Original paper

Geological and geophysical data integration for delimitation of mineralized areas in a supergene manganese deposits

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Resumen

Los métodos geofísicos constituyen una herramienta ampliamente utilizada en exploración mineral. Este trabajo presenta y discute los resultados de estudios geológicos y geofísicos desarrollados en un yacimiento de manganeso de origen supergénico, localizado en la región sudeste de Brasil. La zona mineralizada descrita en levantamientos geológicos fue caracterizada por bajos valores de resistividad (20Ω.m) y altos valores de cargabilidad (30ms), en un patrón similar al descrito en diversos trabajos en depósitos minerales de óxidos y sulfuros en rocas. Modelos geofísicos pseudo-3D permita la generación de mapas para diversas profundidades. Las áreas de alta cargabilidad y baja resistividad definen un patrón de mineralización gonditica con altos niveles de Mn. Áreas considerables con elevados valores de cargabilidad y baja resistividad probablemente resulten de la acumulación de hidróxido de manganeso y hierro, originados del intemperismo en cuerpos de mineral gonditico, disolución, percolación y precipitación.

Palabras clave: yacimiento, manganeso, supergénica, resistividad eléctrica, cargabilidad.

Abstract

Geophysical methods are widely used in mineral exploration. This paper discusses the results of geological and geophysical studies in supergene manganese deposits of southern Brazil. Mineralized zones as described in geological surveys were characterized as of low resistivity (20Ω.m) and high chargeability (30ms), pattern found also in oxides and sulfite mineral deposits. Pseudo-3D modeling of geophysical data allowed mapping at several depths. A relationship between high chargeability and low resistivity may define a pattern for high grade gonditic manganese ore. Large areas of high chargeability and high resistivity may result in accumulation of manganese and iron hydroxides, due to weathering of the gonditic ore, dissolution, percolation and precipitation.

Keywords: deposit, manganese, supergenic, electrical resistivity, chargeability.

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Introduction

The Brazilian economy is traditionally based on mineral extraction for centuries mining attracted the first colonizers to move inland, during the period of Portuguese Colony and Empire. Territorial expansion was motivated by the search for valuable gems and minerals, especially in periods known as Diamond and Gold cycles.

Nowadays, Brazil is positioned among the top seven global economic powers, with a gross domestic product (GDP) based on the export of commodities like soy, beef and minerals such as iron, plus heavy industries, chemical industries and manufacturing.

World reserves of manganese ore is in seven countries, which together make up practically 98% of world deposits: Ukraine (24,14%), South Africa (20,69%), Australia (16,03%), Brazil (10,34%), India (9,66%), Gabon (8,97%) and China (7,59%) (DNPM, 2011).

The world production of manganese in 2010 was 14710 million tons, with Brazil the second largest producer (2,6 million tons), only next to China with 2,8 million tons. Domestic production increased 13% from 2009 to 2010 (DNPM, 2011).

The mining sector is the basis for several productive chains. It's comprises the steps of research, mining and processing. Its current share of gross domestic product (GDP) is 4.2% and represents about 20% of Brazilian exports; it generates 1 million direct jobs, equivalent to 8% of all industrial jobs (MME, 2010). Brazil also produces niobium, iron, bauxite and copper, as well as gold and gems (MME, 2010).

Of critical importance for the maintenance, development and economic growth in Brazil, the mining sector is dependent on basic geological research for the discovery of new mineral deposits. Mineral exploration includes a series of steps of planning and strategies based on the mineral input of interest, ranging from the genetic model and mode of occurrence in the geological environment, research methods and procedures, to economic constraints such as demand, market value and future projection.

Mineral exploration and research are essential for the recognition and incorporation of new reserves, in response to a growing demand for both the domestic market and for export and trade balance. The available tools include direct methods (geological mapping, probing, soil and rock sampling, chemical analysis) and indirect (analysis of remote sensing, geophysical methods) (Moon *et al.* 2007). Due to the low cost and the possibility to cover large areas, geophysical methods are an important tool in mineral research. Aerial geophysical surveys are employed in regional tasks, while detailing is obtained by ground survey. In the latter case, we may mention the use of Electrical and Electromagnetic methods in geophysical prospecting of mineral deposits consisting of sulfides and oxides, often preceded by magnetometric survey (Moon *et al.*, 2007; Telford *et al.*, 2004).

The Electrical Resistivity method has application in the surveys for disseminated manganese due to the characteristic of high electrical conductivity of this metal, often contrasting in relation to the rocks around. The Induced Polarization method is widely applied in this type of research because of the high polarizability of minerals disseminated in the geological environment. This method was developed and optimized primarily for exploration of disseminated sulphides.

Several studies have shown the advantages, disadvantages, benefits and limitations of uses of these geophysical methods mentioned in the detailing and analyzing the morphology of mineral deposits (Alis, 1990; Irvine & Smith, 1990; White *et al.*, 2001; Moreira & Ilha, 2011; Moreira *et al.*, 2012).

This paper discusses the results of geological and geophysical studies conducted in a manganese mine of supergene origin, located in southeastern Brazil. Methods of Electrical Resistivity and Induced Polarization were employed in this work. The main objectives are: to establish relationships between measured physical parameters and mineralized zones in oxides and hydroxides in mapped mining fronts and analysis of the morphology of mineral bodies from the analysis and interpretation of three-dimensional models in terms of electrical resistivity and chargeability.

Material and methods

Geology and genesis of minerals

The area of studies, known as the Córrego do Cocho mine near located in the city of Itapira, State of São Paulo, southeastern Brazil, 177 km from São Paulo city (Figure 1).

