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Abstract

Ore mining fundamentally depends on the definition of its tenor and volume, something extremely complex in disseminated mineralization, as in the case of certain types of deposits of gold and sulfites. This article proposes the use of electrical tomography for definition of a geophysical signature in terms of electrical resistivity and chargeability, in an outcrop of mineralized quartz lode at the end of an inactive gold mine. One of the targets was to analyze the continuity of the mineralized body, the occurrence of new outcrops and the applicability of the method as an auxiliary tool in mineral extraction. Three parallel lines of electrical tomography in a dipole-dipole arrangement, being orthogonal to the orientation of the gold lode, were installed in an area outside the mine. The results allowed the geophysical characterization of the mineralized zone by high resistivity (above 1000Ω.m) and high chargeability (above 30mV/V). The results of the 2D inversion models were interpolated in 3D visualization models, which allowed definition of the contour surfaces for the physical parameters measured, and the morphological pattern modeling of the mineralization. The data reveal the existence of a new lode in subsurface, localized 30m to the south of the lode outcrop. The versatility of the acquisition and data processing indicate the application potential of electrical tomography as a criterion for sampling and tenor definition in ore extraction activities, since it is objective and low cost.

Keywords: ore extraction; sulfides; electrical resistivity tomography; 3D modeling.

1. Introduction

The ore extraction and beneficiation are highly complex fundamental activities in mining ventures. Mining control requires detailed studies about the geological constraints and mineralization controls, sampling rocks for definition of tenor, modeling of mineralized zones, planning procedures for disassembly of rocks, mining and transport logistics, besides a chain of processes and controls in the beneficiation units (Evans, 1993).

In several cases, the recurrence of deformation events and metamorphism result in geological contexts of high structural complexity, with sequences of polyphase folds, installation of fractures and failures in various directions and shears. Such constraints provide the concentration of chemical elements in places where pressure relief, allied or concomitant to the hydrothermal and/or metasomatic processes result in accumulations of minerals of economic interest (McCaffrey *et al*., 1999).

The structural complexity of deposits is sometimes allocated with a wide dissemination of metals such as gold and pyrite in pores, veins or lodes, often filled by quartz and barite. Sampling techniques to estimate traditional reservoirs and quantifica-

tions of tenor in mining are characterized by punctual investigations, which often result in conflict when compared to estimates obtained after the ore beneficiation (Marjoribanks, 2010).

The densification of the sample mesh is conditioned to drilling costs, sampling and chemical analyzes, which in many cases are the only alternatives before the reduction of tenor in mine extraction or disappearance of the mineralized area.

The geophysical investigations are an alternative tool in the detection and predictability of continuity to the mineralized zones of high complexity in mining extraction. Its traditional use in mineral exploration provides the discovery and the detailing of mineral deposits, with results that enable the reduction of costs due to the appropriate leasing of boreholes witnessed (Moon *et al*., 2006; Rodríguez, 2006; Dentith & Mudge, 2014; Alva-Valdivia & López-Loera, 2011, Moreira and Ilha, 2011). Several studies recommend the use of geophysical methods in studies of the genesis and exploration of gold deposits (Doyle, 1986; Foster, 1993).

The articles of Allis (1990), Irvine and Smith (1990) and Locke *et al*. (1999 evaluate the changes of electrical properties in gold deposits resulting from hydrothermal alteration in epithermal systems, with an increase of the resistivity caused by intense silicification and an increase of chargeability by the disseminated sulfides.

Herein, discussed is the use of electrical geophysical methods (DC Resistivity and Induced Polarization) in assessing the continuity of gold lodes within the limits of an inactive mine, located in São Sepé city, Rio Grande do Sul State. The small thickness of the previously extracted layer, high structural complexity and strong deformation of structures, justify the implementation of detailed studies, facing the possibility of recognizing new potentially mineralized zones.

2. Location and geology of the study area

The study was performed in the surroundings of the Cerrito do Ouro mine, located in the São Sepé city, Rio Grande do Sul state, southern Brazil, distant about 270 km from Porto Alegre city, accessed by the BR 290 highway. The mineral resource in the region is represented by gold, coal, limestone and construction materials. Currently, the mining explorations consist in a limestone mine for the production of virgin lime and dolomitic lime for soil acidity correction.

