Resources Evaluation of the NW Lagoa Salgada Deposit in the Iberian Pyrite Belt. A geostatistical approach.

Folha, R.[1]; Jorge de Sousa, A [1]; Rosa, C.[2]

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[1]CERENA – Centro de Recursos Naturais e Ambiente, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal;
[2]EDM – Empresa de Desenvolvimento Mineiro, Portugal.

Abstract

Geostatistical methods have been used for the resources evaluation of mineral deposits. In this work, based on a MSc. Thesis, a geostatistical methodology is used to estimate the resources of Lagoa Salgada Deposit. This is a volcanogenic massive sulphides deposit in the NW part of the Iberian Pyrite Belt (IPB - Portugal) with Zn, Cu, Pb, Au, Ag. The deposit has several ore bodies classified in 3 ore types; *gossan*, massive and *stockwork*; each one located in a specified zone. The use of Direct Sequential Simulation (Soares, 2001) with domains (Nunes et al, 2016) allows the calculation of a grade value to each block with associated uncertainty. This methodology produces several equiprobable images of the deposit considering regional distribution functions of the data and spatial continuity patterns.

The average grade for the simulations in each block is similar to the interpolation estimates done by ordinary Krigging. The uncertainty measures are made with the variability of the grade in each block. Each block is classified as inferred/indicated/measured according to its' calculated uncertainty.

Key_words: Resources Classification, Uncertainty Quantification, Direct Sequential Simulation with Domains, Lagoa Salgada VMS Deposit – Iberian Pyrite Belt.

1 – Introduction

Resources classification is regulated by International recognised Norms such as NI 43-101, National Instrument 43-101, prepared by Canadian Institute of Mining, Metallurgy and Petroleum; PERC Code - Pan-European Code for Reporting of Exploration Results, Mineral Resources and Reserves prepared by Pan-European Reserves and Resources Reporting Committee; or the Australiana Norm JORC Code (Joint Ore Reserves Code) the "Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves". All these regulations refer about the importance of quantifying uncertainty and incorporate it in resources classification although they don't make it an obligation (Rossi et Deutsch, 2014).

Mineral resources are classified according to the knowledge and confidence of the information about a specified resource. A resource is classified as inferred, indicated or measured, and a reserve as probable or proven, according to the nature of the resource and

its economic viability (Sinclair et Blackwell (2006), Rossi, et Deutsch, (2014); NI 43-101; and JORC, 2012).

According to Dimitrakopoulos, 1997, a complete resources model should incorporate more than one estimated value, and an estimation distribution function, but also to provide a more detailed characterization of uncertainty and its consequences (Rossi et Deutsch, 2014).

Simulation model generates several images from reality, that have the same probability to occur, and that can be used for risk analysis to all the subsequent processes in mining engineering. They contribute to feasibility studies, dimensioning and characterization of the several phases of mine planning, design and processes scheduling, financial provisions and production studies, as can be observed in figure 1 (Godoy et Dimitrakopoulos, 2011).
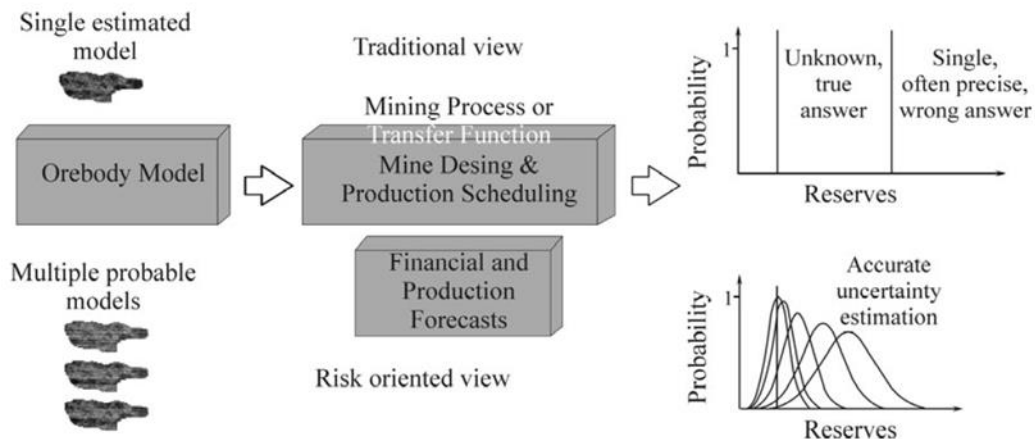
Figure 1 – Conversion of a mineral resource into a mineral reserve: traditional approach vs uncertainty and risk approach (Godoy et Dimitrakopoulos, 2011).