Mining activity in the Córrego do Cocho mine began in the early 90s by Mineração Itapira Ltd. The manganese mineral is extracted from the

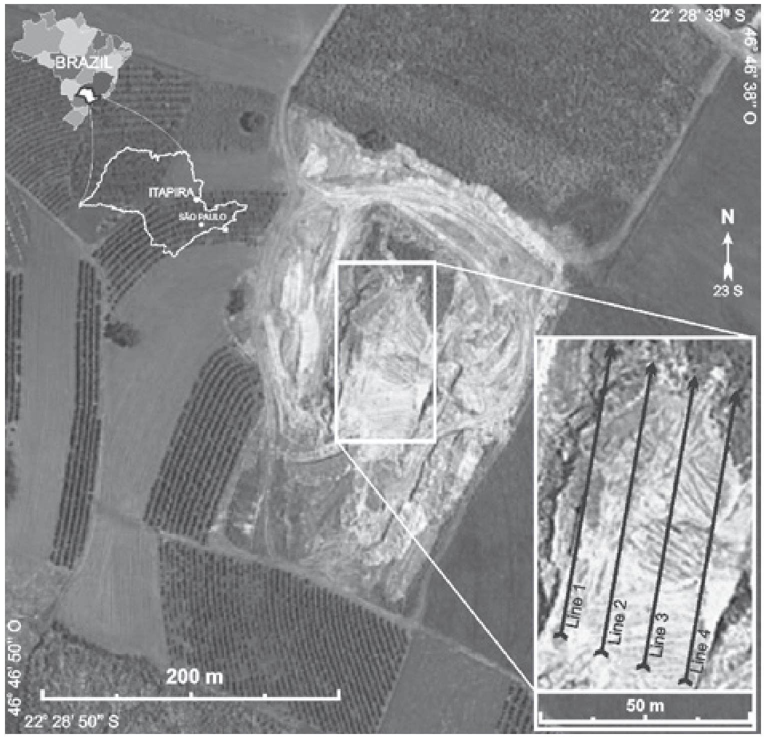

Figure 1. Location of the area of study, with positioning of lines of acquisition of geophysical data in the area of mining of manganese mineral.

mining fronts by direct excavation of saprolite material (Figure 2), which is a processed by homogenization, washing, crushing, grinding and concentration of the ore.

The regional geological context is the Ribeira Fold Belt, characterized by NE-SW trend with tectonic stacking to W toward São Francisco Craton. The lithotypes exhibit main deformation characterized by frontal collision and transpressive component. Transpressive shear zones and thrusts limit tectonic domains.

The Ribeira Fold Belt groups consists of two main lithostratigraphic units: the Amparo Complex and the Itapira Group.

The structures and rocks of the Amparo Complex reveal polymetamorphic classical evolution, initiated by sedimentation of clastic with clays concomitant with intrusions, extrusions and basic tuffs (Wernick, 1967). These rocks resulted in gneissic-migmatitic association of amphibolite facies and granulite in metamorphic event assigned to the

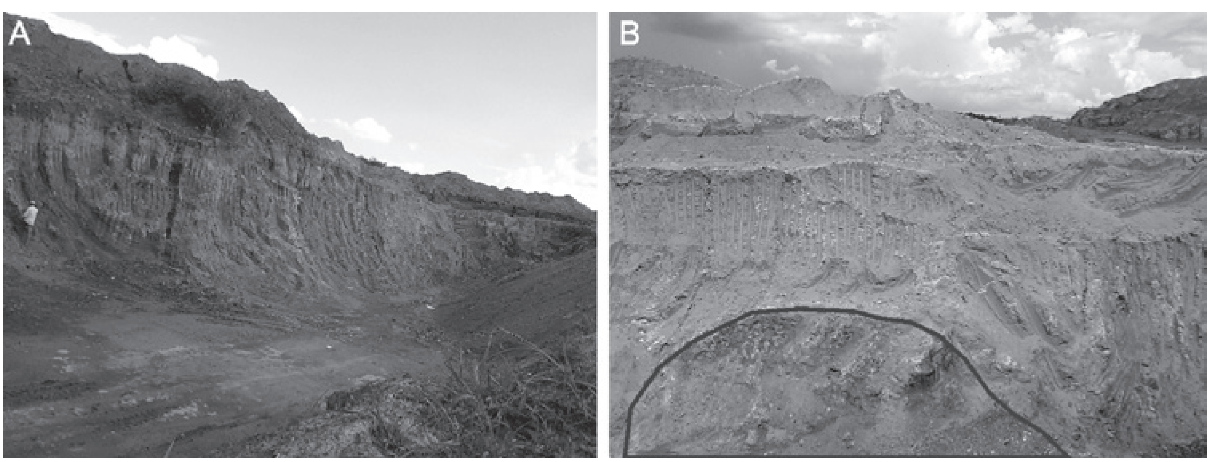

Figure 2. a) Mining front in activity. b) Detail of mineral body exposed.

Mesoproterozoic. In a successive event of tectonic deformation occur recrystallization and intrusion of large granitic masses, resulted in new migmatization of the Amparo Complex during the Brazilian Neoproterozoic Cycle (Wernick, 1978).

The Itapira Group is composed of metasedimentary rocks originated by prograding shallow platform sediments, composed predominantly of muscovite quartzites and paragneisses, and less frequently of migmatites, amphibolites, calc-silicate rocks, schists, metaultramafic rocks, marbles, metasediments of Eleuterio Formation and lenses of gondites (Zanardo, 2003, Angeli *et al.*, 2011).