The unit studied is denominated Sulriograndense Shield, represented by metamorphic, igneous and sedimentary rocks, with Archean and Proterozoic ages, compartmentalized into blocks and bordered by large regional faulting in NE-SW directions (Paim *et al*. 2000).

The Vacacaí Metamorphic Complex comprises an association of volcanic, volcanoclastic and sedimentary rocks, metamorphosed in the green schist grade, and phyllite, quartzite, marbles, hornblende schist and chlorite schist, along with magnesium sequences. This intrusive event is attributed to the Upper Proterozoic (CPRM, 2000).

The structural elements of regional expression reveal the complexity of the tectonic evolution during the geological history, with records of four phases of deformation. The first three phases have resulted in the generation of coaxial folds with axis oriented to NE/SW, where the first two events are expressed in a tangential movement and the third characterized by shear evidences. The final phase of deformation resulted in folds with axis oriented to NW/SE, produced by a strong reorientation in the system of tensions in the Sulriograndense Shield (CPRM, 1995).

Filonian gold mines are represented in the region by ores characterized by associations of quartz veins and lodes with gold and small amounts of iron oxides, pyrite and chalcopyrite. The veins present NE and NW directions and are preferably embedded in metasediments of Vacacaí Metamorphic Complex, subconcordant or discordant to the general structure.

The primary gold deposits in the region of studies are representative of the lode type, with disseminations of gold, sulfites (pyrite and chalcopyrite) and iron oxides, subconcordant or discordant with metassediments of Vacacaí Metamorphic Complex, beside secondary gold accumulations in colluvial/alluvial deposits.

The Cerrito do Ouro mine was active between 1986 and 1993, with an average production of 20Kg of gold per year and reserves estimated in 202,000T, for the medium tenor of 5.65g/T (CPRM, 1995).

The mine has been operated by surface extraction, with perforation and disassembling of the rock exposures, crushing, milling and launching in tanks for cyanide leaching. The solution enriched in gold was filtered in column for adsorption in active carbon, for retention of the metal. The mineralization occurs in a complex zone of quartz veins individually consisting of centimetric venules oriented in several directions. They feature white coloring and are milky hue with reddish along the fractures due to the occurrence of hydrated iron oxides. The gold occurs widely disseminated in the veins and lodes, in concentrations that reach 26ppm, visible only after the beneficiation and associated with pyrite and chalcopyrite (CPRM, 1995).

3. Materials and methods

Readings were performed through electrical resistivity and chargeability in time domain from three parallel lines of electrical tomography in dipole-dipole arrangement, with 5m spacing between electrodes and 10m between lines. The layout of the lines was based on prior structural review, planned to be orthogonal in the veins and lode quartz recognized in a disabled mine (Figure 1).

The geophysical data were acquired through a Terrameter LS resistivity meter, with 250W and 2.5A maximum, by means of the DC resistivity and polarization induced methods. The configuration parameters of the equipment were: 500mA, transmission time in 1s, beginning of readings after 0.2s cutting of current and reading residual voltage in 2 fixed windows and consecutive of 0.1s.

