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Original paper

Geophysical modeling of the manganese deposit for Induced Polarization method in Itapira (Brazil)

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Resumen

Este artículo presenta la aplicación de los resultados del método geofísico de Polarización Inducida (IP) en el estudio de la ocurrencia de manganeso supergénicos en el sudeste de Brasil, con análisis de la arquitectura del depósito en subsuelo, basado en el contraste de las propiedades físicas de los minerales de mena (óxidos hidróxidos de manganeso y grafito) y la roca alrededor. El contexto geológico regional se define por la ocurrencia de tipos de roca que pertenecen al Complejo Amparo y Grupo Itapira. Este Grupo acoge la mineralización en una sucesión de cuarcitas, esquistos y gneises con porciones subordinadas. El estudio geofísico consistió en 10 líneas paralelas de calicatas eléctricas en dispositivo Wenner-Schlumberger, con una separación entre los electrodos de 10m y 50m entre líneas. Los datos de campo permitieron la generación de modelos de inversión 2D posteriormente combinan y interpolados para generar modelos de visualización 3D, de la que eran cuerpos de mineral probables delimitados en profundidad y la comparación de las dimensiones de la formación laterítica reconocidos en el campo. Se reconocieron dos cuerpos independientes de mineral en profundidad, que se caracterizan por valores de alta cargabilidad (por encima de 20mV/V) atribuida a la presencia de grafito en cantidades de hasta 5 %. Los cuerpos de mineral en profundidad mostraron área de cobertura mucho menor para la formación laterítica. Visualización 3D habilitado una estimación de la morfología de los cuerpos, sentido del buceo y la identificación de orientación transversal a la estructuración regional de plegado.

Palabras clave: calicatas eléctricas, manganeso supergénico, grafito, cargabilidad, modelamiento 3D.

Abstract

This paper presents the results of the investigation of a supergene manganese occurrence in the southeast of Brazil, using the Induced Polarization geophysical method. This study aims to characterize the surface and subsurface morphology of one of these occurrences, named São Roque, based on the contrast of the electrical properties of the ore and the host rocks. The ore, which is composed mainly of manganese oxides and hydroxides and subordinated graphite, occurs in the form of small discontinuous lenses hosted by quartzites and schists of the Itapira Group. The geophysical survey consisted on 10 lines of Induced Polarization Tomography using a Wenner-Schlumberger array, with an along-line electrode separation of 10 m for all lines. The IP data were modeled through commercial inversion software to generate 2D section models of chargeability. In order to create a 3D visualization model of chargeability, the 2D inversion models were then combined and interpolated in order to create a 3D visualization model. The 3D model revealed two independent ore bodies in both surface and subsurface, characterized for high chargeability (up to 20mV/V), instead of a single elongated orebody as suggested by the lateritic surface in the field. In addition, the model showed that the orebodies are elongated perpendicular to the area main structural trend and the regional alignment of the lateritic occurrences, which can bring new ideas in terms of local exploration strategies for manganese in this context.

Key words: electrical tomographic, lateritic manganese, graphite, chargeability, 3D modeling.

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Introduction

The Brazilian economy is highly dependent on the mineral sector. Brazil is the owner of the biggest world reserves of niobium (98.2%), barite (53.3%) and graphite (50.7%), second biggest of tantalum (36.3%) and REE (16.1%), third biggest of nickel (13.7%) and tin (10.0%) and fourth biggest of iron (13,6%), manganese (8.8%) and vanadium (1.3%). The mineral sector employs more than one million people directly and indirectly and the sum of mineral extraction in 2013 was more than 77 billion dollars (4.1% of the Gross Domestic Product - GDP) (MME, 2014).

Manganese has great importance in steelmaking industry (to increase the steel strength and resistance to corrosion), to decolourise glass, to make fertilizers, ceramics and especially for the batteries industry (Gonçalves & Serfaty, 1976). As its internal consumption and exportation increases, also increases the necessity of finding new deposits.

Ore is a material from which minerals and metals of intrinsic economic value or interest can be economically extracted at the present time (Peters, 1987; Misra, 1999; Moon *et al.*, 2006; Guilbert & Park, 2007). A prospect is a restricted volume of ground, which is considered to have the possibility of directly hosting an ore body, selected based on some geological idea or an anomalous feature of the environment (Marjoribanks, 2010).

Once a prospect has been defined, exploration work advances through a series of progressive detailing stages where success leads to the next stage and negative results might cause the prospect to be discarded, sold or put on hold until new information, ideas or technology arrive. Exploration techniques will generally go through the main stages: target generation; target drilling; resource evaluation drilling and feasibility studies (Milsom & Eriksen, 2011; Marjoribanks, 2010).

