Carlos A. F. Pires; João E.S. Pereira; Luis E. S. Robaina , LAGEOLAM-UFSM, Santa Maria, RS, Brazil.
Adelir José Srieder , MODELAGE-UFRGS, Porto Alegre – RS – Brazil.

This paper was prepared for presentation at the 8th Congress of The Brazilian Geophisical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

ABSTRACT

The modeling and correlation analysis of geophysical and geochemical data to evaluate the 3D distribution and control of ore grades are not usual procedures in mineral exploration of Au and basic metals. This paper aims to show the results of such modeling and correlation analysis. The method was developed for Volta Grande Prospect (Lavras do Sul, RS, Brazil). Volta Grande Prospect is composed by a series of Au-sulphide-quartz lode veins structurally controlled by radial fractures developed during Lavras do Sul Intrusive Complex. The lode veins show varying degrees of lateral hydrothermal alteration, and also display telescoping mesothermal to epithermal mineral assemblages. The lode veins are emplaced in intrusive granites and also in volcanic and volcano-sedimentary rocks of Hilário Formation. The geostatistical analysis showed the superposition of hydrothermally altered structures in some areas, while 3D kriging modeling revealed the geometry, and also the lithological and structural control of the conductive bodies. The correlation analysis between geophysical and geochemical data revealed the telescoping of different mineralization pulses, each one with different metallic load. The correlation analysis results are in accordance with hydrothermal alteration superposition as seen in field investigations. Therefore, the use of geophysical methods for grade control in sulphide-rich quartz-lode veins is a concrete possibility, since one have an adequate spatial resolution of geophysical surveys.

Key-words: mineral exploration, geophysical and geochemical modeling, ore control, geostatistical modeling.

INTRODUCTION

The indirect geophysical methods in mineral exploration are usually applied to indicate continuity and spatial position of ore bodies. The use of indirect geophysical methods to approach the spatial distribution of element grade takes into account radioactive elements: a) in regional surveys (Maurice & Charboneau, 1987); b) mine scale exploration (Heisings & Zamara Reyes, 1996; Okujeni & Funtua, 1994); c) mineral processing plants (Ashry *et al*., 1995; Leduc *et al*., 1987), or d) in some industrial conditions (Ni-El, 1997; Kalsi et al., 1995). The application of the others indirect geophysical methods for mineral exploration has being limited. Oldenburg *et al*. (1997) evaluated, modeled and combined inversion of geophysical dada (IP, EM, and Magnetometry) with geological data, aiming the ore distribution in Au-Cu porphyry in Mt. Milligan (EUA). Oldenburg *et al*. (1997) were able to distinguish anomaly zones, geometry and spatial continuity of ore bodies.

This paper aims to evaluate and to define a methodology to model, correlate and analyze geophysical and geochemical data that control Au and basic metals grades in Volta Grande Prospect (Lavras do Sul, RS, Brazil), an epithermal Au-Cu vein type ore deposit related to Lavras do Sul Intrusive Complex (Gastal, 1997).

GEOLOGICAL SETTING OF THE VOLTA GRANDE PROSPECT

The Lavras do Sul Intrusive Complex (**LSIC**) (Jost & Wilvock, 1966; Gastal, 1997) is located in the western part Sul-riograndense Shield (Figure 1). The **LSIC** is intruded into granite-gneisses of Cambaí Complex, and into volcanic and volcano-sedimentary rocks of Maricá and Hilário Formation. Some authors have discussed the characterization of **LISC** (e.g. Nardi, 1984; Gastal 1997). These works allow to discriminate three magmatic pulses: a) a Shoshonitic pulse, responsible to monzonitic and monzodioritic terms (northeast and eastern border) and granodioritic and monzogranitic terms (nucleus of **LSIC**); b) an Alkaline pulse, responsible to monzogranitic, sienogranitic and pertite granites terms; and c) a lamprophyric pulse, responsible to basic alkaline magmas (kersanstites, lamprofires, minetes) at final stages.