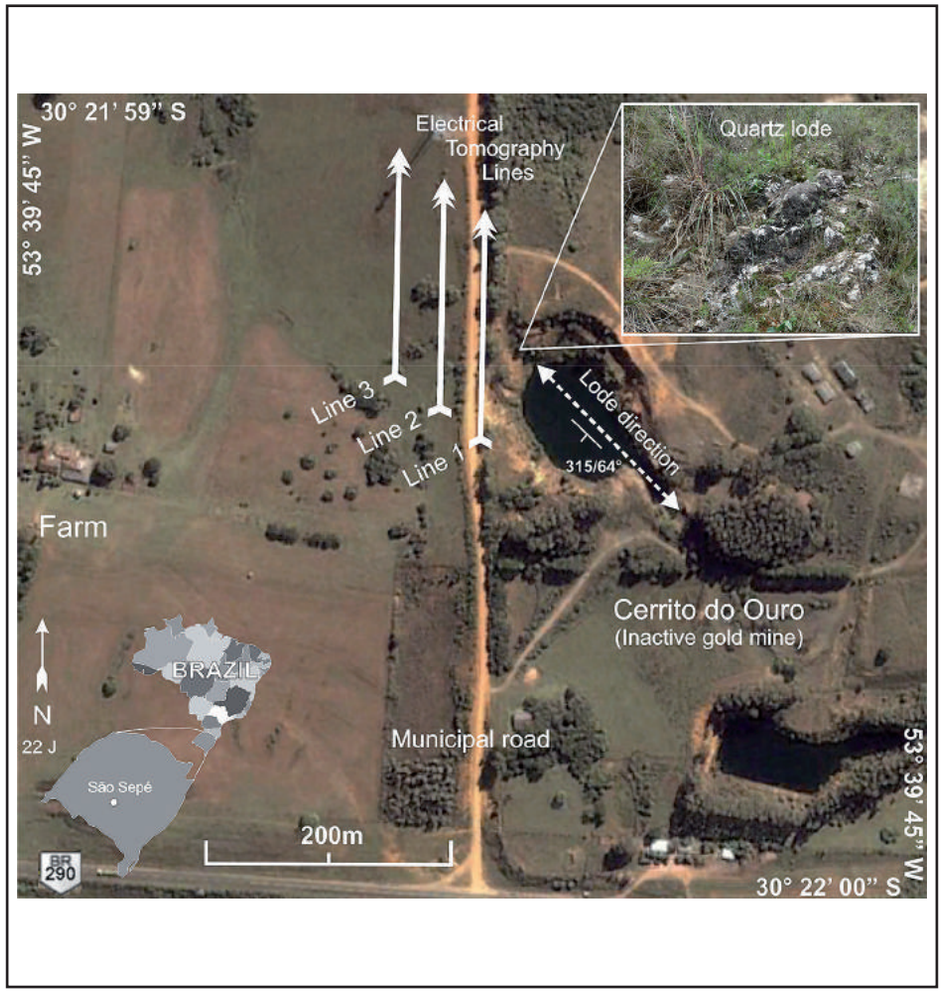

Figure 1
Electrical tomography lines, with orientation and detail of the gold lode.

The measurements acquired in the field were processed in the Res2d-inv program and resulted in sections of resistivity in terms of distance x depth, with a logarithmic graphic scale and interpolation intervals of values in colors. This is a program that automatically determines a two-dimensional model of subsurface, from resistivity or chargeability data acquired in electrical routing essays (Loke and Barker, 1996).

The numeric product of a two-dimensional inversion of data of each section was gathered in a single spreadsheet, which unites the position of the readings along the lines (variable "x"), spacing among lines (variable "y"), depth modeled by the inversion (variable "z") and the value of electrical resistivity (variable "R").

This spreadsheet was used for the generation of 3D viewing models, in a routine of basic steps adopted in mineral research. In this case, the sampling plan is frequently defined from statistic, structural criteria, spatial placement of a mineral accumulation, among others (Moon *et al,* 2006). A simple procedure consists in sampling by a set of perforations perpendicular to the main axis of the structure.

The resolution of the sampling mesh is conditioned to the spacing among the perforations, among lines of perforations and among the amount of samples collected in each perforation. Anyway, the analytical result of the samples is plotted and modeled in two-dimensional terms and later interpolated in 3D terms. Each point of the final 3D model is transformed in a block, with dimensions conditioned to statistical criteria and sampling mesh, to which a grade is attributed, based on chemical analysis and in an average value of density related to the rock that hosts the mineral. The relationship between content and volume enables the calculation of reserves and economic feasibility of the enterprise (Moon *et al*., 2006).

Thus, 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 in mineral exploration and environmental studies (Chen 2011; Moreira *et al*., 2016; Houlding, 2012).

