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Geoelectrical prospecting for a copper-sulfide mineralization in the Camaquã sedimentary basin, Southern Brazil

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Resumen

Este trabajo presenta los resultados de la aplicación del método de electroresistividad integrado con mapeo geológico de la superficie en un área potencialmente mineralizada con sulfuros de cobre, ubicada en el extremo norte de la cuenca sedimentaria del Camaquã, sudeste de Brasil. Esta mineralización se encuentra alojada en arenisca metamorfoseada, silicificada e intensamente fracturada, con abundante presencia de malaquita y azurita en los planos de fractura de la roca. El estudio geofísico consistió en 6 líneas de proyección de calicatas eléctricas en dispositivo Wenner-Schlumberger, con 520 m de largo y separación de 10 m entre electrodos dispuestos en una cuadrícula regular según criterio estructural previamente establecido. Los modelos de inversión muestran una región de baja resistividad en 60 m de profundad, que puede estar relacionada con una zona de sulfuros. Esta zona tiene forma aproximadamente circular, alargada en la dirección NW-SE y con 100 m de longitud. La zona de sulfuros se encuentra rodeada por zonas de alta resistividad relacionadas a zonas silicificadas. La evidencia de una zona arcillosa periférica al depósito es expresa por la abundante aparición de carbonato de cobre en la superficie, en conformidad con los minerales de arcilla y carbonatos que se originan a bajas temperaturas en etapas finales de cristalización en depósitos magmático-hidrotermales.

Palabras clave: cobre, sulfuros, mineralización, hidrotermal, resistividad eléctrica.

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Abstract

In this paper are presented the results of the combination between a resistivity method and geological surface mapping, applied to the study of an area with potential mineralization of copper sulfides sited on the northern edge of the Camaquã sedimentary basin, Brazilian southern. The copper mineralization is housted in a metamorphosed, silicified and fractured sandstone with abundant presence of malachite and azurite in the fractured planes of the rock. The geophysical survey in this work consisted of 6 lines of electric resistivity tomography in Wenner-Schlumberger array, of 520 m long and 10 m of space between the electrodes, arranged in a regular grid according to structural criteria previously established. The inversion models show a low resistivity area in a depth of 60 m that can be related to a sulphidation zone. This zone with a somewhat circular shape is aligned in the NW-SE direction and is approximately 100 meters long. High resistivity areas around it indicate that it is surrounded by a silicification zones. The evidence for an argillic zone peripheral to the deposit is expressed by the occurrence of abundant copper carbonate in surface, since clay and carbonates are formed from low temperature and final stages of hydrothermal crystallization of the deposit.

Key words: copper, sulfide, mineralization, hydrothermal, electrical resistivity.

Introduction

The great abundance and diversity of mineral resources in Brazil has given the country an economic history linked to the mining activity. The increasing demand for commodities, present in both national and international markets, gives the country the role of major exporter of minerals on the world scenario. In this context, the recognition and incorporation of new reserves contribute in a great way to the growth of the economy of the country, since the export of minerals has high relevance to the maintenance of the positive trade balance (MME, 2011).

The great importance of copper in the world's economy has been maintained for decades due to physical and chemical properties, which gives it a wide range of uses in industrial technological development (Chatterjee, 2007). Since the discovery of large deposits is rare, the advances in research technology have led to a revaluation of areas previously declared to be of low economic potential.

Mineral prospecting studies are important for the discovery, qualification and quantification of new deposits not only at the beginning, but also during the ore exploration in order to expand reserves and increase the life span of the project. Mineral deposits are non-continuous and rare in the geological record, and their discovery requires long term research and large investments.

The traditional procedures used in the discovery and characterization of new mineral deposits comprise rock and soil sampling, chemical analysis and direct tools such as drilling, besides indirect tools such as geophysical methods (Moon *et al*., 2006).

Most of the known deposits in Brazil were discovered by geochemical prospecting and geological surface mapping, as the action of weathering agents in tropical environments enables the release and dispersal of most of the chemical elements associated with economic mineral accumulations (Licht, 1998).

However, the discovery of high tonnage and low volume deposits is becoming increasingly scarce through these series of procedures, besides of the grown of more distant discoveries from urban centers, which increases costs or even impairs the mining of eventually discovered deposits. Current and future prospects in mineral research should consider deeper deposits, so not susceptible to weathering action processes where conventional geochemical prospecting is ineffective (Moon *et al*., 2006; Marjoribanks, 2010).