The Lavras do Sul region have a number of Au-Cu quartz lode veins. These lode veins are related to hydrothermal alteration zone controlled by regional and radial fractures developed during resurgent dome of the **LSIC** (Strieder, 2001), mainly by WNW-ESSE ones. The main lode veins in Lavras do Sul region are located both on the Hilário Formation volcano-sedimentary rocks (Merita, Cerro Rico, and Saraiva), and also on **LSIC** (Cerrito do Pires, Cerrito do Rezende, Aurora, Valdo Teixeira, Santo Expedito, Butiá Block, Zeca de Souza, Taruman, Pitangueira, São José, Dourado, and Paredão), as shown in figure 2. The Volta Grande Prospect shows a large number of such lode veins, emplaced in intrusive granites (**LSIC**) and also in volcanic and volcano-sedimentary rocks of Hilário Formation.

The **LSIC** intrusion was the heat source inducing and maintaining the hydrothermal system (Mexias, 1990; Mexias *et al*., 1990a). The degree of contact metamorphism changes from higher amphibolite, close to **LSIC** contact, to green schist 500 m apart (Mexias, 1990; Mexias *et al*., 1990a). Mexias (1990) and Mexias *et al*. (1990a) Characterize tree main phases of hydrothermal alteration in Volta Grande area: i) potassic alteration; ii) propilitic alteration; iii) phyllic alteration. Strieder *et al*. (2001), on the other hand, defined two types of hydrothermal alteration zone assemblages: i) Aurora type and ii) Valdo Teixeira type. These two types of hydrothermal zone assemblages produces distinctive geophysical (gamaespectrometry and magnetometry) signature (Strieder *et al.*, 2001).

Gavronski (1964) divided Volta Grande Prospect into 7 areas: 1, 2-South, 2-North, 4, 5, 5A, and Merita (Figure 3). The limits between these areas are not well-defined, but they are take the most mineralized fracture system. The Volta Grande Prospect is characterized a series of vertical fractures that play an important role in 3D control of ore bodies. These fracture zones show brittle features that enabled mineralization and compositional zoning of ore body (Strieder *et al.*, 2001).

METHODOLOGY

Three types of data were available for modeling Volta Grande Prospect mineralized areas: i) geophysical data (**CSAMT** - ***Controlled Source Audio-frequency Magneto-telluric***); ii) geochemical data (Au and Cu grades from some drillholes), and iii) geological data (geometry of hydrothermalized fracture zones and geological map). The CSAMT data were obtained by Zonge Ltd. (Zonge, 1995). Au and Cu grades are from a number of drillhole surveys during 1959-1962 (**DNPM**), 1974-1978 (CPRM), and 1984 (**CRM**). The geological map and fracture zones geometry are from Strieder (2001). The data integration method might incorporate 3D analysis of a large number of data and, as long as possible, use logical mathematical algorithms for such a ore body.

MODELING OF CONDUCTIVE BODIES

A first experimental evaluation of **CSAMT** data showed that Au and Cu grades (drillhole data) correlate to apparent resistivity lower than 600 Ωm. Such a result is to be expected, since the hydrothermal zone are sulphide rich. Then, in order to consider 3D geometry of the mineralized ore zone, **CSAMT** data was classified into 6 intervals: i) ≤ 600 Ωm; ii) 600-800 Ωm; iii) 800-1200 Ωm; iv) 1200-1600 Ωm; v) 1600 – 2000 Ωm; and vi) 2000 – 2400 Ωm. Contour interval map showed vertically conductive structures (Pires, 2002) for areas 1, 2, and 4 of Volta Grande Prospect.

The type of variographic model is denominated "nested models", since it can be seen as a combinations of simple models. This feature is related to different scales of data variability. In these cases, a different scale of data variability means two or more mineralized structures that are associated in different depths. The modeled **CSAMT** data can be compared with original data for cross-validation. The frequency histograms of estimation error for the areas 1, 2 and 4 present a Gaussian distribution; the mean and standard deviation of estimation error is very low The mean is 4,13Ωm in area 1; 13,4Ωm in area 2 and 11,4Ωm. The standard deviation is 335,4Ωm in area 1,343,4 in area 2 and 184,4Ωm in area 4. The correlation coefficients (true-estimate value) are high (0,86 in area 1, 0,84 in area 2 and 0,86 in area 4). All these parameters indicate that geostatistically modeled **CSAMT** data are accurate, and then estimated values can be used for further analysis.