2 – Resources Calculation Methods

There are several methods for resources calculation that can be classified as traditional or geostatistical methods (Sinclair et Blackwell, 2006). Some of the traditional are: sections, polygonal, triangular, regular grid, inverse distance weighting methods (Sinclair et Blackwell, 2006). Geostatistical methods study the spatial patterns of the sampling data, possible anisotropies, define the main directions of continuity, and try to reproduce this pattern in all the area that is being studied.

There are several geostatistical methods, since which, estimation and simulation methods. In this work it was used a simulation approach.

2.1 – Geoestatistics methods

Geostatitstics methods, introduced by Matheron in 1962, are a statistical methodology to study a natural phenomenon. They pretend to incorporate both intrinsic components to the evaluation of a natural ore deposit, the structure and randomness of the spatial distribution of a grade in a mineral resource (Isaaks & Sristava, 1989).

The measurement of the spatial continuity can be made by the variogram. $\gamma(h)$ geostatistical tool. That is a measure tool of the pattern of spatial continuity and homogeneity of a natural phenomenon from which only a small part is known (Soares, 2006).

This measure is made according to a distance h, through several directions (θ). It's calculated by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} [z(x_\alpha) - z(x_\alpha + h)]^2 \qquad \text{Eq. 1}$$

Where $N(h)$ is the number of pair of points, in direction *(θ), for the distance h*; $z(x_\alpha)$ is the measured value of a variable in a certain location and $z(x_\alpha + h)$ the measured value in a location at a distance $z(x_\alpha)$.

The experimental variograma is modelled according to the adjustment to a function or several that better represent the continuity of the grade between pairs of samples. These models can be spherical, exponential, *Gaussian* or power. In the case of the better adjust be made by several functions there are imbricated structures (Soares, 2006).

The spherical structure, used in this work, is represented by:

$$\gamma(h) = \begin{cases} C_i \left[1.5 \frac{h}{a_i} - 0.5 \left(\frac{h}{a_i} \right)^3 \right] & with \ \ h \le a_i \\ C_i & with \ \ h > a_i \end{cases} \qquad \text{Eq. 2}$$

Nugget effect was also used in this study in both variables in three ore-bodies, representing variability in smaller scale than sampling and/or variability induced in the sampling scale by non-systematic errors and monitoring.