One of the techniques used for the search and investigation of an orebody is exploration geophysics (Reedman, 1979). Its use begins in the reconnaissance stages, where airborne methods are applied in regional scales for the definition of new prospects, and continues into most detailed stages where ground methods are employed directly towards delimitating the orebodies in subsurface (Ford *et al*., 2007). Geophysical surveys are aimed at measuring rock properties (electrical, magnetic, density, mechanical, etc.), which may reflect or have straight relationships to economic mineralizations. Measurements that are considered anomalous (that is, above area background) are then analyzed to determine its nature, size, position and shape as a prelude for a follow-up detailed exploration stage, usually drilling (Keller & Frishknecht, 1970; Moon *et al*., 2006; Dentith & Mudge, 2014).

Electrical methods are vastly used in mineral exploration. As they are essentially ground methods, they are mainly applied to local studies like prospect investigation for subsequent drilling (Robinson, 1988). Amongst several geoelectrical methods, the Induced Polarization Method (IP) is important in base metal exploration because it depends on the surface area of the conductive mineral grains rather than their connectivity; therefore, the method is especially sensitive to disseminated mineralization (Keller & Frishknecht, 1970). IP effects can be very strong at the surface of grains of conducting minerals such as graphite and metallic sulfides. Graphite is generally considered a drawback for the method. It is often said to be a ‘’indicator of pyrite’’ due to their similar (both high) polarization responses (Moon *et al*., 2006).

The IP method has been historically used for the search of disseminated sulfide and gold ores (and graphite in a lesser extent), in the most variable geological settings (Pelton & Smith, 1976; Moreira *et al*., 2012; Langore & Gjovreku, 1989; Allis, 1990; Izawa *et al*., 1990; Irvine & Smith, 1990; Locke *et al*., 1999; Dentith & Barrett, 2003). However, few references can be found about the use of IP method in the search and investigation of manganese primary and secondary ore deposits (Moreira *et al*., 2014; Ramazi & Mostafaie, 2013).

This paper presents the results of the IP method applied on the study of a supergene manganese occurrence in the southeast of Brazil, with the aim of analyzing the orebody architecture in subsurface based on the contrast between the ore minerals (Mn oxides, hydroxide and graphite) and host rocks.

Study area

The site of study is located in the northeast of São Paulo State, Brazil, around 6 km to the east of Itapira city (Figure 1).

The area is located in the Alto Rio Grande Fold Belt, Central Sector of Mantiqueira Province, Brazil (Hasui & Oliveira, 1984). The Alto Rio Grande Fold Belt is a Middle Proterozoic tectonic province, thrusted upon fragments of a

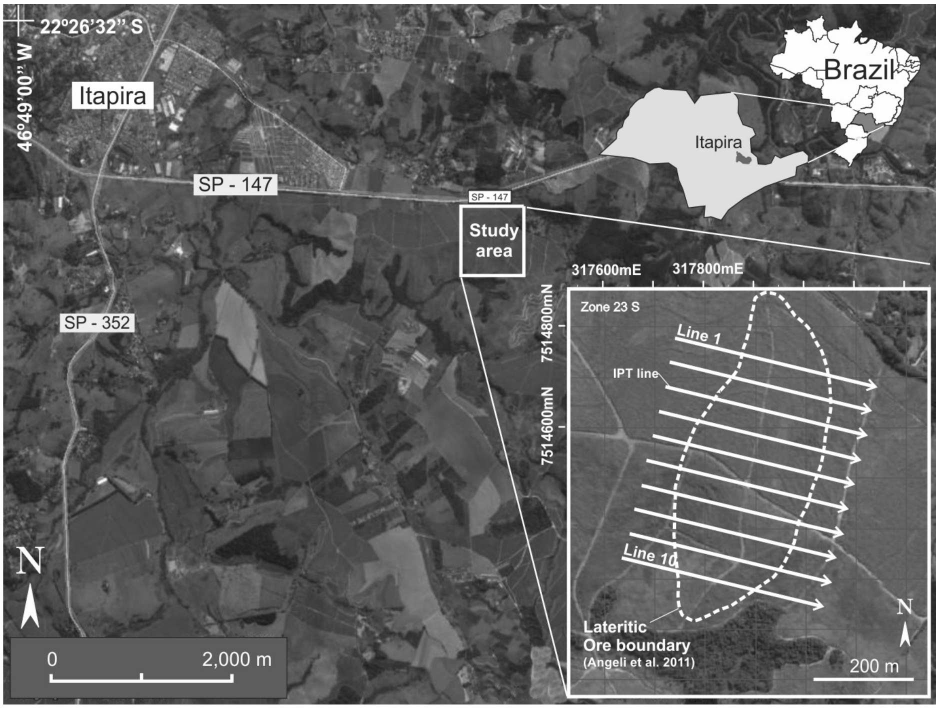

Figure 1. Map showing the location of the study area and location of the IPT survey.