In evolutionary terms, the Itapira Group is interpreted as a metavulcanosedimentary sequence of Proterozoic with syn-tectonic granitoids associated and subdivided into two distinct units (Oliveira *et al.*, 1998; Lazarini, 2000): a lower sequence consisting of pelites, greywacke, arkoses, intercalated with sediments of sandy clay, clay sandy clay, aluminous pelitic, marl, banded iron formations and manganifer sediments. The top sequence is composed of pelites, psamitic pelites, aluminous pelites, marls, limestone, marbles and manganifer sediments. The metasedimentary rocks of the Itapira Group, directly associated with gondites, represent metamorphic lithologies generated from a platform progradational sequence, consisting of muscovite schist, talc schist, muscovite quartzite, quartzite interbedded with mafic and ultramafic rocks, whose foundation is represented by migmatitic and gneissic rocks of the Amparo Complex. The evidence suggests an active tectonic environment with rapid transport of immature sediments of volcanic contribution to the genesis of manganifer protomineral in the area of studies (Verissimo, 1991).

More than a dozen gonditic bodies are discover in the region, which present a greater or lesser extent, classic profiles of weather alteration with enrichment in oxides and hydroxides of manganese. The genetic processes of supergene enrichment of the manganese protomineral are attributed to events that occurred between the Eocene and the Miocene, related to the formation of the South American Surface, attributed to climatic variations and tectonic reactivation (King, 1956).

The manganese protomineral found in the Itapira Group is classified by genesis as a silicate protomineral composed mainly of quartz and spessartine in approximately similar proportions, and calcium silicate protomineral, with quartz, spessartine, pyroxenes, amphiboles, plagioclase, carbonates and epidote.

In the Córrego do Cocho mine the silicate protomineral dominates, with textures and deformation structures in directions NW-SE and NE-SW, which occurs in paragneisses and quartzites spessartine, in the form of lenses aligned towards NE, corresponding to a single layer stretched and broken boudinage (Angeli *et al.*, 2011). The gneisses have leucocratic banded feldspathic quartz coarse-grained with fractures filled with oxides and hydroxides of manganese.

The mineral being exploited in mining fronts occurs in oxidized form, comprising oolites, pisolites and concretions near the surface, and massive mineral, banded and stained at depth. The main minerals are represented by spessartine, manganifer clinoamphiboles, rarely scapolite and piroxmangite. Litioforite also occurs and cryptomelane, pyrolusite, hausmannite, manganite and hollandita, plus nsutite, gahnite, jacobsite, yofortierite, psilomelana venular, woodrufite and todorokite (Angeli *et al.*, 1984).

Espessartine is the most abundant mineral, cemented by matrix rich in cryptomelane, whit occurs as amorphous crystals and preserve features related to the supergene alteration of espessartine. Psylomelane occurs in the shape of gray crystals, semi rounded, most frequently near the surface along the cryptomelane in both the matrix itself and close to the spessartine crystals. Total reserves of mineral for the Córrego do Cocho mine reach about 2.0 Mt, with 344,664 t of metal averaging a grade of 28% MnO2 (Angeli *et al.*, 2011).

Geophysical methods

We used methods of Electrical Resistivity and Induced Polarization, using the technique of electrical profiling.

Resistence is an intrinsic property in soil and rock, defined by current density over gradient of electrical potential. Resistivity changes an earth material, either vertically or laterally, produce changes in the relations between the applied current and the potential distribution as measured at the surface, and reflect changes in composition, extent, and physical properties of the subsurface materials. Properties that affect resistivity of a soil or rock include porosity, water content, composition (clay mineral and metal content), salinity of pore water, and grain size distribution.

The Electrical Resistivity method is based on generating an electric field by injecting an electric current (I) through metal rods, called the transmitter circuit (Sheriff, 1989). The electric potential (ΔV) produced by this field is captured by a receiver circuit, which can also be represented by metallic rods or non-polarizable electrodes. Applying Ohm's Law the electrode spacing, represented by K factor, enables measuring the apparent resistivity parameter (ρa) for various depth levels (1):

$$\rho a = K \frac{V}{1} \quad \Omega\,\mathrm{m} \tag{1}$$

Induced polarization is a phenomenon of electric current stimulation observed by a voltage signal in the subsurface materials (Sumner, 1976). This method consists in using an electrodic transmission device for injecting a pulsed, periodic electric current intro the subsurface, the response is obtained via a receiver circuit consisting of non-polarizable electrodes.

Chargeability is defined by the transient potential variable between two points on the transient decay curve normalized by the primary potential (Lowrie, 2007). In a dipolar arrangement, the current electrodes form a transmitter pair, while the potential electrodes form a receiver pair. When the current is interrupted, the voltage across the potential electrodes does not drop immediately to zero. After an initial abrupt drop to a fraction of its steady-state value it decays slowly for several seconds. Conversely, when the current is switched on, the potential rises suddenly at first and then gradually approaches the steady-state value. The slow decay or rise of part of the signal is due to induced polarization, which results from two similar effects related to the rock structure: membrane polarization and electrode polarization. In this work chargeability measurements were performed in the time domain, in terms of milliseconds (ms), defined as:

$$M = \frac{1}{V_c} \int_{t2}^{t1} V_t \, dt \quad \mathrm{ms} \tag{2}$$

Field work was, based on resistivity and chargeability measurements along a line, with the aim to investigate variations at one or more depth levels, through a dipole-dipole arrangement. This arrangement is characterized by the use of even by spacing electrodes, oriented and displaced linearly.