This scenario favors the increasing use of geophysical methods as a fundamental tool in any project of prospecting and mineral exploration acting as a guide to sampling and analytical quantification by geochemistry in soil, rock and water samples. The geophysics also gains emphasis for being a non-invasive method, applicable to a wide variety of scales showing the possibility of obtain geological information at great depths, regardless of rock exposures and description of drill cores (Lowrie, 2007; Dentith & Mudge, 2014).

The prospect of sulfides by electrical geophysical methods – such as electrical resistivity and induced polarization (IP) – are highly promising due to the electrical resistivity and chargeability contrasts where deposits with disseminated or filonian sulfides and oxides are characterized by low resistivity and high polarizability (Irvine & Smith, 1990; Allis, 1990; Bakkali, 2006; Locke *et al*., 1999; Moreira *et al*., 2012; Vieira *et al*., 2016).

The various mineral occurrences located in Camaquã Basin, southern Brazil, have great potential for mining purposes for prospection of basic metals, besides a metallogenic and structural context favorable in face of various copper and gold mines described at a regional level. In this context, this work has the aim to develop the geophysical study in detail of a copper occurrence on the northern edge of Camaquã Basin, where the Electrical Resistivity Tomography (ERT) technique was applied.

Area location and history

The area of study is located northwest of Caçapava do Sul city in Rio Grande do Sul (RS), 240 kilometers from Porto Alegre, the state capital. It can be reached through the BR-290 highway, and 1.5 kilometers after the intersection with BR-392 highway, through a dirt road which can be accessed from the Cerrito do Ouro village (Figure 1).

The region has a long history related to mining activity of copper and gold. The interest in the region was sparkled in the late nineteenth century, and it has been occupied ever since through the drive of mining. The presence of copper associated with gold and silver attracted several companies which built facilities aiming to explore these minerals at a viable cost over the last century (Ronchi & Lobato, 2000).