4. Results

The data obtained during the geological recognition reveal that in position 100m of line 1, there occurs the intersection of the mineralized lode, in part previously consumed during the period of the mining activity, and composed of a quartz matrix, with disseminations of gold, pyrite and chalcopyrite, seated in mica schist. This association of geological elements allows setting a geophysics signature of high resistivity and high chargeability for the mineralized zone (Figure 2).

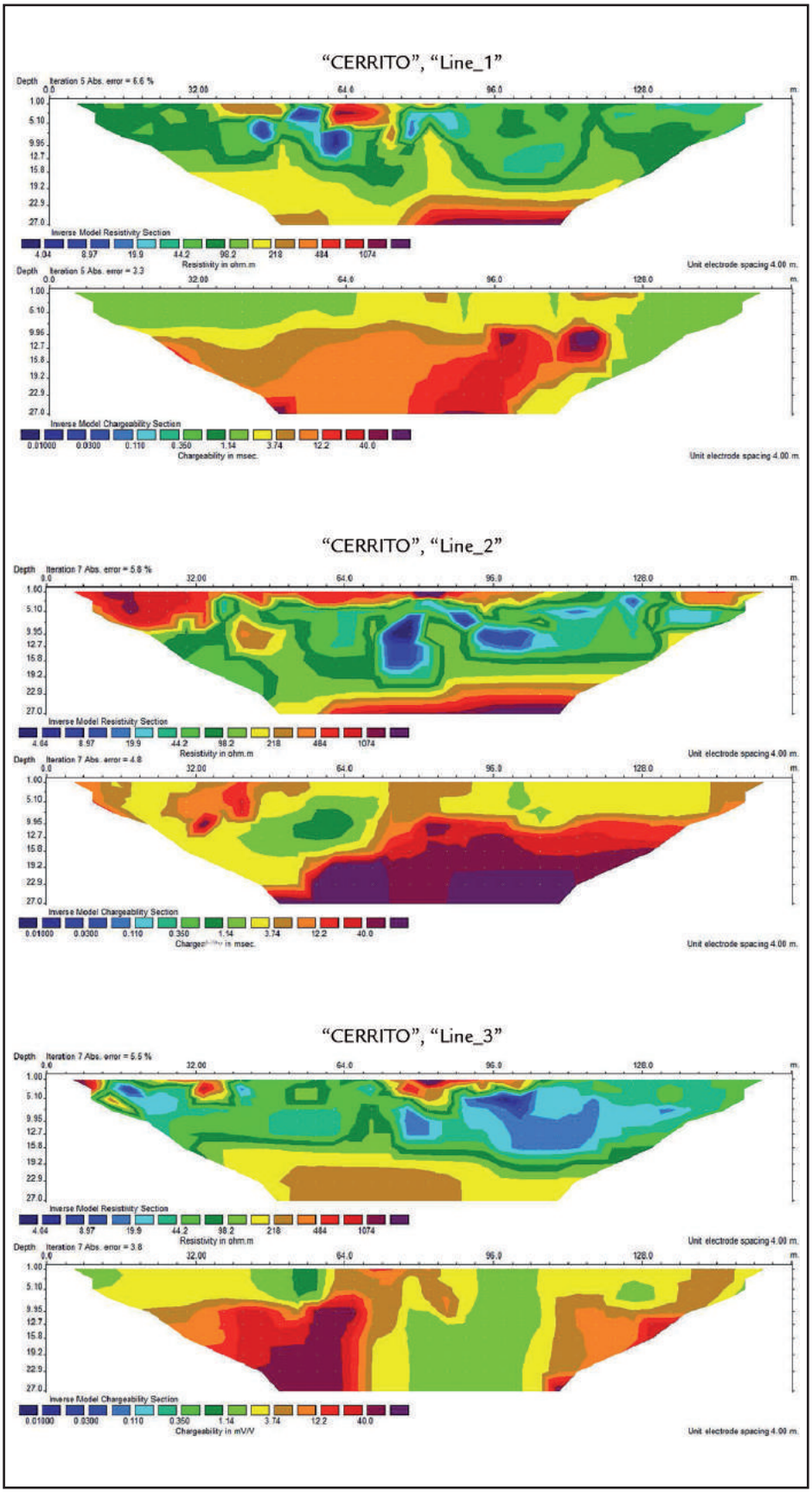

Figure 2
Inversion models
for resistivity and chargeability.