We adopted a 5m spacing between electrodes and investigation on 8 depth levels. The acquisition parameters were: 100mA current, a decay time of 10ms, single reading window with 100ms, acquisition time of 2s, four acquisition cycles and concomitant readings of resistance and chargeability. In chargeability readings, non-polarizable electrodes were used in a copper sulfate solution (Cu-CuSO4).

A Terrameter SAS 4000 resistivity meter was used, it consists of a single module for transmitting and receiving data with a resolution of 1 mV, 100W of power and four channels of reading, calibrated for transmission of periodic cycles of low frequency alternating current. This procedure enables the filtering of noise during data acquisition (ABEM, 2006). In the area of the mine 300 m of electrical routing were performed, divided in 4 lines of 75m in parallel arrangement in N17o direction and 10m spacing between lines (Figure 1).

Results

The field data were tabulated and processed initially by the RES2DINV program (Loke & Barker, 1996), models of inversion sections with a distance and depth were generated, together with topographic correction (Figure 3 and 4).

The inversion process consists in the superposition of a series of rectangular blocks connected to the field points in the pseudo section, i.e. the section generated by field data in theoretical depth. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation of points with the maximum space between electrodes (Edwards, 1977).

The subroutine of direct modeling is used to calculate the values for apparent resistivity, and a nonlinear least square optimization technique is used for reversal routine (DeGroot-Hedlin & Constable 1990, Loke & Barker, 1996). The result is presented in the form of sections with distance versus depth in terms of pseudo section, calculated section and inversion model. This paper presents only the inversion model in terms of resistivity and chargeability.

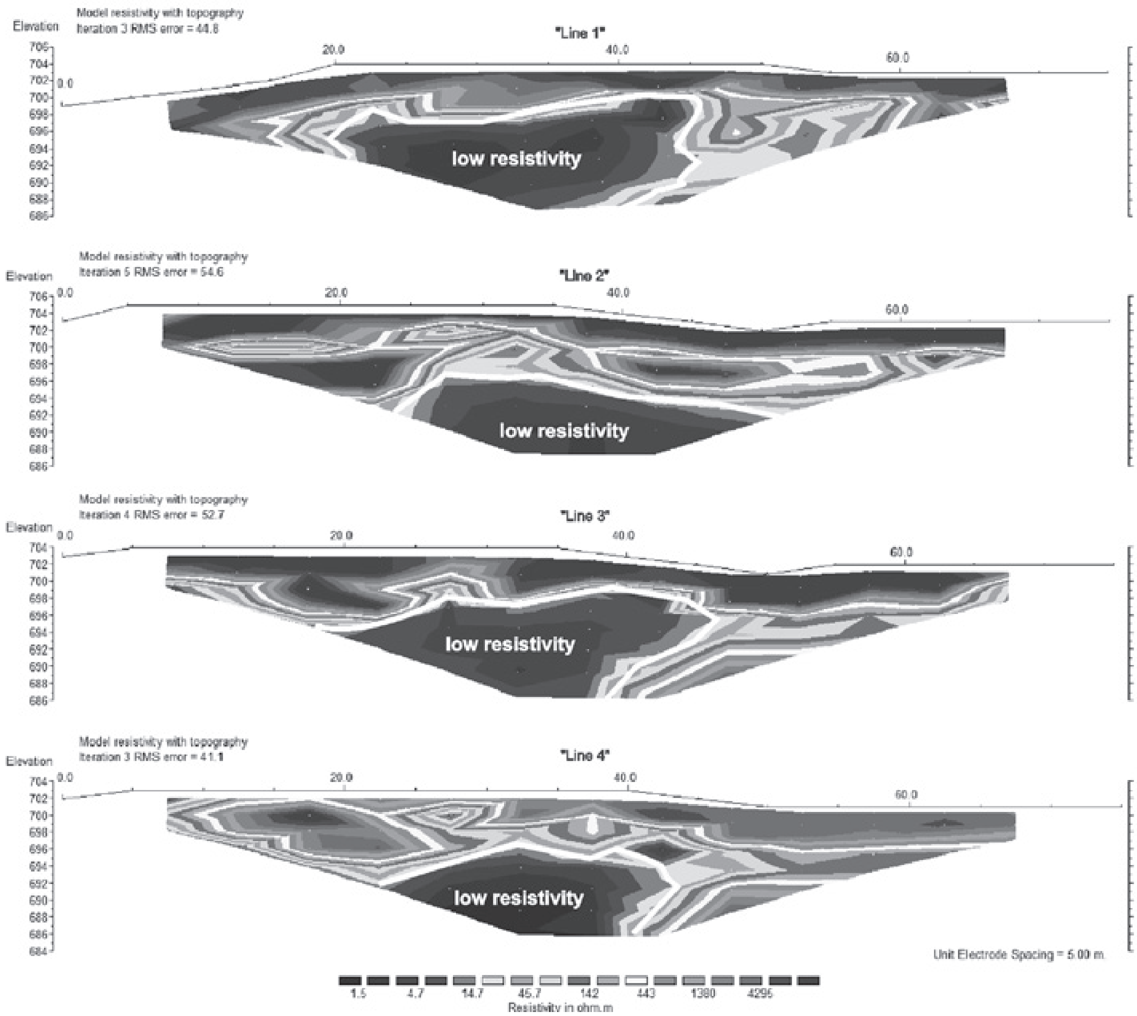

Figure 3. Resistivity inversion models

The relevant factor RMS error is a large contrast between maximum and minimum value measured, which hampes the optimization processing method (Figure 5).