The wireframes of modeled apparent resistivity are related to **NW-SE** structures (in area 1 and 2) and related to **SSW-NNE** structures (in area 4). In sub-surface, these wireframes come with vertical structures formed by enlargement or juxtaposition of NW (area 1 and 2) and NE (in area 4) structures as identified on the surface. These conductive bodies show correlation with the Au and Cu grades available in exploration surveys undertaken by CRM. The geometry and 3D continuity of the mineralized bodies can be seen in figures 2a, 2b and 2c.

CORRELATION ANALYSIS

Two variables, measured in the same 3D space with or without concurrent punctual sampling, can show some degree of similarity in data variability. This similarity can be recovered by correlation analysis between two variables, which is performed by a number of ways (Campos Velho & Ramos, 1997; Retamoso et al., 2002). The correlation between two variables (ρ*g*) is a numeric measurement, without dimension, to establish the relation between two aleatory variables. In the case of Volta Grande Prospect, the variables "ρ" (apparent resistivity) and "*g*" (Au grade) are random and display log-normal distributions. The linear regression between a dependent variable (*g*) and a independent (ρ) one is a relation obtained from their values. The linear coefficient of correlation "r" provides a measurement of relations between "ρ" and "*g*" (Table 1). This work search for the correlation between apparent resistivity (independent variable) and Au and Cu grades (dependent variables). The geophysical data (**CSAMT** apparent resistivity) is more abundant than geochemical data (Au and Cu grades). The theoretical base to correlation between Au and Cu contents (geochemical variable) and of apparent resistivity data (geophysical variable) is due to geological process of mineralization of Volta Grande Prospect (Lavras do Sul, RS). The Au and Cu occurrences in **LSIC** is linked to sulphide minerals in structurally controlled hydrothermal alteration zones (Mexias, 1990; Mexias *et al.*, 1990a; Mexias *et al.*, 1990b; Strieder *et al.*, 2001a). This conditions guarantee a significant contrast of resistivity between hydrothermalized zones and country rocks, even in sulphide-disseminated zones. Then, one can recognize a cause-and-effect relation (the grater conductivity, greater sulphide content) in the Volta Grande Prospect.

The correlation analysis depends on the building a data bank where variables display the same spatial coordinate. It is to be remembered that geochemical and geophysical data have also different sampling support. Finally, the geochemical data are restricted to the upper few meters, while geophysical data reach far deep in sampling bulk resisitivity. Then, a group of procedures was established to built such a data bank (Pires, 2002): i) determination of coordinates (xyz) and value of apparent resistivity for the small blocks center (geostatistical modeling); ii) calculations of geometric center coordinates (xyz) for each dipping borehole sample containing Au and Cu grades; iii) calculation of average Au and Cu grades for blocks of similar size and coordinate as that for geophysical data. The resulting data bank has a small number of sampling blocks for correlation analysis.

The Au or Cu grades (dependent) is correlated with apparent resistivity (independent variable) through linear regression lines (Table 1). The values for regression line adjustment and correlation coefficient are given for each linear regression line. The linear regression lines (Table 1) suggest the existence of two data group, since two regression lines can be proposed for a bettrer adjustment. This feature is better visualized in areas 1 and 4, specially for Au grade vs. apparent resistivity. Area 2 shows a dispersion of data, and just a single regression line can be calculated.

The most important feature of the correlation analysis is clearly the existence of two data set for the same variables, even under very different sampling support. This feature can also be poorly observed in frequency histograms mainly for Au and Cu grades, as a tendency for multy-modality. These different data sets under correlation in the areas 1 and 4 of the Volta Grande Prospect suggest different processes (causes) in the same sampling space. Different Au and Cu grades distinguish these two data set for the same interval of apparent resistivity values. It can be proposed the presence of superposed mineralization phenomena or processes, but each one distinctively charged in its metallic load (Au and Cu). Two Au and Cu grades for the same apparent resistivity value (independent variable) suggest that the conductivity increase in the hydrothermal alteration zones is not related with the metallic load, but with changes in the electric properties of the hydrothermally altered rocks.

The presence of two regression lines for apparent resistivity and Au and Cu grades in the areas 1, 2 and 4 of Volta Grande Prospect highlights the occurrence of at least two hydrothermal pulses. The overlap of hydrothermal pulses with different physico-chemical characteristics in the same geological structure (fracture zones, for example) is a common mineralization mechanism. This mechanism is usually known as telescoping (Guilbert & Park, 1996; Augustithis, 1995; Jensen & Alan, 1881).