The interpolation of the inversion models positioned in a parallel way allowed the generation of maps of depth and the extrapolation side of parameters, in an attempt to subsidize the analysis of continuity of structurally controlled bodies. The signature of lode mineralized geophysics provided the modeling 3D in terms of isosurface (1000Ω.m and 30mV/V) for the physical parameters resulting from the process of inversion 2D (Figure 3). The lode mineralized presents continuity to outside the mine according to the direction NW by at least 20m further (range of coverage side of geophysical surveys).

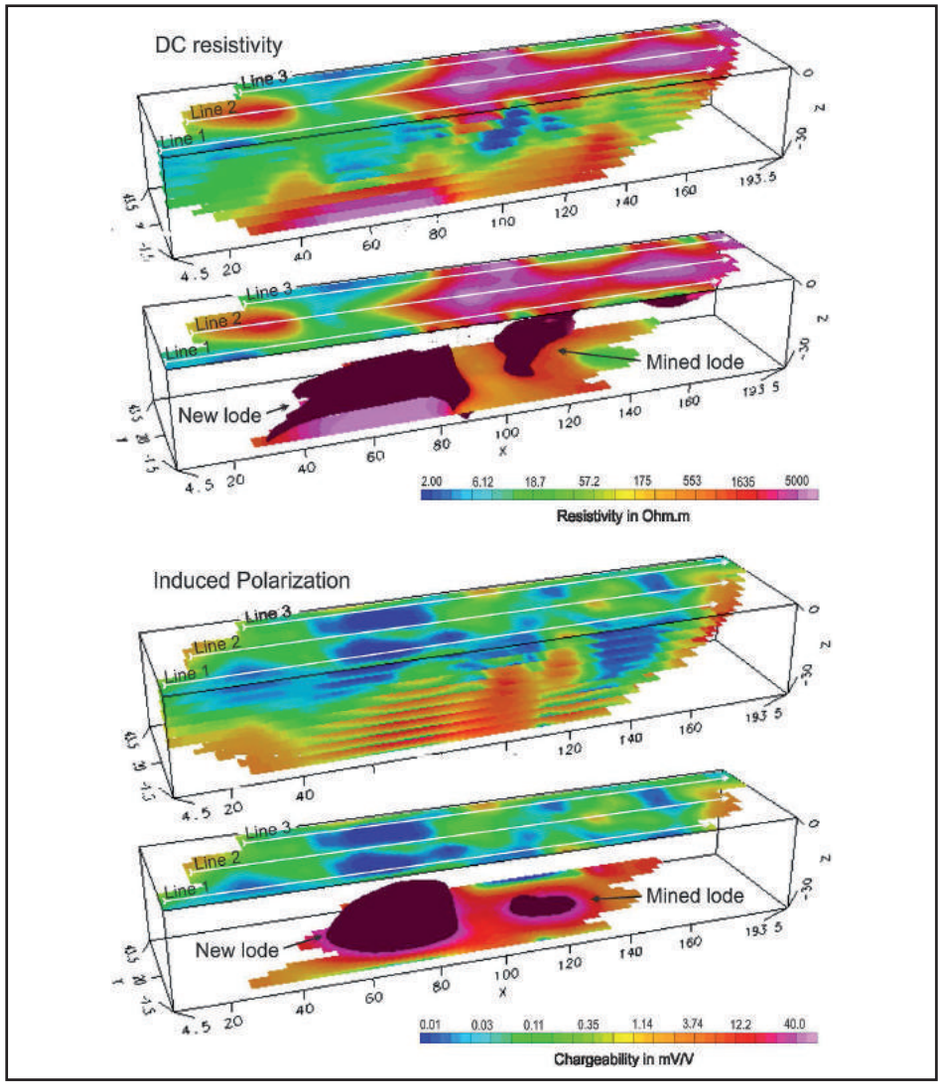

Figure 3
3D visualization models for electrical resistivity and chargeability in slices and isosurface of 2500Ω.m and 30mV/V.