microcontinent formed in successive orogenies during the Archean and Early Proterozoic. The geological and geochronological history of these terranes show subsequent metamorphic episodes of crust-forming and reworking of continental material since 3.4 Ga until 600 Ma with the Late Proterozoic Brasiliano Orogeny (Tassinari & Campos Neto, 1988; Campos Neto, 1991; Lazarini, 2000).

The surrounding geology is represented by lithotypes of the Amparo Complex (infracrustal basement rocks) and metasediments of the Itapira Group (Mesoproterozoic supracrustal rocks).

The Amparo Complex is composed of high-grade metamorphic rocks including migmatites and ortogneiss of tonalitic to granodioritic composition. The group is marked by a complex structural pattern resulting from superimposed tectono-metamorphic events that has shaped the area since Archean times (Fiori *et al*., 1978; Artur *et al*., 1979; Fiori *et al*., 1980).

The Itapira Group, which hosts the manganese occurrences in the area, is an allochthonous metavolcano-sedimetary sequence, trusted over the older rocks of the Amparo Complex. The group is composed mainly by quartzites, schists, quartz schists, silimanite-garnet paragneisses and subordinated gondites (Wernick, 1976; Arthur, 1980; Veríssimo, 1991; Angeli *et al.*, 2011). The rocks of the Itapira Group show a complex structural pattern, characterized by high angle dextral sense shear zones that are consistent with a transpressive deformation in a ductile to ductile-brittle regime. The main structures are tight folds, refolded or not and sheared folds with steeply-dipping angles in their axial portions.

Artur (1980) recognized at least three phases of regional metamorphism and deformation in the area, resulting from recurring collision events from the Palaeoproterozoic to the Neoproterozoic. The last event, the Brasiliano/Pan-African, was responsible for the reactivation of older crustal structures, folding and shearing, leading to the formation of a sequence of synforms and antiforms with fold axial plane strike NE-SW, perpendicular to the axial plane strikes of the previous deformational event, which is NW-SE.

The individualization of each unit in the field is a difficult task, due to the complex structural pattern caused by the superimposed metamorphism and deformation that affected both groups. However, it is know that the units are organized as a set of sinform-antiform structures, where the sinformsare represented by lithologies of the Itapira Group and the antiforms are represented by the Amparo Complex (Wernick, 1976).

A few lateritic manganese occurrences are found in the area, of which some of them have been studied in terms of their mineralogical and chemical composition, genesis and ore processing (Zanardo, 2003; Veríssimo, 1991; Angeli, 2011). The occurrences are arranged in a NNE-trend, coincident with the area main structural trend and separated from each other by a few hundreds of meters (Figure 2).

The ore is residual and consists of secondary manganese oxides and hydroxides formed by the weathering of silicate and silicate-carbonate protores. Lithiophorite, cryptomelane and pyrolusite make up the highest grade ores, derived from the dissolution and redeposition of Mn from the protores.

Two different types of protores are found in the deposits: silicate protore (essentially quartz and spessartite in equal proportions) and silicate-carbonate protore (rhodochrosite, rhodonite, pyroxenes and amphyboles in addition to quartz and spessartite). Graphite is found in both ore and protore, in amounts that can reach up to 10% (Veríssimo, 1991; Angeli *et al*., 2011). The mineralogy of the protore and the presence of graphite suggest a terrigeonous source for the metal and a meta-sedimentary origin for the manganese orebodies (Veríssimo, 1991).

The formation of primary sedimentary and residual manganese ore deposits is determined by the interaction of several processes, which may include its extraction from the source rocks, its fluvial transportation and its precipitation when in favorable pH and Eh conditions. In addition, chemical weathering can lead to the development of high-grade