Line 1 is located next to an active mining front, where there are outcrops of exposure of manganese ore. The georeferencing of the lines of electrical routing enabled to relate contrasting areas of physical parameters detected in inversion models, with zones of mineral concentration (Figure 6).

Concentration areas of high-grade minerals are characterized in the inversion model of line 1, as amounts of above 30ms chargeability and resistivity below 20Ω.m, in a pattern caused by oxides and hydroxides in soil and saprolite. This range characterizes disseminated sulphides and gold in various geological settings (Alis, 1990; Irvine & Smith, 1990; White *et al.*, 2001; Moreira & Ilha, 2011; Moreira *et al.*, 2012).

The central low resistivity portion is present in all resistivity section, though smaller variations in dimension. There is also correspondence in chargeability sections, characterized by high values beyond the limits of low resistivity areas, mostly in sections 2 and 4. The central area in sections corresponds to gonditc manganese ore concentrations exposed in mine front and directly correlated with the line 1.

However, the areas of high resistivity and high chargeability probably consist in manganese hydroxides from the destruction by weathering and hydration of the gonditic ore bodies, with dissolution and remobilization for vertical percolation and recristalization, in a similar processes found in gossans formations (Taylor, 2011; Biondi, 2003). These minerals are disseminated in depth and are characteristic of electric insulation, with in polarization intensity very similar to gonditic manganese ore.

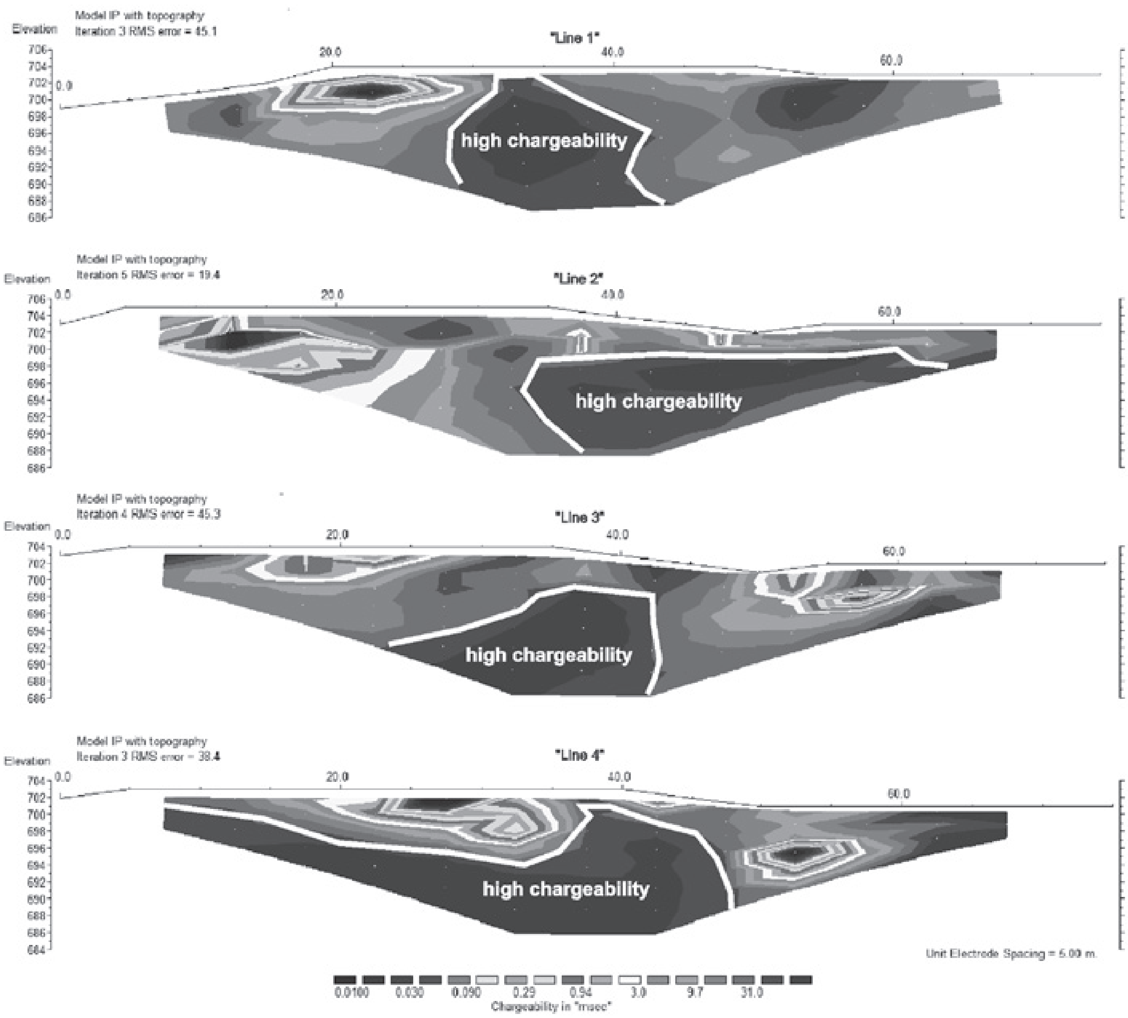

Figure 4. Chargeability inversion models with topography.

The values derived from inversion in terms of resistivity and chargeability were again tabulated and processed by Oasis Montaj platform, developed by Geosoft, for pseudo-3D modeling and 2D maps by interpolating previously processed data (Figure 7). These products were used for integration sections and presentation maps at relevant depths of pedogenetic mineralization, characterized by soils and saprolitic levels (Figure 8). Tridimensional presentation merely consists in pseudo-3D models.