2.1 – Simulation Approach – Using Uncertainty

The knowledge of a certain reality (a)) is known by several sample data (b). While estimation methods, as ordinary Krigging (c), provide a smooth version of reality and are good to estimate average grades being the BEST linear estimator, simulation procedures (d) give several equiprobable scenarios that reproduce the distribution of the conditioning data and the spatial continuity pattern. The result will be a set of possible scenarios, each one reproducing the probability distribution function of the data and the continuity pattern. Their average, similar to Krigging, plus the study of the variability of the grades in each block (e). The multiple responses address variability in each block.
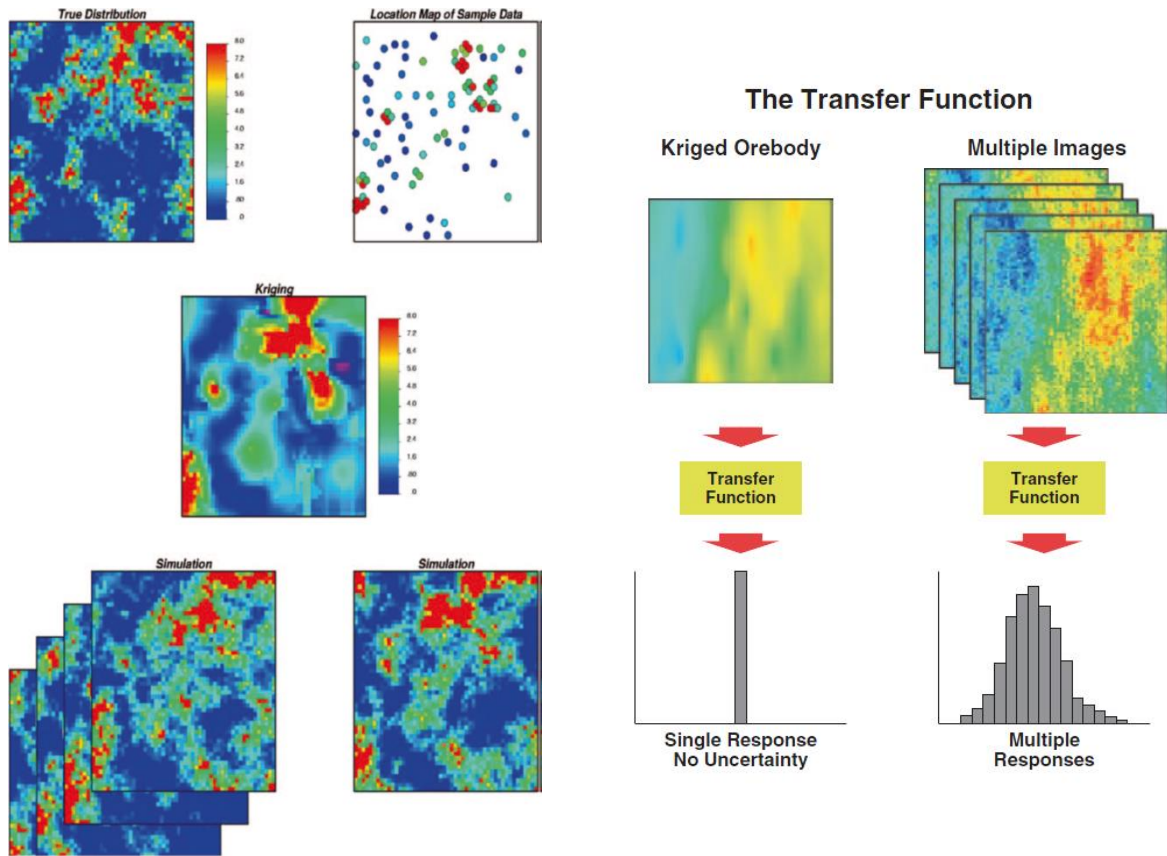
Figure 2 – Comparison of estimation Krigging and Simulation results (Rossi et Deustch, 2014).

2.4 – Case Study: Lagoa Salgada Deposit (IPB)

Lagoa Salgada Deposit is a polymetallic volcanogenic massive sulphides deposit in the NW part of the Iberian Pyrite Belt (IPB – Portugal) (figure 3a) and b)) with Zn, Cu, Pb, Au, Ag and other minerals (supergene enrichment), that lies bellow ~130m of Tertiary Basin of the Sado River. It is composed by 3 main mineralization types, corresponding each one to a different spatial domain: *gossan*, massive sulphides, *stockwork*.
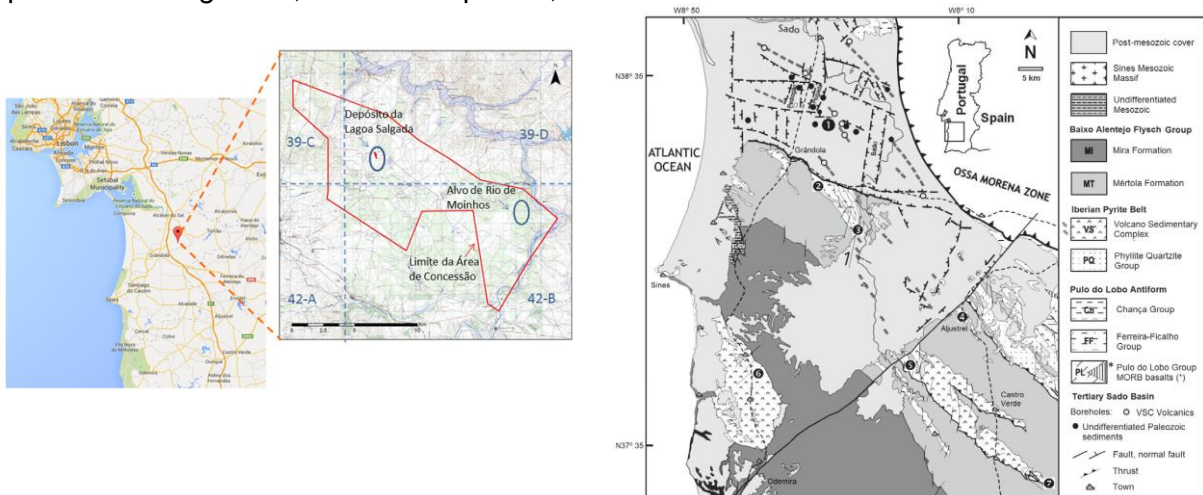
a)   b)