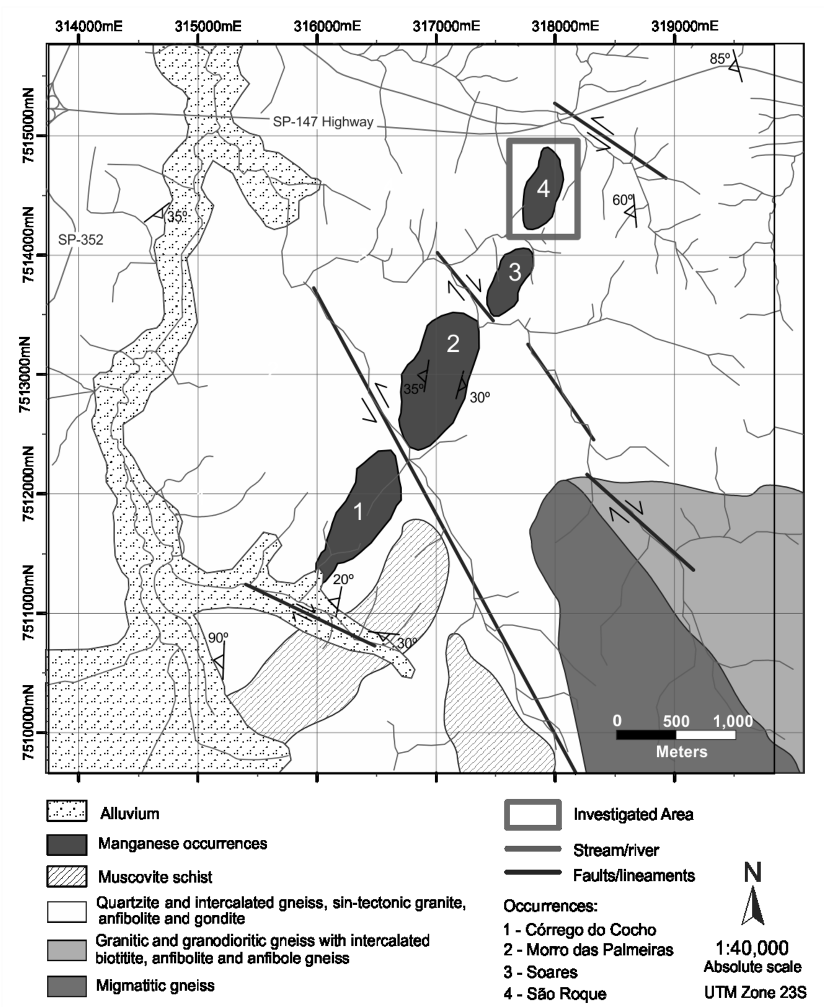

Figure 2. Simplified geological map of the study area. Modified from Angeli (2011).

residual (secondary) deposits (Stanton, 1972; Roy, 1992; Maynard, 2003; Misra, 1999; Guilbert & Park, 2007; Polgári & Gutzmer, 2012).

Gondites are metamorphosed sedimentary manganese-bearing arenaceous and argillaceous sediments with spessartine and quartz, besides rhodonite and other manganese silicates (Roy & Mitra, 1964). Eventual lateritic alteration can occur to the manganiferous protores under humid tropical to subtropical conditions, causing the remobilization of Mn and its precipitation as secondary manganese minerals (Sethumadhav *et al*., 2010).

Lateritic manganese cappings are originated from the physicochemical weathering of primary manganese deposits, including gondites. The weathering and transport of elements inside the lateritic profile modify the primary mineral content of the deposit, both vertically and horizontally (Wolf, 1976; Taylor, 2011). The leaching of manganese from higher surface levels causes them to become impoverished in that element and enriched in iron, leading to the formation of lateritic iron ore cappings on the surface and manganese enriched surfaces in the intermediate parts of the lateritic profile. As the laterization processes continues, manganese lateritic surfaces are formed in the intermediate parts of the alteration profiles, as a result of the vertical and oblique element mobilization (Wolf, 1976; Taylor, 2011). The leaching of the undesirable elements and the concentration of the manganese in the lateritic profiles might lead to the formation of high grade, economic deposits (Stanton, 1972; Park & MacDiarmid, 1975).

Lateritic ore cappings are a very important feature in terms of manganese exploration, as they are easily recognized in the field because of the characteristic black color they bring to the ground. However, their greater areal extent when compared to the primary deposits very often causes the overestimation of the concealed primary deposits.

Methods

The occurrence was studied using Induced Polarization Tomography (IPT), carried out within an area of approximately 500m by 600m. A total of 10 lines were positioned perpendicular to the local main structural trend, NNE, parallel and spaced 50 m to each other. The total length was 420 m for each line (two multi-electrode cables with 21 stations each), with an along-line electrode separation of 10m for all lines. Were performed a total of 10280 measures, of which half the readings of electrical resistivity and half of chargeability.