The Au and Cu occurrences in the **LSIC** are structurally controlled Au-quartz lodes, related to expressive hydrothermal alteration zones. Strieder *et al*. (2001) identified at least two different types of hydrothermal alteration zones in **LSIC**: i) Aurora-type hydrothermal zone; and ii) Valdo Teixeira type hydrothermal zone. The Aurora type hydrothermal zone represents a mesothermal pulse, whose main minerals are amphibole, calcite, quartz, chalcedony, pyrite, calcopyrite, magnetite, galena, and rare esphalerite. The Valdo Teixeira type hydrothermal zone represents a lower temperature pulse (epithermal), and shows mineral assemblage such as sericite, epidote, quartz, pyrite, and rare galena and calcopyrite. The hydrothermal alteration assemblage in area 2 of Volta Grande Prospect is Aurora type (Strieder *et al.*, 2001); superposition of Valdo Teixeira type hydrothermal assemblage in area 2 is very limited. On the other hand, in areas 1 and 4, there is an overlap of the two types, as can be deduced from Mexias (1990). This feature can explain the correlation results discussed above.

FINAL DISCUSSIONS AND CONCLUSIONS

The modeling and integrated analysis of geophysical and geochemical data for mineral exploration purposes should be focused in cause-and-effect relation in order to take improved results. This seems to be the case for areas 1, 2, and 4 of Volta Grande Prospect (Lavras do Sul, RS, Brazil). A number of statistical and geostatistical procedures were applied before correlation analysis of geophysical and geochemical data, in order to distinguish between geophysical effects.

The 3D modeled apparent resistivity enabled to define the geometry, and the dimensions of the conductive structures. The 3D modeled conductive bodies in areas 1, 2, and 4 are lithological and structurally controlled. In any case, they main control is fracture zones, oriented NW-SE in areas 1 and 2, and NNE-SSW in area 4. The fracture zones were, then, open chanells for different episodes of hydrothermal solution flow.

The correlation analysis between Au and Cu grades, and apparent resistivity in areas 1, 2, and 4 of Volta Grande Prospect showed they are negatively correlated, and there exists two data set in correlation. The negative correlation can be expected from cause-and-effect relation, since the hydrothermal mineral assemblages have varying degree of sulphidation. In this way, greater the hydrothermal alteration and sulphidation, greater the conductivity of the altered zones. The presence of two groups of geophysical and geochemical data as seen in correlation diagrams suggests the superposition or telescoping of hydrothermal pulses. This feature was particularly evident in areas 1 and 4, where field surveys corroborate the superposition of different hydrothermal pulses by identification of distinctive mineral paragenesis (Mexias, 1990; Strieder *et al.*, 2001). It is to be remembered that areas 1 and 4 show evidence of more vigorous superposition of hydrothermal pulses than area 2.

The modeling and the correlation analysis of geophysical and geochemical data in Volta Grande Prospect (Lavras do Sul, RS, Brazil) suggest that further mineral exploration surveys can be projected. However, these mineral exploration surveys face some problems. At first, it should be noticed that **CSAMT** device is designed for deep investigation, and its spatial resolution is small compared with mineralized structures. The hydrothermalized fracture zones show thickness commonly < 15 m (Strieder, 2001); at the same time, the mineralized structures are laterally repeated in intervals < 30 m (Strieder, 2001). These features indicate that geophysical tools should be able to discriminate such structures. It os believed that Spectral IP (**SIP**) can provide important help in defining the distribution and the geochemical control of the ore bodies in Volta Grande Prospect (Lavras do Sul, RS, Brazil). SIP surveys can provide a larger number of inverted and modeled geophysical blocks (small size blocks) to be correlated with Au and Cu grades. In the same way, modeling magnetometric, gamaspectrometric, and geochemical data in 3D space can improve largely ore control for mineral exploration. Improving and detailing correlation analysis can also enable co-kriging evaluation of such a mineral deposit (Pires, 2002).

