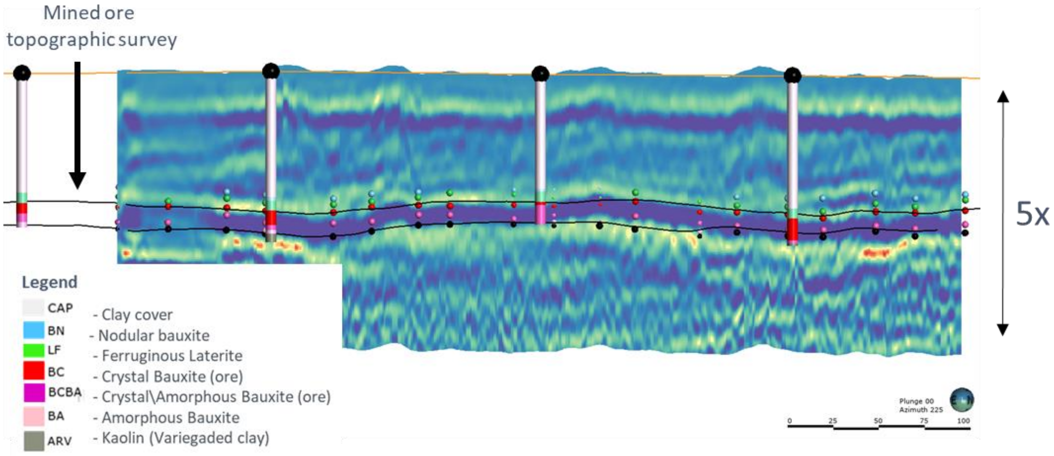

Figure 14. Geophysical section showing the correlation between boreholes, the contacts of the layers surveyed during geological mapping (colored dots) and the bottom and top mined ore survey (continuous black line).

4. Conclusions

Due to clay cover of approximately 10m to 15m, the radar signal is absorbed by the environment and instead of rebounding, it is retained, generating interference, loss of analytical capacity and masking more detailed information. In this way, 20 MHz UltraGPR instrumentation which was developed specifically for use in bauxitic and other lateritic weathering sequences was chosen, trying to filter characteristic noise signals and also to emphasize abrupt lithological changes, with thicknesses over 50 cm, in this way, being able to map the top and base contacts between lateritic and clayey layers.

The processed data appears to map the top and base of the bauxitic layer. Therefore, interstitial layers within the bauxite did not have a clear distinction between the crystallized bauxite (BC) and crystallized/amorphous bauxite (BCBA) lithotypes.

The results showed nearly perfect correlation with boreholes and a clearer geometry definition among lithological contacts, confirming that UltraGPR is a suitable method for bauxite exploration since it leads to improvements on geological models' accuracy. During mineral exploration in regional targets, the UltraGPR survey can be used to obtain a preliminary information regarding ore thickness and its potential, supporting the drilling plan and a more assertive and agile decision making. Similarly, mine planning and operation may benefit from better control and precision of geometry in the short-term models and represents an opportunity for operational savings through the optimization of financial resources from the drilling grids.

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