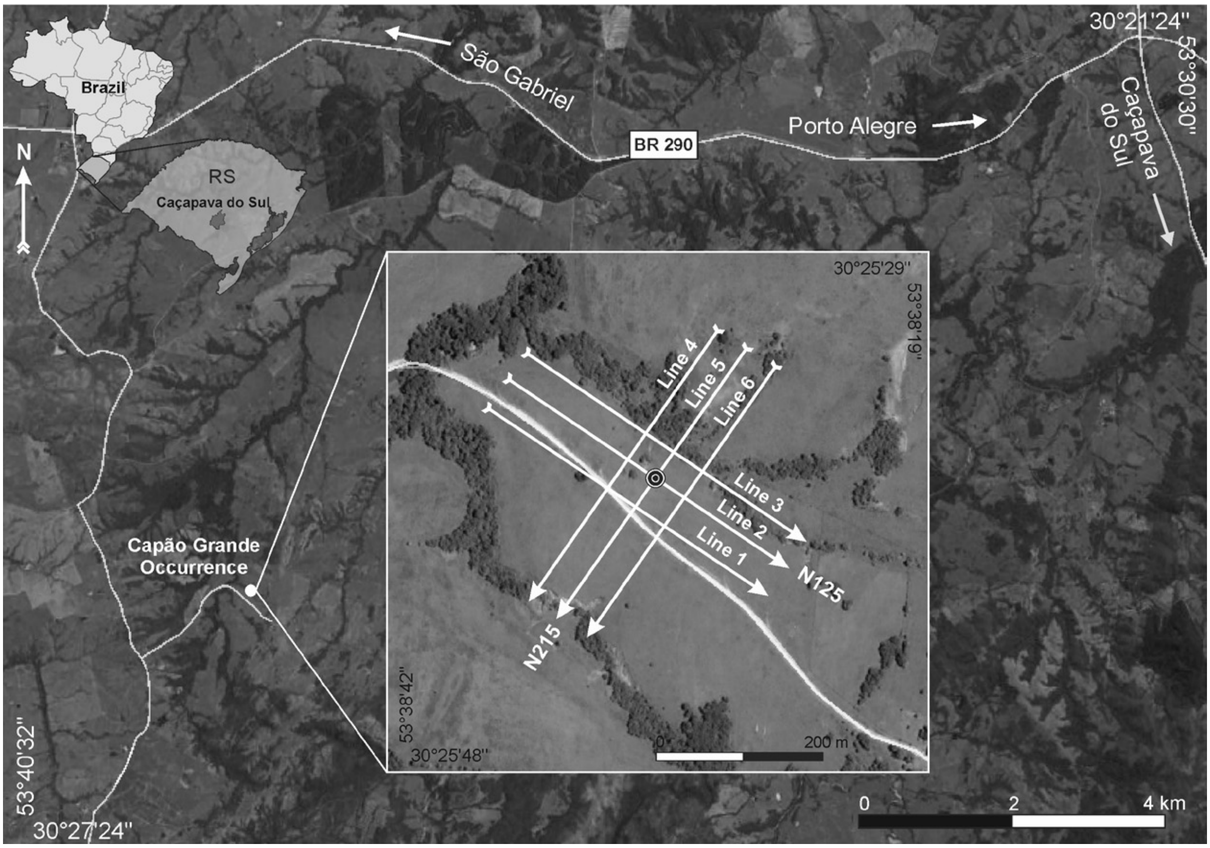

Figure 1. Location of the study area, with detail to the arrangement of lines of purchase.

After more than 100 years, mining activities were interrupted due to the low prices of metal commodities in the international market. The long term exploration also led to the exhaustion of the reserves around the year 1992. Currently, the mining activity in the city is restricted to limestone mining.

The study area consists in a cupriferous occurrence named Capão Grande, recognized by geochemical studies in stream sediments in research campaigns carried out by the National Department of Mineral Production (DNPM) in 1965. At first, the occurrence was considered by Bocchi (1970) as of no economic interest for mining due to small volume and ore content. However, the author highlighted the importance of conducting a detailed research in the region thanks to the favorable geological conditioning, porosity and fracturing.

Geology

The study area on the northern edge of the Camaquã Basin is seated on igneous and metamorphic terrains inside the Sul Riograndense Shield. The Camaquã Basin is a tectonic depression generated and developed during the final stages of evolution of the Dom Feliciano Belt, associated to a system of tardi- to post-orogenic basins related to the end spasms of Brasiliana/Pan-Africana Orogeny (Neto *et al*., 2004).

The Camaquã Basin has an elongated shape of N30E general direction, about 100 km long and up to 100 km wide (Neto *et al*., 2004) that can be understood as the record of the superposition of different types of basins, tectonically, geochronologically and thermodynamically individualized, with its own geological characteristics and distinct mechanisms of subsidence (Holz & De Ros, 2000). The Basin has been treated in terms of subsidence and filling pulses interrupted by deformation events, uplift and erosion, what generates a complex pattern of filling (Kazmierczak, 2006).

The type of filling of the Camaquã Basin was alternated between volcanic activity - represented by lavas and pyroclastic and epiclastic deposits - and siliciclastic deposition, which together with the tectonic, generated a filling where more deformed units are superimposed by less and less deformed units (Holz & De Ros, 2000). The record of sedimentary and igneous rocks present in the Basin comprise a time interval of 450-620 Ma and are devoid of significant features of regional metamorphism (Borba, 2006).

The study area is located near the contact with metamorphic basement, represented by volcanoclastic, epiclastic, and chemical rocks of the Campestre Sequence of the Vacacaí Metamorphic Complex. In the region there are also outcrops of rocks which belong to Maricá Group and the Acampamento Velho Formation, held in Cerro do Bugio Group (Figure 2).