Figure 3 – Lagoa Salgada Deposit: a) Prospecting and exploration contract.;b) Regional Geology Framework of Lagoa Salgada Deposit, NW Iberian Pyrite Belt. Massive Sulphides Deposits: 1 = Lagoa Salgada, 2 = Caveira, 3 = Lousal, 4 = Aljustrel, 5 = Montinho, 6 = Salgadinho, 7 =Neves Corvo (modified from Oliveira et al., 2011).

3 – Methodology

The mineralization-geological model is built. Then the block model is done according to the limits of the previous model. Univariate, bivariate statistics and variography is done for the grades of zinc and copper of the sampling data and main directions of variography are determined in the case of each variable. Ordinary Krigging estimation is performed and 60 sequential direct simulations with domain restrictions are conducted.

Direct sequential simulation with domains methodology that was proposed by Nunes et al (2016), after Soares (2001), can be described in these steps:

1 - Zones definition for all simulation grid nodes.
2 - Random sequence through a random path that visits all the nodes of the grid.
3 - Simulation of the value $z^s(x_0)$:

Estimation in x_u of the local mean and estimation variance with simple Krigging; $\left[(z/x_u)^*\right]_{sk}$ and $\left(\sigma_{sk}^2(x_u)\right)$, conditioned to the experimental data (z(Xα) and to neighbours nodes previously simulated $\left(z(x_\alpha)\right)^*$ in a neighbourhood u.

4 - Definition of the regional probability distribution function $F_z(z)$ that is re-sampled according to the estimation mean and variance from simple Krigging.
5 - Choose of a value of $z^s(x_0)$ from de $F_z(z)$.

From a Gaussian distribution $G\left(y(x_0)^*, \sigma_{sk}^2(x_u)\right)$, generation of the value y^s.

E return of the simulated variable $z^s(x_0) = \varphi^{-1}(y^s)$.

6 - This value is added to the node as conditioning of the simulation of the next node to be simulated.
7 - Same proceeding until all the nodes are simulated.

Recoverable functions for grade, tonnage, quantity metal are calculated for zinc and copper variables.
Uncertainty is studied using percentage of "*intervalo interquartilico relativo*". Resources classifications are proposed according to uncertainty intervals.

4 – Results

A geological wireframed conceptual model was performed at EDM and then transformed into a block model that covered all the masses of the three types of mineralization.