Data were collected through a Wenner-Schlumberger array, multi-electrode cables (21 take-outs each) and non-polarizable porous-pot electrodes (Cu-$CuSO_4$). The Wenner-Schlumberger array has good signal-to-noise ratio and imaging resolution (Dahlin & Zhou, 2004), and has been successfully used in the prospecting and 2D and 3D modeling of mineral deposits (Moreira *et al*., 2012; Moreira *et al.*, 2014). The opening and saturation of cavities for placement of the electrodes with solution of $CuSO_4$, resulted in minimum contact resistance and a great signal-to-noise ratio.

The equipment used was an ABEM Terrameter LS (Sweden), which consists in automatic and programmable single transmission/reception module with the capacity to acquire Spontaneous Potential (SP), DC resistivity (ER) and Induced Polarization (IP) field data. Data are then automatically registered into the equipment internal memory, in the chosen data file format, without any human interference (ABEM, 2012).

The survey acquisition parameters were: injected current = 500mA; injection time = 2s; acquisition time delay = 0.2s and a single acquisition time window of 0.1s, with the adoption of a ceiling of 3% of maximum standard deviation in relation to the average of measured values. These parameters were fixed after preliminary tests in the field, for verification and analysis of disturbances as power lines, telluric noise, EM coupling, among other.

The inverse modeling was done using the Res2dinv software (Geotomo Software, 2003), where 2D model sections of chargeability were generated, with the addition of data from topography. The Res2dinv is a 2D inversion software, which automatically defines a bi-dimensional model of the subsurface (in terms of distance versus approximate vertical depth) from resistivity and IP data, obtained from geoelectrical surveys (Griffiths & Barker, 1993).

The 2D model sections were then exported from Res2dinv and re-imported into the Oasis Montaj Platform (Geosoft), in order to create a 3D visualization model for the chargeability, without adjustment of topographic data. 3D visualization models generated from geophysical data are of great help in the understanding of complex geological structures and hydrological problems, like the flow of pollutants and modeling of ore deposits

(Chambers *et al.*, 2006; Aizebeokhai *et al.*, 2011; Moreira *et al.*, 2012). The visualization model was created interpolating the IP data from each section, using the Minimal Curvature algorithm.

Discussion

The data presented in terms of pseudosections feature areas of high chargeability in the central portion, with a tendency of continuity subvertical and reduction of values with the increase of depth (Figure 3). This pattern is accentuated in sections calculated with highlight of central areas and outlining a flank of high values toward the end of the lines are joined on-site deleted in inversion models.

The maximum depth obtained in pseudo-sections was 70m. The maximum depth after the process was 85m, defined in the form of automatic during the processing, before the unavailability of direct data for calibration, as testimonials or contacts geological outcropping.

The IP data revealed a low chargeability pattern for the investigated area as a whole. Apart from its central portion, where high chargeability values were detected in the lines 4 and 6, the average chargeability rarely overcomes 8mV/V. The lines 4 and 6, in the central portion of the area, showed significant IP anomalies in their central-eastern parts, characterized by chargeability values higher than 20mV/V, which were correlated to the manganese ore (Figures 4A and 4B).