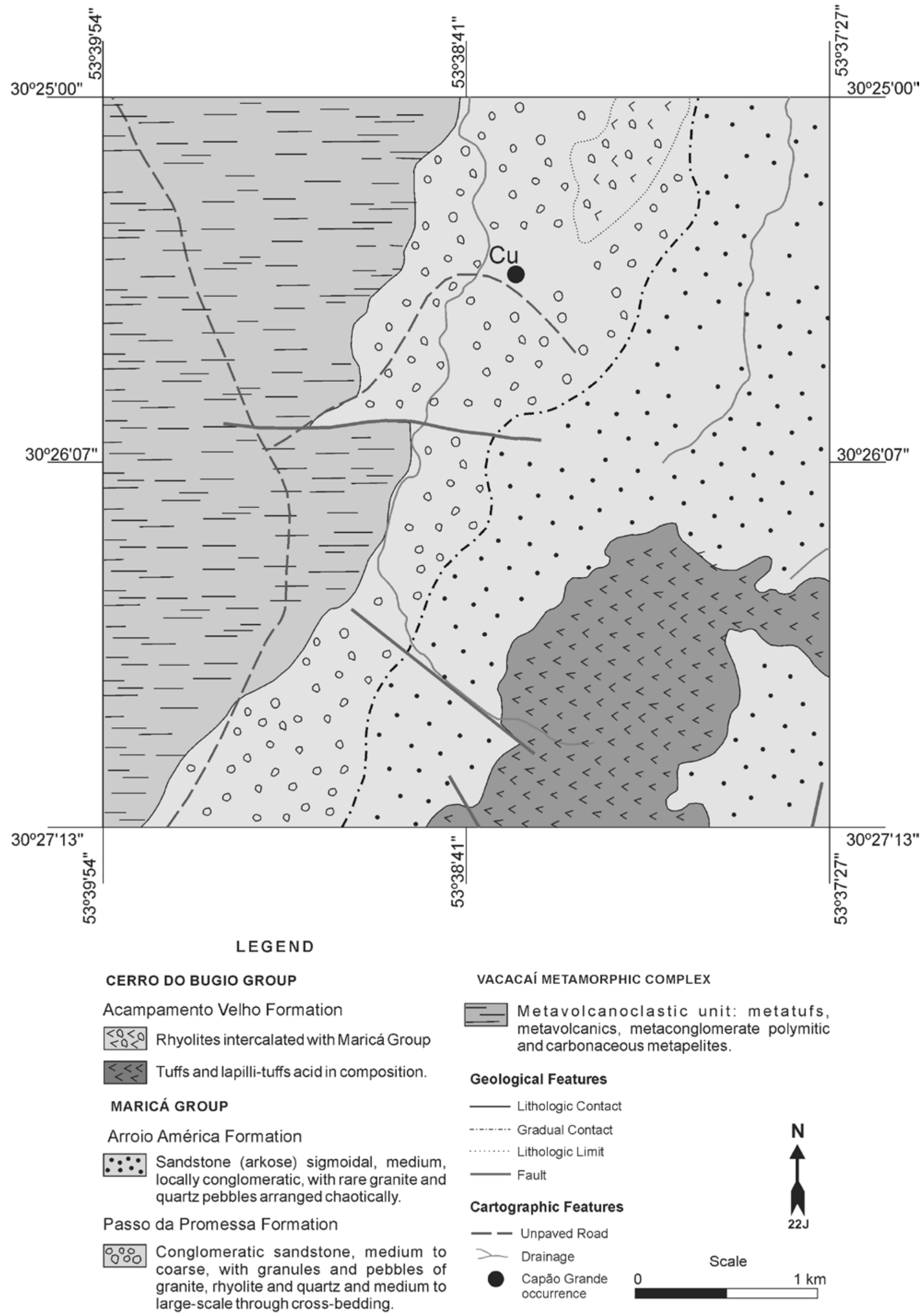

Figure 2. Geological map of the study area (Adapted from Porcher, 1995).

The Capão Grande copper occurrence is hosted in a lithotype included in the Passo da Promessa Formation, basal unit of Maricá Group. It occurs in a single outcrop in northeast direction in an extensive area of field, approximately 10 meters long by one to two thick.

The host rock is represented by intensely silicified metarenites, medium-grained, reddish-brown, apparently without preserved sedimentary structures and highly fractured. The indications of mineralization are expressed by the abundant presence of malachite and azurite, both supergene copper minerals that occurs in the interstices of the rock weakness planes (layering or fractures) or as disseminations in the pores of the rock.

Materials and methods

In this work, the DC resistivity method was employed by electrical resistivity tomography technique (ERT) in Wenner-Schlumberger array. The geophysical data was acquired through six lines with 520 m long and 10 m spacing between non-polarizable porous-pot electrodes that allow the percolation of $CuSO_4$ supersaturated solution in the ground. This configuration aims to reduce the contact resistance and nullify the parasitic currents generated by the use of metallic electrodes.

