The use of Conditional Simulation for Drill Hole Spacing Evaluation and Decision-Making in Telégrafo Project, Northern Chile

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ABSTRACT

The Telégrafo copper – gold deposit is located in the Centinela district of the Antofagasta region in northern Chile. Telégrafo is a porphyry copper deposit of Eocene – Oligocene age which has a total mineral resource in measured, indicated and inferred categories equal to 2.6 billion tonnes with an average grade of 0.38 per cent copper.

Currently the project is in the prefeasibility study phase, including an infill drilling campaign to improve the knowledge of the deposit that should result in an improvement of the mineral resource classification. In this context was decided to review the classification criteria in order to optimise the drill hole density necessary to support the project.

This paper presents an application of conditional simulation to evaluate the risk related to drill hole spacing, using a geostatistical approach that mimics the process of evaluation of resources from the perspective of geological modelling and grade estimation.

The first step of the approach is the generation of conditional simulations using the available samples to generate several plausible scenarios of the deposit in terms of copper grades and geological units. These scenarios are considered as the unknown reality of the deposit and sampled by synthetic drill holes in order to replicate the geological model process and copper resource estimation.

In this way it is possible to establish differences between the possible scenarios and the generated resource estimation models for several simulated drill hole spacing alternatives. These differences or errors can then be quantified in terms of estimated mean, metal content and tonnage over different production volumes.

The resulting errors were useful in assisting the decision making process related to the design of drill hole spacing for each category of mineral resource in the Telégrafo project, and to redistribute the budget associated to the drill campaigns for the next stage of the project.

INTRODUCTION

The Centinela district comprises a 40 km long segment of the late Eocene to Early Oligocene porphyry copper belt of the Antofagasta region of northern Chile (Figure 1). Successful exploration programs conducted by Antofagasta Minerals SA in the Centinela district since early 1990s have discovered three deposits that are currently in operation. These are the Tesoro and Tesoro NE copper oxide ore deposits, from which ore is processed in a SX-EW plant, and the Esperanza porphyry copper – gold deposit, ore from which is processed in a traditional concentrator plant. Elsewhere in the district there are several other projects, including Mirador, Telégrafo, Caracoles and Polo-Sur that are at varying stages of development.

The Telégrafo porphyry copper – gold deposit is located immediately south of the Esperanza mine, and has a total mineral resource in measured, indicated and inferred categories of 2.6 billion tonnes with an average grade of 0.38 per cent copper and 0.11 g/t gold.

A recent evaluation of mineral resources at Telégrafo included an upgrade of 3D geological model based on the drill hole database, key geological sections and district-scale surface geology maps. The 3D model was built using an implicit model of the limits (distance between contacts) with Leapfrog software (Cowen *et al*, 2002) and includes the modelling of major faults, the main lithological units, alteration zones and zones of copper and iron sulfides. The grade estimation model for copper, gold, molybdenum, etc was estimated inside geological domains that were defined from geological units using co-kriging and ordinary kriging (Rojas, 2010).

Currently the Telégrafo project is undergoing a prefeasibility study that includes infill drilling to improve the knowledge of

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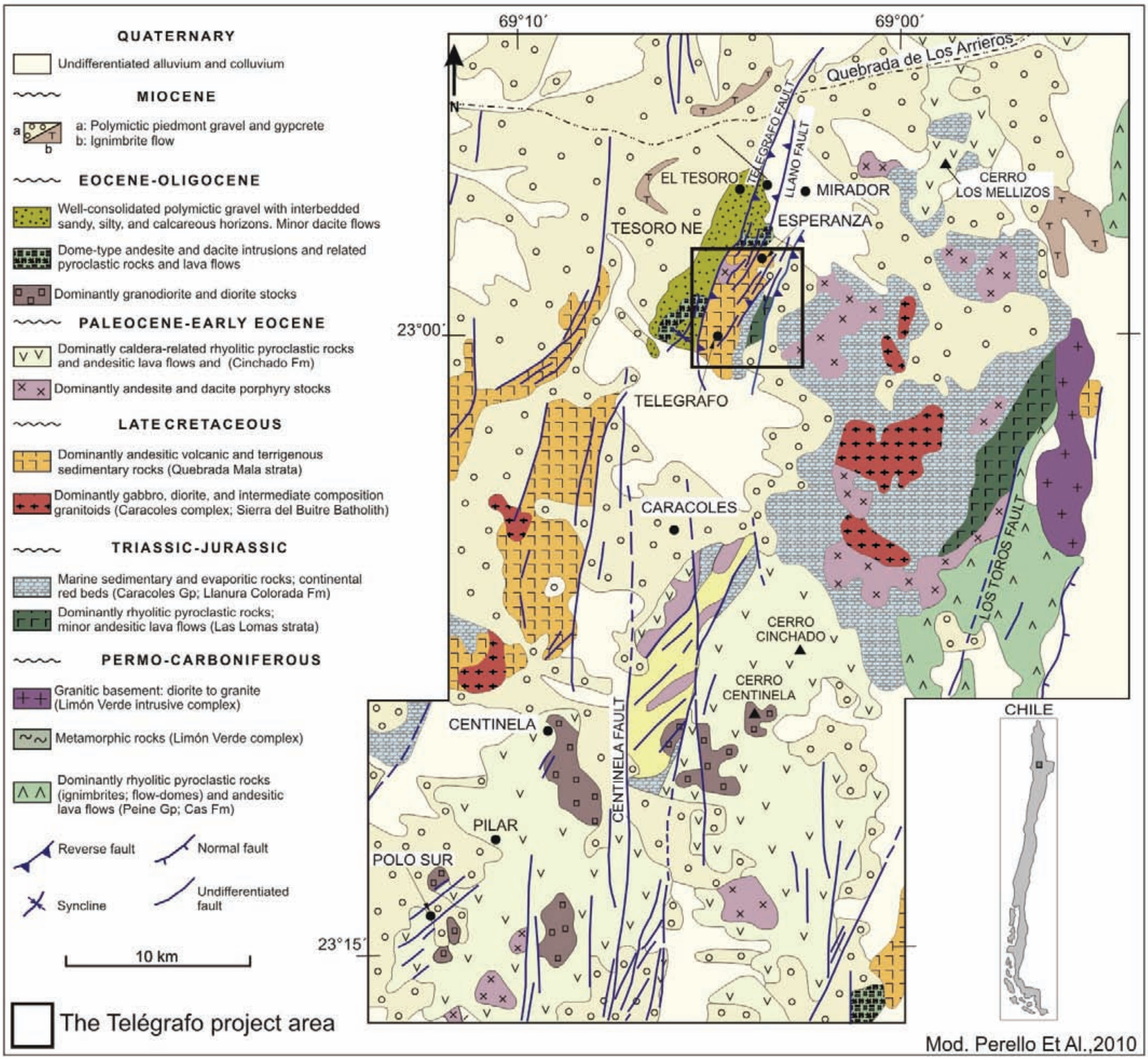