The regionalization of the blocks that are assigned to each domain was performed in Geosoft Target software, in EDM - Empresa de Desenvolvimento Mineiro and then visualized in SGems. There can be identified, in blue the *gossan*, in green the massive and in red the *stockwork*.
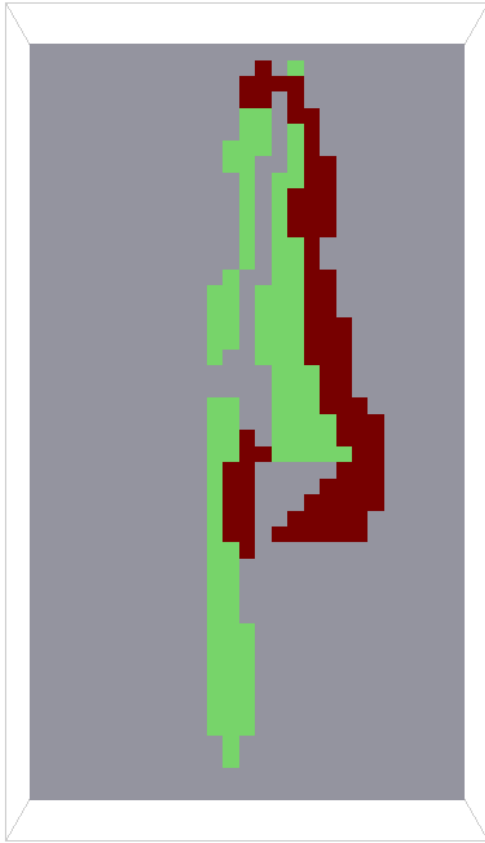
Domains of *gossan*, massive and *stockwork* of the model are identified in a grid with 10x10x5m blocks.
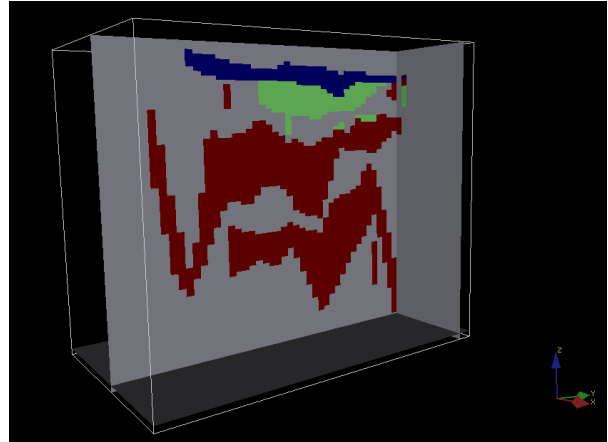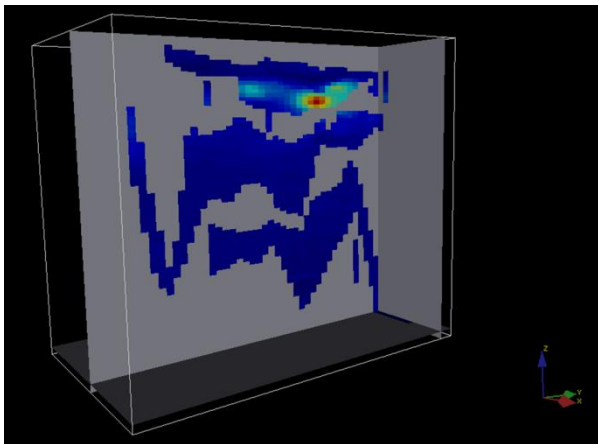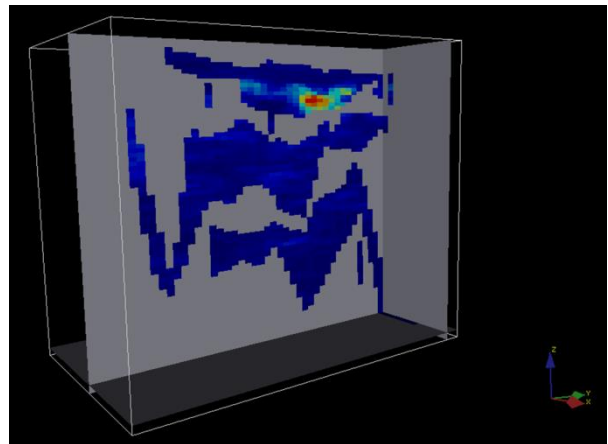

Figure 4 – Zones identification: *gossan*, massive sulphides, *and stockwork*.

The Direct sequential simulation with zones was performed in a CERENA programme, IST. 60 simulations where performed for each variable.

Simulation A

Simulation B

Figure 5 – Two simulations results of the zinc values.