The Wenner-Schlumberger array is a hybrid arrangement that combines the Wenner and Schlumberger arrangements. It considers a set of electrodes with the same constant spacing, in contrast with the classical Schlumberger array used for vertical electrical soundings (Loke, 2000; Milson & Erikssen, 2011).

The lines were arranged in a regular grid, according to the structural criteria established in previous works which consider the crossing of major regional structures (Ilha, 2010; Silva, 2010). In this way, lines 1, 2 and 3 were distributed in the direction N125 and lines 4, 5 and 6 were arranged in the direction N215, all spaced 40 m from each other. The topographical data was acquired with a Differential Global Positioning System (DGPS) with Trimble software that allows the use of the Geographic Information System (SIG) existent.

The equipment used for the acquisition of resistivity measurements was the Terrameter LS, manufactured by ABEM Instrument (Sweden). This equipment consists of a single module for transmitting and receiving of automated signals from previous programming, with 250W, resolution of 1 μV and maximum current of 2.5 A (ABEM, 2012).

The field measurements were initially processed by the software Res2Dinv, where bidimensional resistivity models for the subsurface were generated from the smoothness-constraint least squares inversion considering the topography adjustment (Geotomo Software, 2003).

The implementation of the smoothness-constraint least squares inversion in the Res2Dinv software is based on the division of the subsurface into rectangular blocks, with the resistivity values adjusted to fit the field measurements (Degroot-Hedlin & Constable, 1990; Loke & Baker, 1996). This optimization focus on reducing the difference among the apparent resistivity values calculated and the ones measured in field, by the resistivity adjustment of the block models, which difference is expressed by the RMS (Root Mean Square) error and, simultaneously, aims to minimize the model roughness (smoothness constraint) (Loke & Baker, 1996). In this work, the robust constraint algorithm was used in the data processing.

The numeric product of bidimensional inversion of the data from each section was used to generate 3D visualization models in the Oasis Montaj platform, where the 2D data obtained in Res2Dinv program were modeled from the minimum curvature algorithm for smoothing the core values in relation with the limits of the investigated area. The range of 8 Ω.m and 300 Ω.m values were modeled as a 3D surface in an attempt to evaluate the shapes of the low and high resistivity zones, respectively.

This process is part of a routine of basic steps adopted in mineral research. In this case, the sampling plan is frequently defined from statistical, structural, spatial placement criteria, among others (Moon *et al*., 2006). A simple procedure is sampling by a set of holes perpendicular to the main axis of the structure, followed by a parallel set of hollowing lines.

The resolution of the sampling net is conditioned to the space between holes, their lines and among quantities of samples collected by holes. Nevertheless, the analytical result of the samples is sampled and modeled in bidimensional terms and later interpolated in tri-dimensional terms. Each point of the final 3D model is transformed in a block with dimensions conditioned to statistical criteria and sampling net, to which content based in chemical analysis and a mean value of density related to the rock that hosts the mineral is attributed. The relationship between content and volume enables the calculation of reserves and the economic feasibility of the enterprise (Moon *et al*., 2006).

Geophysical 3D visualization models derived from 2D sections provide a very wide comprehension on the complexity of geological structures and models of mineral deposits (Kemp, 2000; Zanchi *et al*., 2009; Aizebeokhai *et al*., 2011; Akiska *et al*., 2012).

Results and discussion

The sections are presented in terms of distance *versus* depth, with a logarithmic color scale. The processed resistivity data show a range of variation with values between 6 Ω.m and 590 Ω.m, where warm colors represent high resistivity values and cold colors represent low resistivity values. In general, the sections exhibit a predominance of high values in the shallow and intermediate portions, and low values at higher depths (Figure 3).

Over-all, all resistivity inversion models present, with high or low presence, a high-resistivity zone in the center of the section between 170 m to 380 m along the line. This range of high values outlines most of the horizontally elongated elliptical zones sections with values above 305 Ω.m. Another feature well seen in all sections is the change from high to low resistivity values around 30 m depth. The lower values culminate in a significant area with values below 20 Ω.m located in the center of the sections and below 50 m depth. The maximum depth of the inverted models was 80 m, but apparently the low resistivity zone exceeds it.