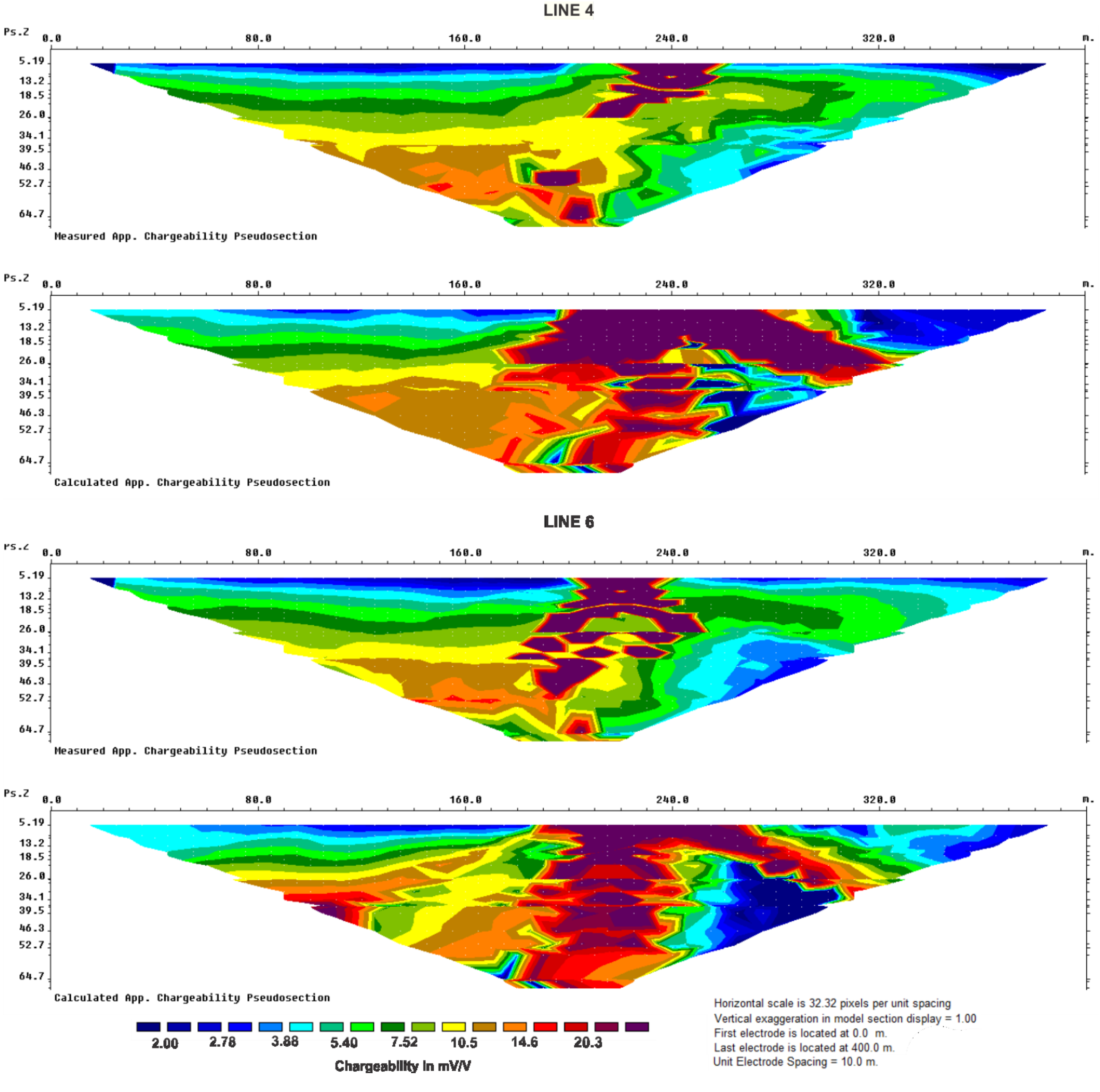

Figure 3. Pseudosections and calculated sections of the chargeability for lines 4 and 6.