The average of the 60 simulations is similar to the results of the ordinary Krigging. Recovery functions of tonnage, grade, and quantity of metal according to cut-off grade were studied and compared with Krigging results.
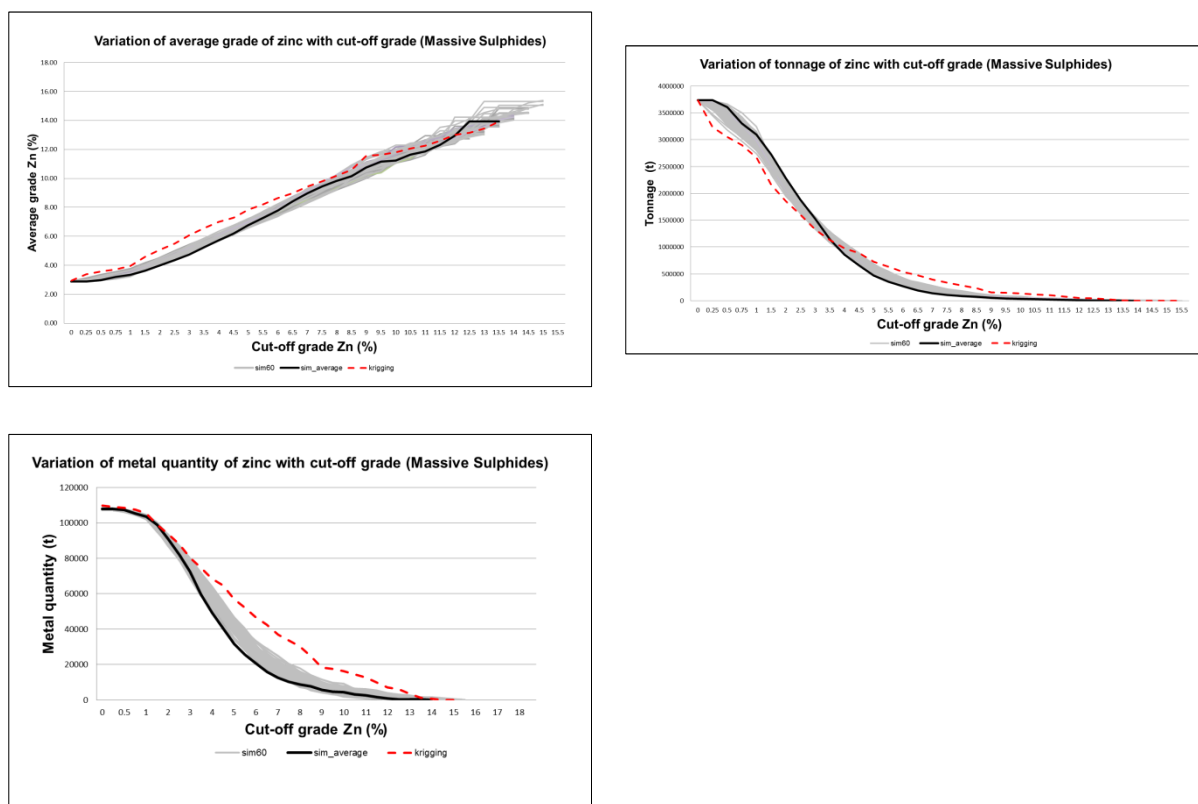

Figure 6 – Average grade, tonnage and metal quantity of zinc according to cut-off grade.

The uncertainty study performed with the "*intervalo interquartílico relativo*" in zinc estimation gave 7.4 Mt of potential mineralization in the more deep and distal zones of the ore-bodies. The estimated resource is only 8.96Mt with an average grade of zinc of 1.68% and metal quantity of zinc of 150,400t. A 2% Zn cut-off study was performed which results are in the table 1. A 35% threshold value was chosen to split indicated from inferred resources in each mineralization type.

Table 1 – Zinc resources: Indicated – inferred, cut-off grade of 2% and 35% uncertainty threshold.

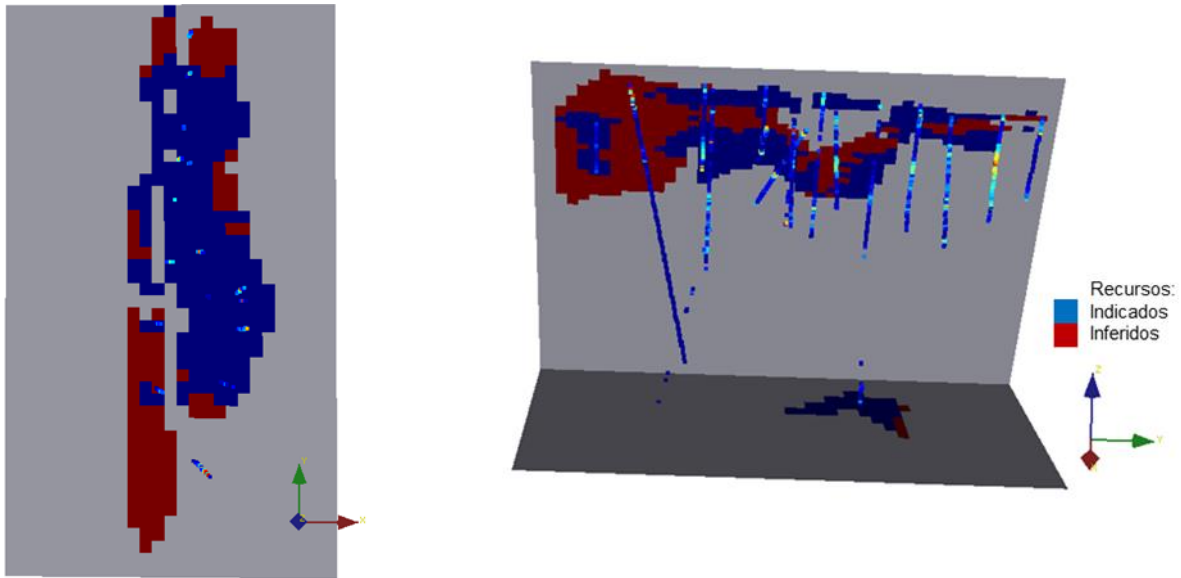| Recovery Functions	Indicated Resources				Inferred Resources				Total Resources
	GOS	MSX	STWK	Total	GOS	MSX	STWK	Total	Total
Tonnage	0	1,338,360	717,690	2,056,050	0	1,493,400	0	1,493,400	3,546,630
Average Grade Zn(%)	0	2.63	2.63	2.63	0	3.97	0	3.97	2.66
Metal Quantity Zn (t)	0	44,641	18,868	63,509	0	49,812	0	49,812	94,452