The data also shows the existence of another body with similar signature and positioned with the center in 70m in line 1, with dimensions very much higher than the lode previously recognized. This second lode occurrence moved approximately 30m from the general orientation of extraction, holding the direction N315/65°. Later field checks did not reveal any evidence of a second lode in the exhibitions of mining.

The spatial disposition of lode bodies was due to deformational events prevailing in the geological past in the region of studies. The Vacacaí metamorphic complex is the product of a tectonic multiphase, with structures of deformations overlapping and recurrent, describing the occurrence of the four phases of regional deformation. In this scenario, the fourth phase was decisive in the establishment of systems of mineralization and the current morphological pattern of the deposits.

This last stage has provided a new compressive strain, orthogonal to the previous phases, which resulted in folds with a low angle dip by simple shear of second cleavage plans. With the end of the predominantly compressive strain, the region becomes subject to a distension strain, to which is attached an important plutonic event that must have been created, responsible for the ascension of São Sepé granite, intrusive alkaline affinity (CPRM, 1995).

Apparently there were metal leaching processes in the phase in synchrony with higher metamorphic degrees and deformation, with migration of fluids by hydrothermal processes, in the midst of the fracture system installed during the distensive regime (end of D4 phase). The completion of this system by hydrothermal fluids resulted in the generation of veins and lodes, sometimes disconnected and represented by a complex system of quartz veins, with wide dissemination of gold and sulfites.

This association of elements and the influence of structural architecture in morphology and composition of epithermal gold mineralization are described in studies developed in several other deposits (Richard and Atkinson 1986; Foster 1993).

5. Conclusion

The results enabled the establishment of a characteristic pattern in terms of physical properties for a quartz lode mineralized in gold, in addition to its continuity beyond the limits of the inactive mine, by the use of an electrical tomography technique and morphological analysis of the structures through inversion 2D and posterior 3D modeling of geophysics data. The analysis and interpretation of the results were based on regional geological evolution, structural

context and genesis of deposits.

Furthermore, it was possible to recognize a new quartz lode, based on the geophysics signature defined for the lode previously recognized. This second body will be comparatively greater, not on the surface, and localized around 30m to the south of the lode mining. Such signs indicate the possibility of incorporating new reserves, upon the setting of tenor through direct sampling and chemical analyzes.

The predominance of mineralization and deformation multiphase systems resulted in the generation of deposits of small expression, represented by lodes and disconnected networks of quartz veins, with presence of disseminated gold and sulfites. The opening of spaces and the subsequent filling by hydrothermal solutions occurred in conditions of distension, with generation of shear fractures.

This context indicates the predominance of epithermal deposits, intimately associated with the crests of folds, whose weathering action provided the wide dissemination of gold in the drainage network. The geochemical prospecting in their traditional technique sampling of sediment demonstrated great effectiveness for the discovery of several primary mineralizations.

Samplings of the core obtained by drilling or channeling in trench are also traditional techniques in the definition of tenor in mining activities. However, the widely disseminated mineralization limits the effectiveness of isolated and localized sampling procedures, with the possibility of absence of tenor on bodies that are highly demineralized or detection of their high levels of foreign impoverishment, which characterizes an event of random spatial variance, also called "nugget effect" (Chilés and Delfinr, 2012).

This scenario justifies the use of sampling procedures or multipoint research that are comprehensive and sensitive to the presence of sulfitic mineralization, such as Electrical geophysical methods. The geophysics signature of high resistivity and high chargeability in sulfite hydrothermal mineralization is attested in several studies on mineral exploration (Allis 1990; Irvine and Smith 1990; Locke *et al*., 1999; Moreira *et al*., 2011).

The proven potential in the recognition and detailing of mineral deposits, speed and versatility in the combined acquisition through DC resistivity and Induced Polarization by tomographic equipment, are incentives for the use of geophysics in planning and mining activities, for the setting of mineralized zones in mining fronts, or in work for the increase of reserves within the limits of deposits previously recognized, complemented by the sampling and quantification of tenor.

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