Besides the central zone with high resistivity values, there are others with minor proportion which are present in all sections reaching values greater than 590 Ω.m. Around 160 m along the line, it is observed a small resistive zone at about 70 m deep, which culminates with a significant vertical zone with resistivity values above 305 Ω.m in section 5. Another highly resistive zone represented in all sections is located between the distances 430 m to 490 m with resistivity values greater than 590 Ω.m. These zones are distributed in the vicinity of the low resistivity zone located 60 m deep.

Next to the surface and center sections (more precisely where the outcropping mineral occurrence is located), there is a predominance of intervals with average resistivity ranges that reach values up to 305 Ω.m. It is important to note that the mineral occurrence is described in highly silicified meta-sandstones, different from the other outcrops described in the region where the rock presents certain crispness and preserved primary structures, as such as cross-bedding.

Therefore, the analysis of the resistivity inversion models enables the recognition of two main zones: resistive zones, characterized by values greater than 300 Ω.m and a conductive zone (or low resistivity), characterized by values below 20 Ω.m located in depth in the center of the sections.

The cementation of the host rock by quartz and carbonates observed in the surface results in a decrease of porosity which leads to higher resistivity values. Therefore, areas with moderate to high resistivity are probably an indicative of silicification to be found on the top and side portions of the low resistivity region (Figure 4).

The top resistive zone - or area above the sulfide zone - is represented by intense silicified rock outcrop, cut by subvertical veins of copper carbonate. Although absent in surface, it is likely to find sulphidation in disseminated or venular forms in higher abundance as the depth increases.

The area with low resistivity values on the other hand points to the occurrence of highly conductive materials. Electronic conduction in metallic minerals (free movement of electrons) reduces the resistivity of metal-bearing rocks. Particularly at high ore concentrations the bulk resistivity decreases significantly. This feature confirms the existence of a zone enriched in metal ore minerals, probably represented by copper sulfide minerals, as such as chalcopyrite, calcosite and bornite (Figure 4).

Accordingly, the conductive area present at 60 meters deep represents a possible area of sulphidation with elongated form in the NW-SE direction, surrounded by the silicification zones.

The copper carbonates observed on mineral outcrop are indicative of an occurrence related to final stages of crystallization generally present in the peripheral portions of the mineral deposit. For this reason, their content gradually decreases at greater depths. Metal sulfides, in turn, tend to have higher levels towards the sulphidation zone.