Among the various algorithms available in the program, we adopt the method of minimum curvature for data interpolation. Interpolation is a mathematical procedure for adjusting a function of the unsampled points to values obtained from sampling points. Starting from the sampled points a lattice is defined with spacing relative to the points. The value of each node in the lattice is calculated by selecting closest known points, which are then filtered to smooth the resulting contours and allow the best fit to the original values.

The pseudo-3D model of electrical resistivity is characterized by high values of electrical resistivity at surface (above 1000Ω.m), with a gradual reduction in values accompanied by the increase in depth, especially for low values in shades of blue (below 100Ω.m). In the pseudo-3D model of chargeability with low values at the surface (below the 1ms), increase in depth, highlighted in shades of red (above the 30ms) in the area corresponding to the predominance of low resistivity values (Figure 7).

To verify the continuity of this pattern of values in other portions of pseudo-3D models, isovalues maps were generated for depths previously established, limited to 693m and 697m depths, rotated by angle and viewed from W to E (Figure 8).

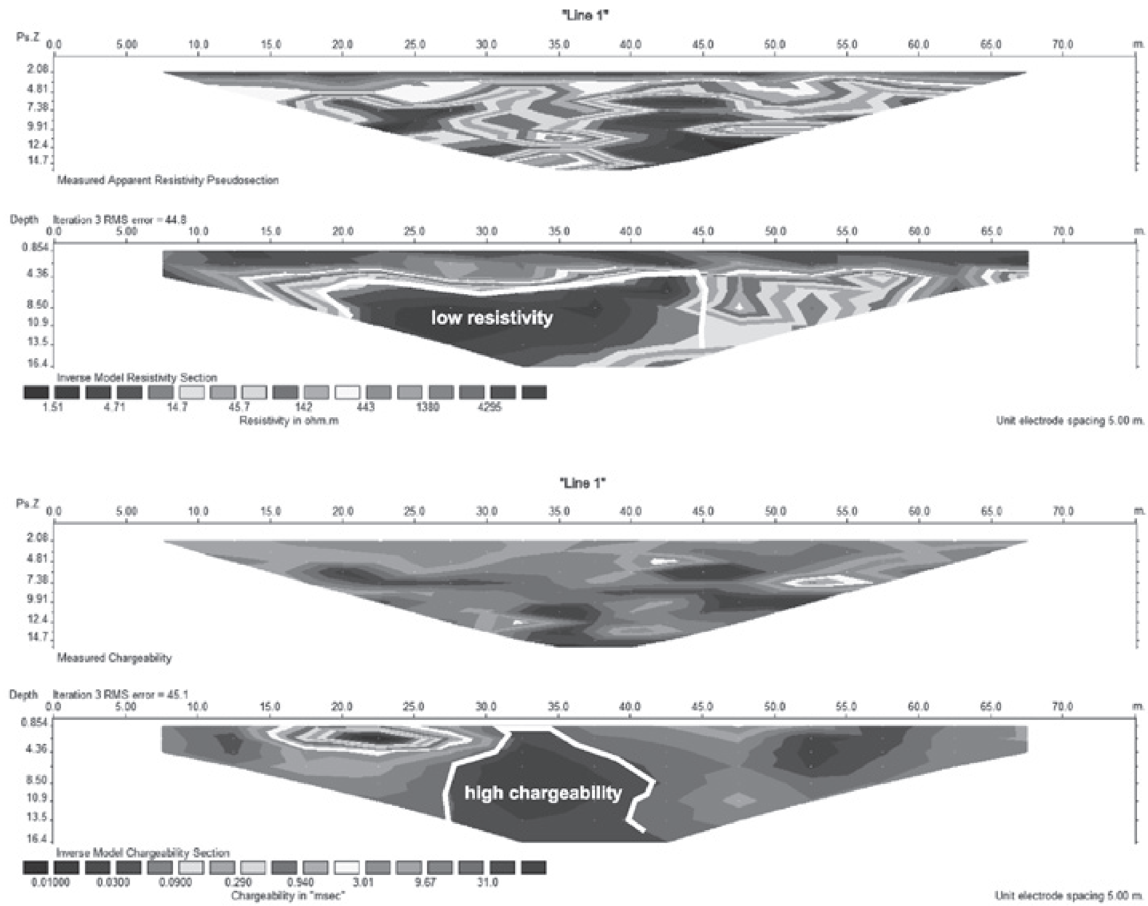

Figure 5. Resistivity measures and inverse model (above) and chargeability measures and inverse model (below) to Line 1.

A depth of 693m corresponds to the front mining ramp, where the mineralized bodies correspond to the inversion model of Line 1 outcrop. Between 697m and 693m little modified saprolite soil predominates, with fragments of rock, foliation and banding preserved and recognizable in the field, where the mineralized bodies present massive structure and intensely fracturing.

The depth of 697m represents the soil interval lacking fragments of rock, where manganiferous mineral concentrations occur as manganese hydroxides.The maps for both depths reveal no existence of low resistivity relations (above 100Ω.m) and high chargeability (above 30ms) for the other lines, coincidence being apparently limited to the western portion of the maps (position of line 1) (Figure 7).

The comparison of maps for 693m elevation reveals a central area with electrical resistivity quite homogeneous, corresponding to a domain with contrasting chargeability, where higher values in the central and east portions occur, coincident with lines 3 and 4, and moderate to low values west, coincident with lines 1 and 2. The comparison between the maps for 697m elevation also follows this pattern, although relatively higher electrical resistivity values predominate, besides relatively lower values of chargeability.