Figure 7 – Indicated (1), Inferred (2) resources with a cut-off grade of 2% Zn and 35% uncertainty threshold.

The uncertainty study performed with the "*intervalo interquartílico relativo*" in copper estimation gave 1.4Mt of potencial mineralization.

The estimated resource of copper is 14.8Mt with an average grade of copper of 0.27% and metal quantity of copper of 39,447t. A 1% Cu cut-off study was performed which results are in the table 2. A 35% threshold value was chosen to split indicated from inferred resources in each mineralization type.

Table 2 - Copper resources: Indicated – inferred, cut-off grade of 1% and 35% uncertainty threshold.

Recovery Functions	Indicated Resources				Inferred Resources				Total Resources
	GOS	MSX	STWK	Total	GOS	MSX	STWK	Total	Total
Tonnage	13,545	264,480	40,890	318,915	0	54,720	0	54,720	373,635
Average Grade Zn(%)	1.1	1.52	1.23	1.46	0	1.46	0	1.46	1.42
Metal Quantity Zn (t)	149	3,857	502	502	0	798	0	798	5,306

4 - Conclusions

Uncertainty knowledge is essential to a more accurate resources classification, into measured/indicated/inferred. DSS_zones respects the distribution of the original variable and the continuity patterns, so it's a good tool to understand the goal of this work.

Direct sequential simulations with zones allow the use of regionalized continuity patterns into each zone. This promotes a better understanding of the variability in deposit with several orebodies like NW part of Lagoa Salgada, in Iberian Pyrite Belt.

The average grade for the simulations is similar to the estimates done by ordinary Krigging. The uncertainty measures are made with the variability of the grade in each block. Each block is classified as inferred/indicated/measured according to its calculated uncertainty.

The uncertainty study performed with the "*intervalo interquartílico relativo*" in zinc estimation gave 7.4 Mt of potential mineralization in the more deep and distal zones of the ore-bodies. The estimated resource has 8.96Mt with an average grade of zinc of 1.68% and metal quantity of zinc of 150,400t. A 2% Zn cut-off study was performed and a 35% threshold value was chosen to split indicated from inferred resources in each mineralization type.

The resources are 3.5Mt with an average Zinc grade of 2.66% and a metal quantity of zinc of 94,452t. For 35% uncertainty, indicated resources are 2.056Mt with an average grade of 2.63% and metal quantity of Zinc of 63,509t. Inferred resources are 1.49Mt with an average grade of 3.97% and metal quantity of 49,812t.

Copper resources are 14.8Mt with an average grade of 0.27% and metal quantity of copper of 39,447t. The study presents 1.4Mt of potential mineralization.

With 1% copper threshold, resources are 373,635t with 1.42% of average grade of copper and 5,306t of quantity of metal of copper. Indicated resources are 318,915t, with na average grade of 1.46% and quantity of metal of 4,508t of copper. Inferred resources are 54,720t, with na average grade of 1.46% and metal quantity of 798t.

Lagoa Salgada deposit should continue to be study, namely other elements from this polymetallic resource.

More drilling campaigns should be performed in Lagoa Salgada Deposit and geostatistical approached to the data can be useful to understand grades distributions and measure uncertainty. Geological and geostatistical integrated studies should be continued.

More studies on the population above 5% zinc should be conducted to understand preferential alignments. These alignments can lid to new discoveries of areas with good potential.

Acknowledgements

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