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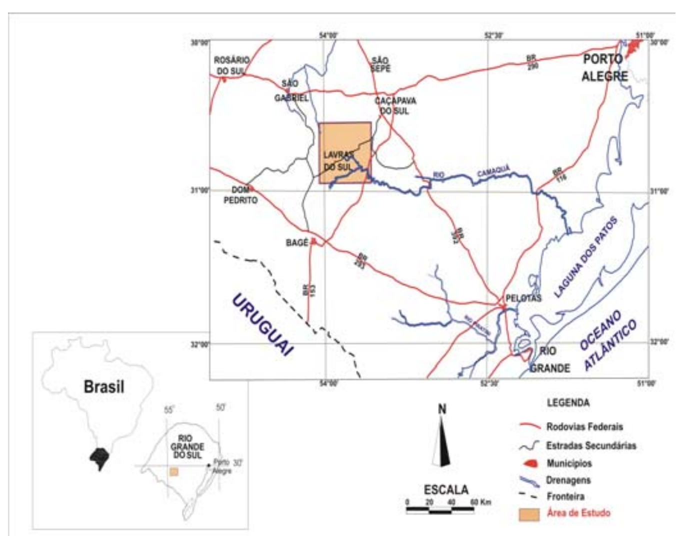

Figure 1 – Lavras do Sul Intrusive Complex (Localization map).

A B C

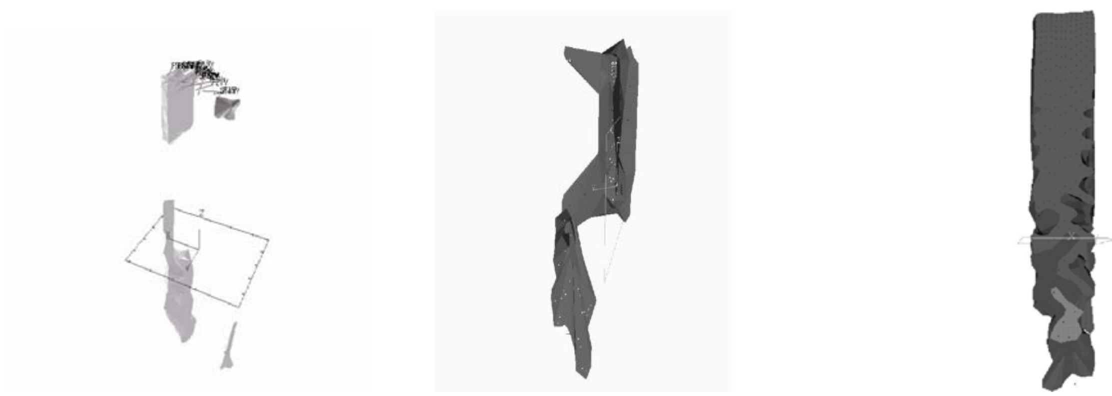

Figure 2 – 3D geometry of modeled low resistivity zone in Volta Grande Prospect (Lavras do Sul, RS, Brazil): a) Area 1,. b) Area 2 c) Area 4.

Table 1 – Linear regression lines showing the correlation between geophysical and geochemical data for Volta Grande Prospect (Lavras do Sul, RS, Brazil). A, B and C are linear regression lines for apparent resistivity *vs*. Au grades in areas 1, 4, and 2 respectively; D, E and F are linear regression lines for apparent resistivity *vs*. Cu grades in areas 1, 4, and 2 respectively.

	Apparent resistivity *vs.* Au	**Apparent resistivity *vs.* Cu**
Area 1	**A** **Au** =-0,0006 x (Apparent resistivity) + 0,1619 **r** = 0,93 **Au** =-0,0004 x (Apparent resistivity) + 0,5335 **r** = 0,93	**B** **Cu** =-0,0006x(Apparent resistivity) + 0,1623; **r** = 0,86 **Cu** =-0,0006x(Apparent resistivity) + 0,1440; **r** = 0,24
Area 4	**C** **Au** =-0,0013x(Apparent resistivity) + 0,3607 **r** = 0,22 **Au** =-0,0022 x (Apparent resistivity) + 3,012 **r** = 0,39	**D** **Cu** =-0,0008x(Apparent resistivity) + 0,1619; **r** = 0,99 **Cu** =-0,0008x(Apparent resistivity) + 0,4426; **r** = 0,22
Area 2	**E** **Au** =-0,001x(Apparent resistivity) + 0,273; **r** = 0,97	**F** **Cu** =-0,001x(Apparent resistivity) + 0,2696; **r** = 0,26