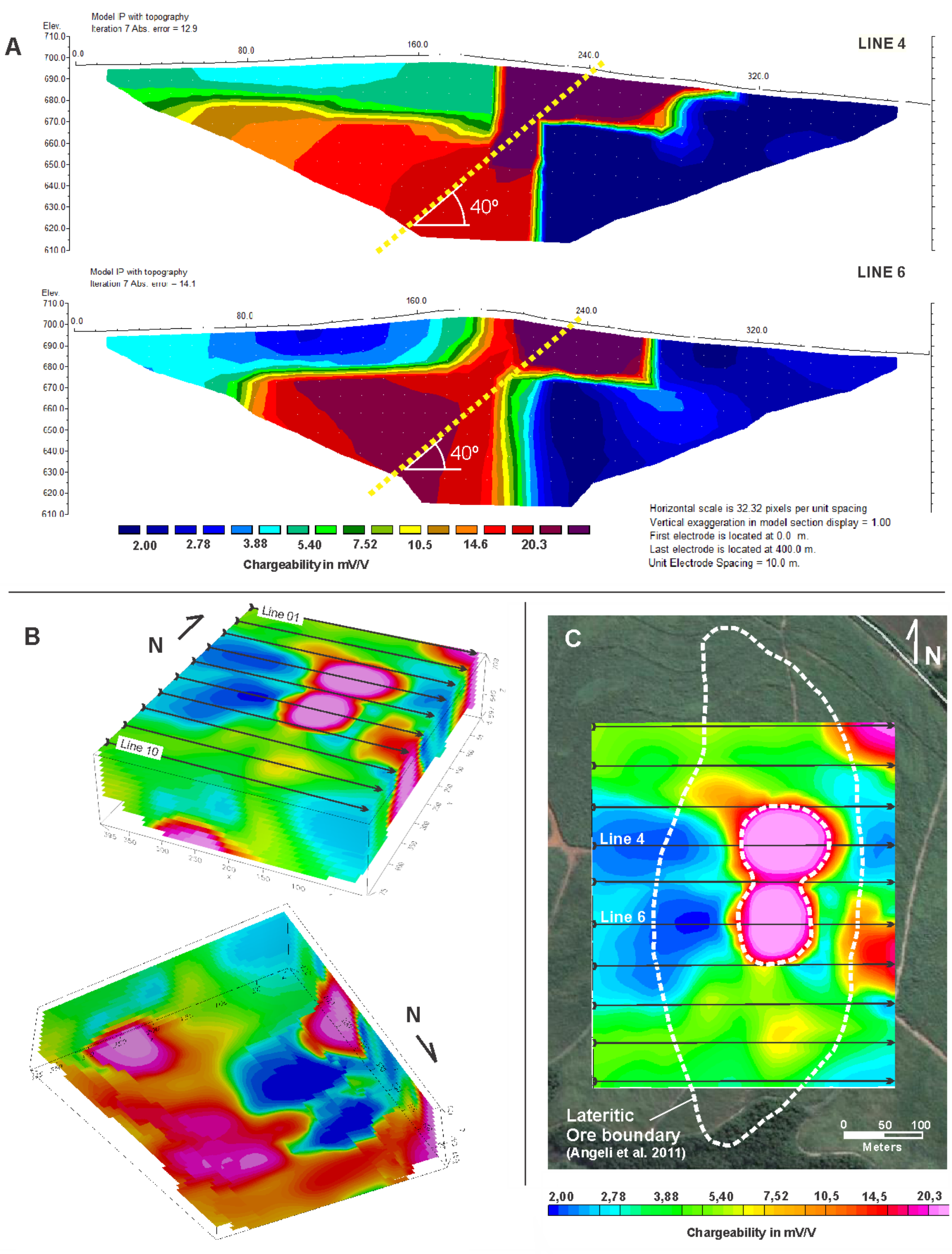

Figure 4. A) Most representative 2D model sections of chargeability; B) 3D Voxel model of chargeability, with top and bottom view for northwest; C) Discrepancy in area between the mapped lateritic ore and the near surface ore (about 3 m deep).

The errors of adjustment in both sections (12.9 and 14.1) reflect the standard deviation or variability of the data in relation to the average of the values. The high chargeability areas, presented in sections 4 and 6, have good vertical continuity into the deeper portions, with no end in sight, based on structural data obtained in the field, although it could be considered some smoothing effect during the data processing. The anomalies, which are coincident with the manganese lateritic cover in the surface, extend at least 50 m down-plunge towards the west at angles of about 40º (Figure 4A).

When projected to the surface, the central anomalies define an area much smaller than that of the manganese ore capping mapped and recognized during the geophysical survey (Figure 4C). A possible explanation for the discrepancy between the mapped occurrence in the field and the modeled geophysical orebody can be presented in terms of survey configuration. The 10 m electrode spacing used in the data acquisition resulted in a 2D modeled section with a minimum investigation depth of about 3 m, which is possibly deeper than the lower limit of the lateritic cover, with a maximum thickness of 1m verified in the field. Therefore, the high chargeability values are possibly related to the primary ore, instead of being related to the ore capping itself.

Finally, an isosurface was created based on the IP voxel model with the aim of evaluating the morphology of the high chargeability zones (values above 20mV/V) and their correlation with the deep mineralization (Figure 5).

The chargeability isosurface revealed the existence of two independent orebodies in the subsurface, instead of a single one elongated parallel to the regional strike (NNE) as suggested by the boundaries of the lateritic cover. Also, the isosurface showed a good vertical continuity of the orebodies at least to a depth of 80 m below surface, with a dip of about 40º to the WNW direction.

The orebodies are elongated along a WNW-ESE direction, therefore roughly perpendicular to the area main structural trend and the regional alignment of the lateritic occurrences. A possible explanation for this is that the orebodies were most likely originated previously to the last deformational event that culminated with the generation of the synform and antiform structural pattern with fold axis striking NE-SW.