Electrical resistivity is sensitive to factors such as mineral content, porosity, grain size, presence of clay minerals, among others (Keller and Frischknecht, 1966). The materials that constitute the geological profile are basically represented by quartz and clay minerals derived from weathering of schists and quartzites, besides other minerals constituents of the mineralization.

The portions of soil near the surface are characterized by high resistivity values owing to absence of moisture, predominance

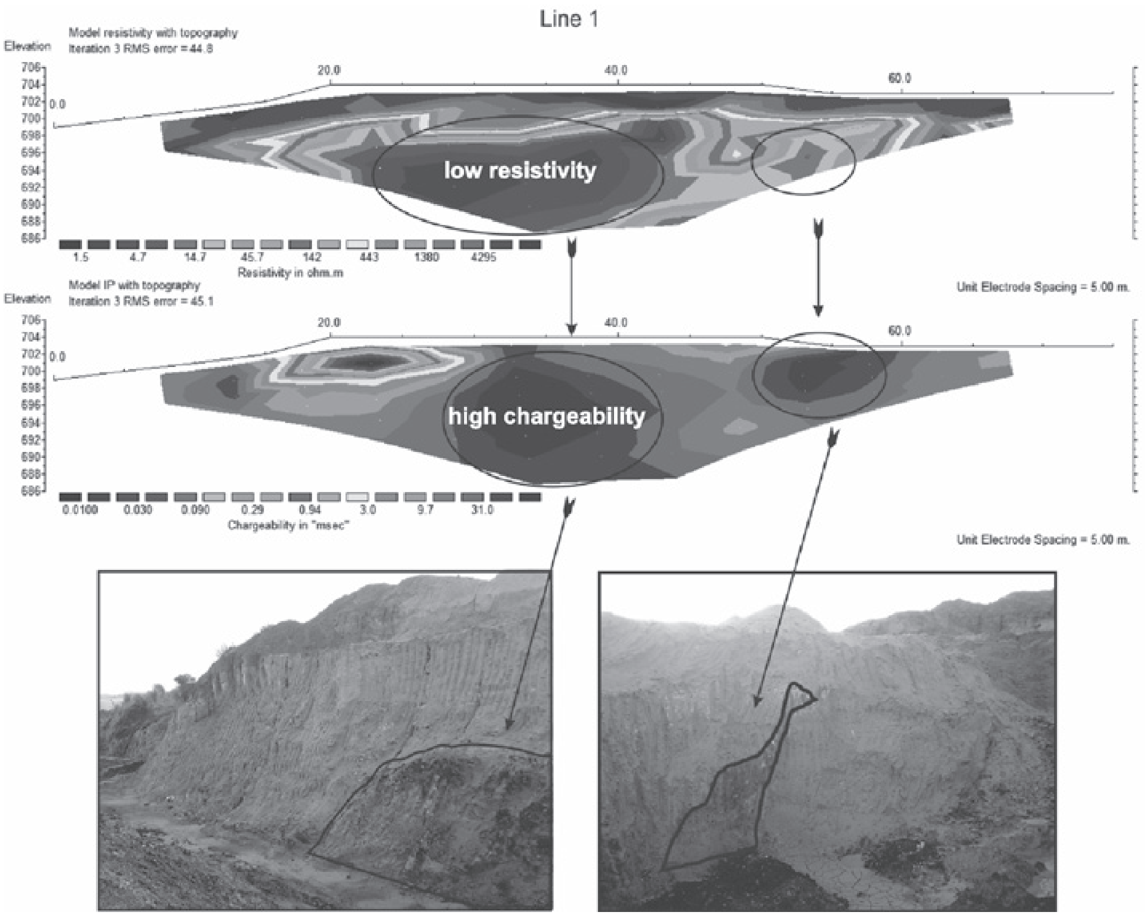

Figure 6 – Inversion models in terms of electric resistivity and chargeability, with emphasis on areas of low resistivity and high chargeability, related to mineralized zones exposed in front of mining located nearby.

of quartz and variable amount in hydrated minerals. While the silicates and hydroxides behave as electrical insulation, this mineral presents polarization intensity contrast.

The measures of chargeability are also partly influenced by geological conditioners similar to electrical resistivity, mainly mineral content. This aspect is determining for the polarizability of geological materials, very intense in disseminated sulfides, moderately intense for oxides and hydroxides and less intense in silicate minerals. Although there are processes of electrolytic polarization in the presence of moisture or clay, the polarizability is of little relevance to the presence of sulfides and metallic mineral responsible for the phenomenon of electronic polarization.

Thus, the areas of high chargeability revealed in the maps probably correspond to areas of manganese accumulation. The high grade Mn is found in gonditic ore bodies, characterized by high chargeability/low resistivity, whereas the disseminations in manganese hydroxides are represented by high chargeability/high resistivity, which consists in low grade in Mn, currently dumped as mine waste.

Conclusions

This paper shows that the combined use of geophysical methods correlated with geological descriptions of mineralized zones is a technically feasible procedure in in short term mine planning. The calibration of geophysical data with proven mineralized areas, can result in much higher detail when acquired only from surveys for sampling and chemical analysis, and thus in a relatively precise control of mining.