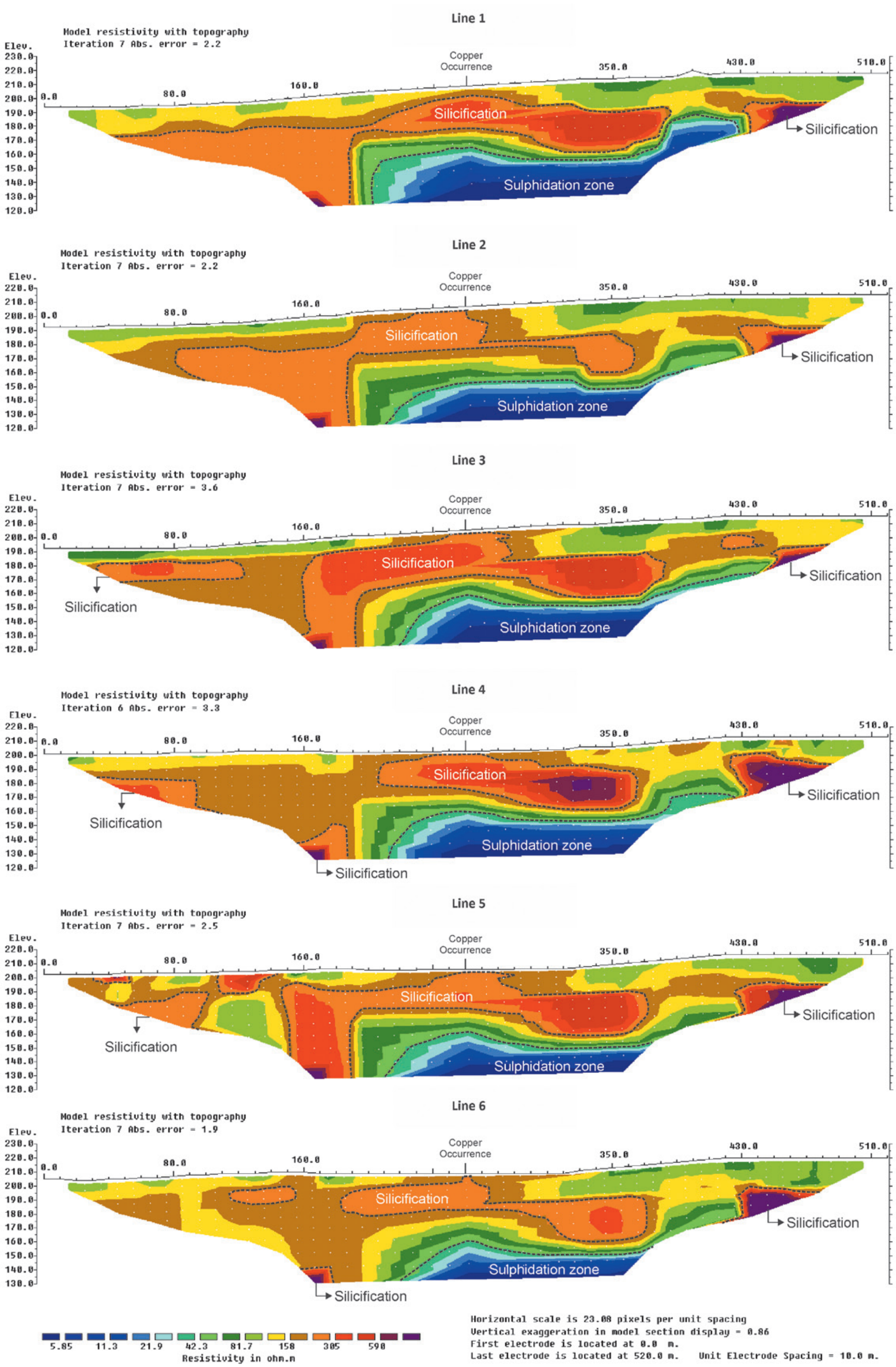

Figure 3. Inversion models for resistivity.