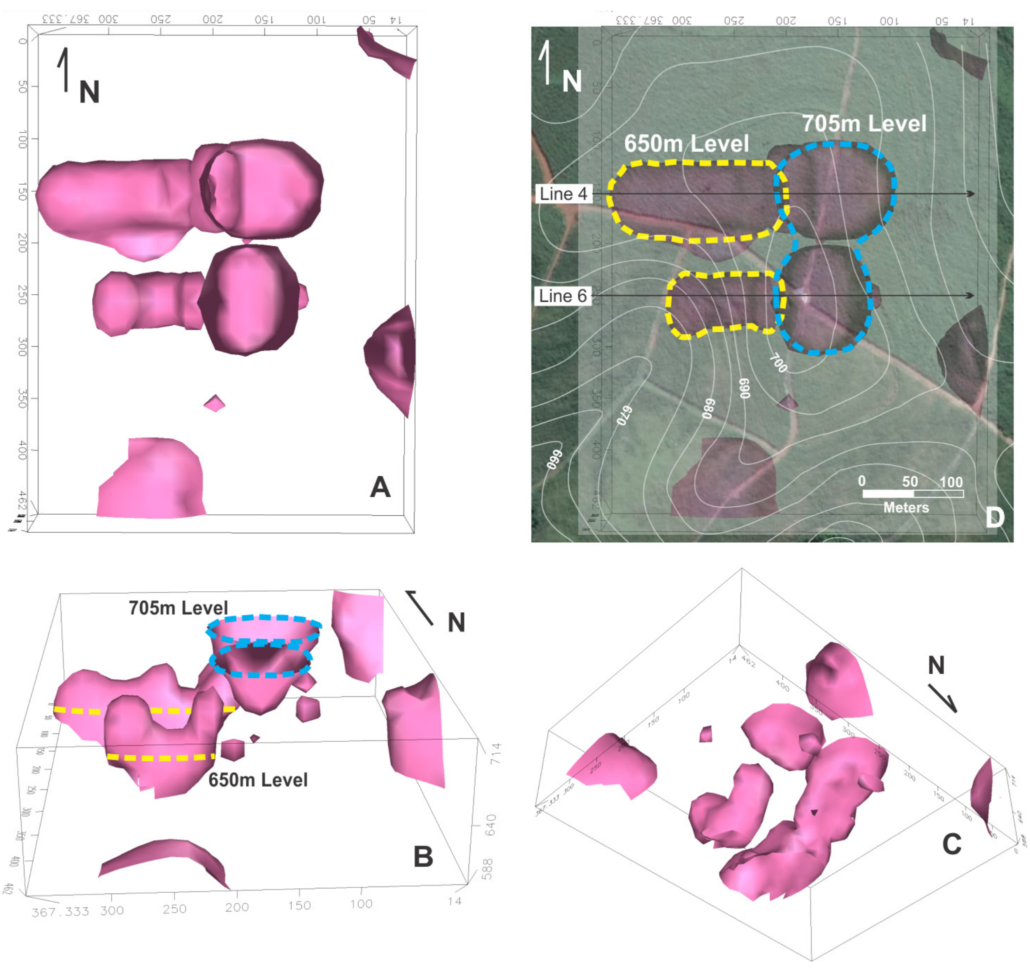

Figure 5. High chargeability isosurface models: A) View from top; B) View from side; C) View from below (the structure remain open). D) Surface projection of the underground orebodies.

Conclusion

The IP method showed good efficiency in the reconnaissance and morphological characterization of the orebodies in subsurface, mainly due to the presence of disseminated graphite (up to 5%) in the lateritic/manganese ore and protore, besides the Mn oxides and hydroxides, essentially due to the presence of graphite in the ore, because the polarization of oxides is very low.

These results demonstrate the applicability of the geophysical ground methods, specially the IP, as a support tool in the identification and selection of exploration targets for test drilling. The use of relatively inexpensive tools for the identification and selection of best drilling location can be a good strategy for saving time and money in mineral exploration projects.

Lateritic manganese ore cappings are key elements in the reconnaissance phases in regional mineral exploration, as they are easily identified in the field due to their characteristic black color. However, their great areal extent in the field as the result pedogenetic processes often lead to miscalculations on the resources and reserves of the concealed primary deposits.

The 3D visualization model was very important for delimitating both the areal extent and depth continuity of the concealed primary deposits, hidden below the lateritic surface. In addition, the 3D model was fundamental for the individualization and morphological characterization of the two orebodies in subsurface, dislocated from the central region of the lateritic cover and elongated perpendicular to the main regional structural trend.

The presence of graphite in the ore and protore was considered crucial for the success in the applicability of the IP method, due to its high polarizability in relation to the host rocks, which are quartz-feldspatic in composition. The genesis of the graphite is related to the origin of the manganese ore in a marine environment, under strong reducing conditions that allowed for the preservation of the dissolved organic matter in the sediments. Regional deformational and metamorphic events resulted in the conversion of the organic matter into graphite and in the generation of the gondites, which did supergene enrichment processes then concentrate.

The orientation of the orebodies in subsurface, contrary to the main structural trend, brings new possibilities for the revaluation of the several other manganese occurrences in the area through geophysical investigation. The IP method revealed to be a very efficient tool for the characterization and 3D modeling of the manganese orebodies in subsurface, in aid on the target location for direct sampling and chemical analysis.

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