Understanding the existence and continuity of mineral bodies for grade control

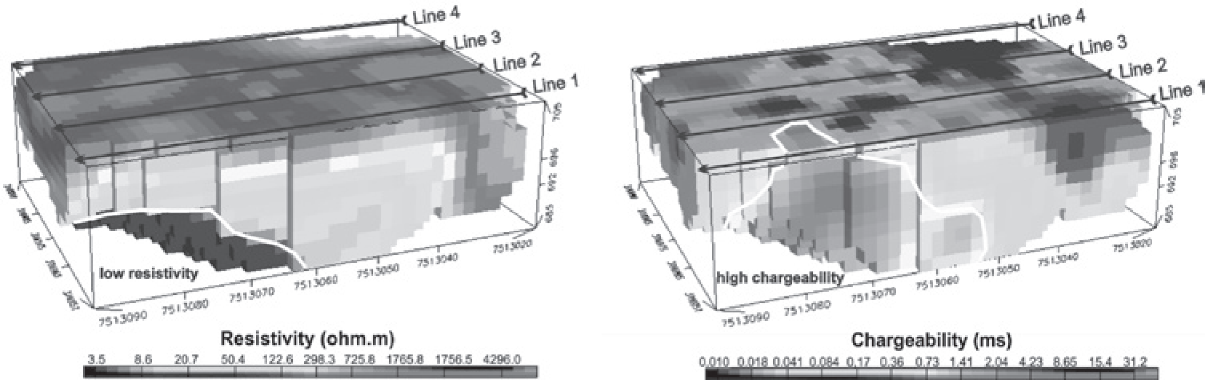

Figure 7. Pseudo-3D models for electrical resistivity and chargeability generated by interpolating lines of routing previously processed, with vision for east.

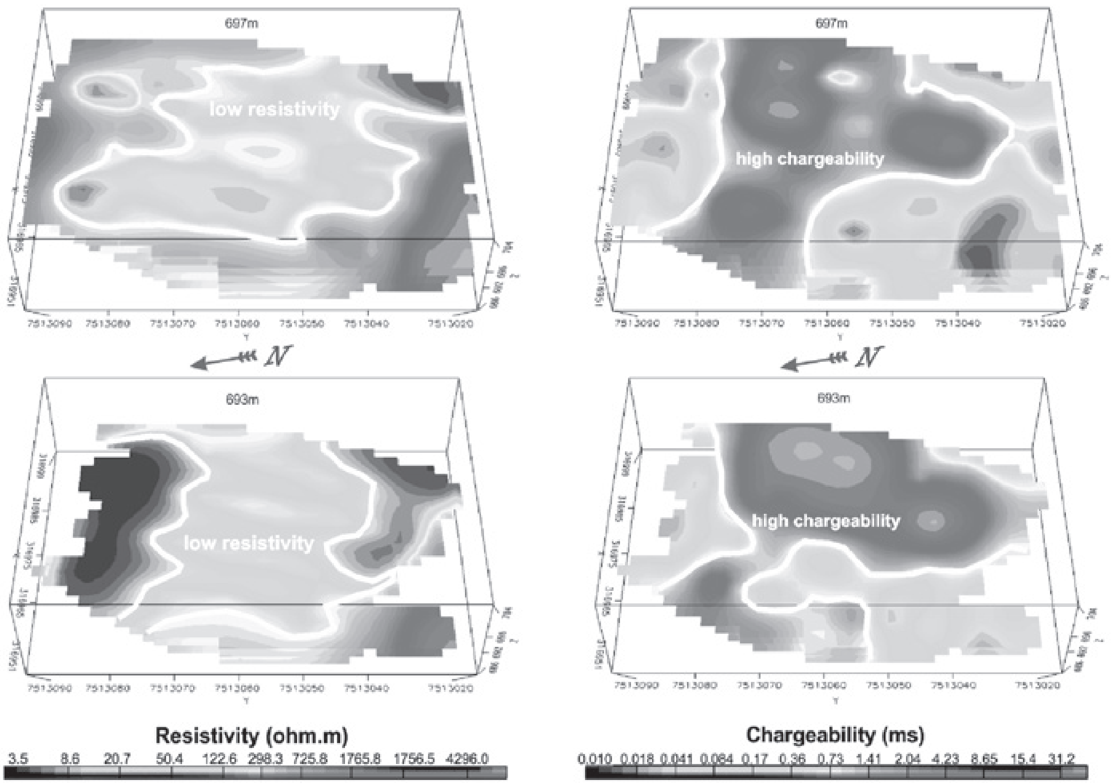

Figure 8. Maps of resistivity and chargeability for 693m and 697m quotas

in mining procedures is quite difficult even by conventional techniques of drilling and sampling, especially in complex deposits, with mineral distribution not linked to structural or stratigraphic controls. This procedure can result in errors when estimateding volumes.

In this paper a manganese deposit of supergene origin, with oxides and hydroxides of manganese disseminated in the interval of soil and saprolite, currently in the process of mining, besides structurally controlled mineral at greater depths, contained in schists and gneisses, was evaluated.

The application of geophysical methods of Electrical Resistivity and Induced Polarization in this complex geological context allowed the mapping of mineralized zones in interval of soil and saprolite. The initial calibration between areas of exposed mineral resulted in a geophysical signature of high chargeability and low resistivity by high grade, as described in several studies of deposits of oxides and sulfides contained in rock.

The classic signature of oxide deposits in sulfide by means of the above mentioned geophysical methods can be expected for primary or non-weathered deposits. For the case of mineral deposits of secondary origin, whose genetic determinants are controlled by weathering processes, factors such as humidity, porosity and clay mineral content, have great influence on measurements of electrical parameters.

However, this pattern does not apply to the inner portions of the deposit, with considerable areas characterized by high chargeability and high resistivity. Due to evolution of the deposit and mineral neoformation processes, this pattern suggests that the presence of disseminations of manganese hydroxides is characterized by low grade.

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