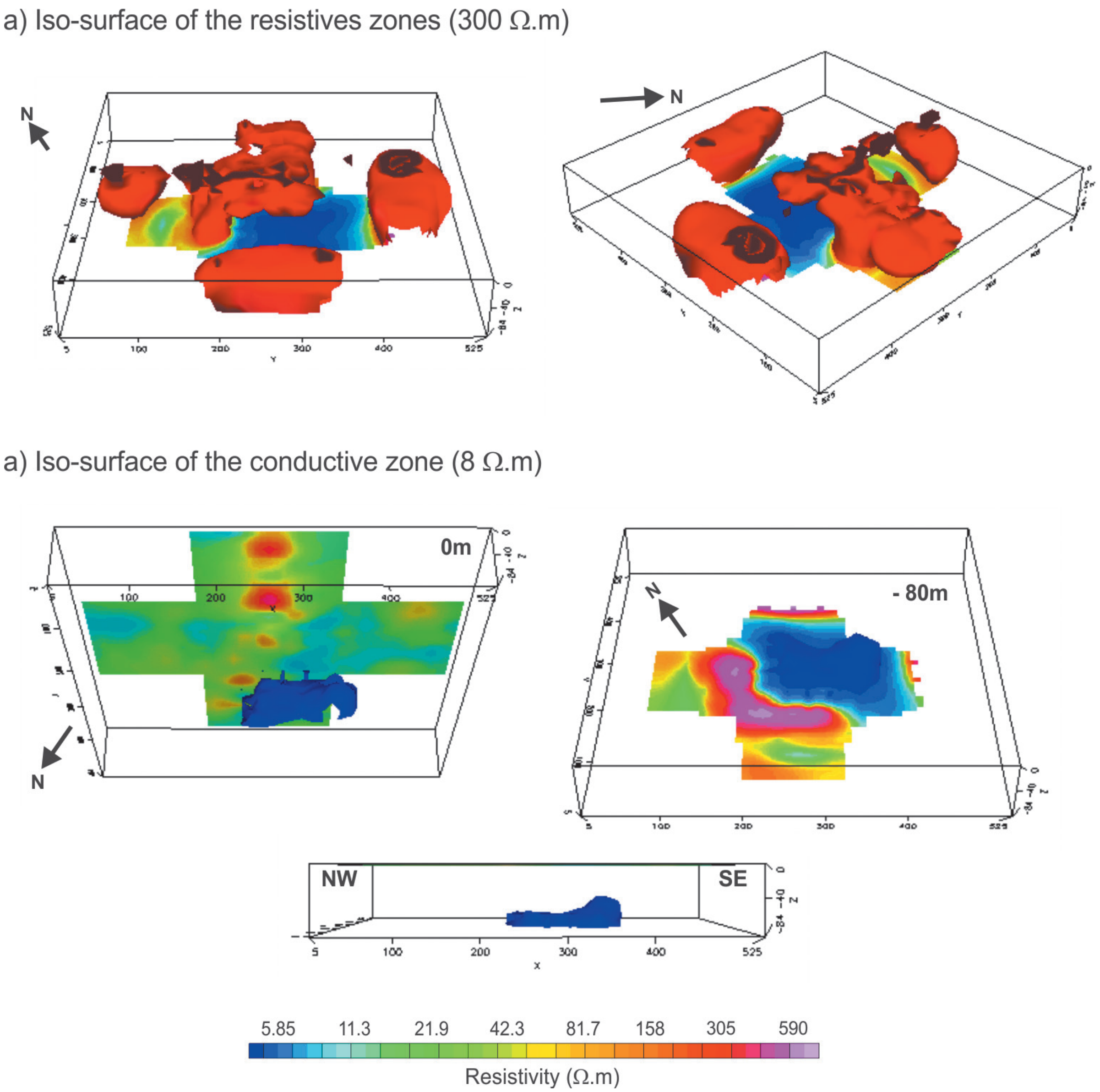

Figure 4. a) 3D visualization models with design of high resistivity zones (silicification, in red) and b) low resistivity zones (probable mineralization, in blue).

Conclusions

The results obtained by the resistivity method, combined with geological data and field recognition, were satisfactory to characterize the cupriferous occurrence and in delineation of a promising target for direct prospecting campaigns through drilling surveys.

Based on the field recognition, it was possible to identify evidences of mineralization represented by copper carbonates (malachite and azurite), which occurs in form of silicified and impregnations in fractured metarenite. Such elements are associated with peripheral portions of hydrothermal sulfide deposits and therefore indicators of possible presence of sulfides in depth.

The combined analysis between 2D and 3D resistivity models allowed the recognition of a possible mineralized body in depth and zones of marginal silicification, characterized by low and high resistivity values, respectively.

The sulphidation zone, possibly with the highest levels of ore in the area, is characterized by an elongate body of approximately 100 m in the NW-SE direction. It was not possible to establish the maximum depth of the mineralized body, as apparently there is continuity below 80 m (maximum depth of the inverted models). Therefore, the limited investigation depth only allowed the detection of the upper limit of the sulphidation zone. Besides that, the limits of this zone to the south were not mapped due to the limited coverage of the survey.

The silicification zones are surrounding the main ore body and are characterized by the predominance of silica, which occurs as cement of pores of the adjacent rock. Present from shallower portions to greater depths, this area may be subdivided into two major zones: top silicification zone (or above sulfide zone) described in mineral outcropping occurrence, and lateral silicification zones.

Evidence of an argillic peripheral zone of the deposit are expressed by abundant occurrence of copper carbonates on the surface. Clay and carbonates are formed in low temperatures in the final stages of crystallization from hydrothermal deposits. The absence of a significant argillic zone may be an indicative of the low content of clay minerals in the metarenite.

A second phase of the geoelectrical study could focus on the acquisition of longer lines for increased depth investigation and greater coverage of the southern part, as means to improve the estimation of the total ore body volume.

The features recognized in the field, along with the identified architectural elements of the deposit with the aid of geophysics, corroborate with the hydrothermal-magmatic model, especially for types such as copper-porphyry and low-sulphidation epithermal, previously described in other mineralization of Cu (Au) distributed throughout Camaquã Basin. However, for better interpretations regarding the storage model, further studies are required on surface geochemistry and also direct analysis by means of drilling and sampling.

Acknowledgments

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