FIG 1 - Regional geology map showing the location and geology of the Telégrafo project within the Centinela District, Northern Chile.

the deposit, which should in turn result in an improvement of the mineral resource classification. This drilling program has two principal objectives:

1. to convert inferred resources to at least indicated resources for the life of mine orebody, and
2. to define the optimal drill hole spacing so as to ensure that at least 80 per cent of mineral resources within the initial five year pit can be classified as measured resources (proven reserves).

The number of drill holes to achieve both of these objectives will be dependant upon the resource classification criteria applicable to the Telégrafo deposit.

This paper deals with the resource classification criteria of Telégrafo from the perspective of quantifying the variability associated with both the geological model and grade estimation. In previous geostatistical studies the variability of the geology has been addressed using as estimation a conditional simulation of categorical variables: indicator kriging, sequential indicator simulation, truncated Gaussian simulation (Galli *et al*, 1994), plurigaussian simulations (Amstrong *et al*, 2003). However, more recent studies have addressed this issue from the point of disrupting the 'geological model' after database process (Deraisme, Miranda and Rojas, 2010).

To achieve this we proceeded to simulate various scenarios of a simplified geology for which conditional simulations of copper grade were made. Several outputs of the deposit ('stochastic images') were generated. Subsequently, we attempted to generate each of these images from models based on different fictitious drill hole spacing grids. This was then used to calculate the estimation errors at different grid spacing of drill holes and therefore determine the optimal mesh for each category of resources.

SIMPLIFIED GEOLOGICAL MODEL

The hypogene porphyry copper alteration and mineralisation at the Telégrafo deposit is associated with multiple, dike-like, porphyritic intrusion of granodioritic composition. Potassic alteration in the main-phase at Telégrafo yield a K-Ar age for hydrothermal biotite of 43.8 ± 1.1 Ma (Perello *et al*, 2010). An isometric view of the deposit and the main geological units is shown in Figure 2. A supergene event was developed in the district area after the primary ore formation that caused oxidation and leaching of the primary sulfides and the profile with the upper leached zone, an intermediate zone of copper oxides and primary ore in the bottom (Figure 3).

Operational experience shows that in the models of porphyry copper deposits there are specific geological boundaries that can generate problems in the process of reconciliation between short-term (mine) and long-term models. Often the contacts between mineralised and barren zones are those that generate greater variability in the reconciliations, although once inside any of these major geological domains the variability is restricted to grades estimated. At the Telégrafo project, the geological contacts that should lead to greater variability are:

1. leached versus oxide zones,
2. leached versus sulfide zones, and
3. oxide versus sulfide zones.

Therefore the major geological units which were simulated are the leached, oxide and sulfide zones (Figure 3).

SCHEME USED FOR CALCULATING THE ESTIMATION ERROR

The overall procedure to calculate the estimation errors associated to several drill hole spacings can be seen as similar to the geological resource modelling process. Figure 4 presents the main steps of the process, where the deposit or unknown reality (Step 1) is replaced by conditional simulations of geology and copper grades. The drilling step is replaced by the generation of fictitious drill holes (Step 2) and used as input to generate the resource models (step 3) which are finally contrasted via reconciliation with the starting conditional simulations (Step 4).

In this way a set of resource models (geology and copper grades) related to several drill hole spacings can be compared against the simulated realities to calculate the modelling-estimation errors.

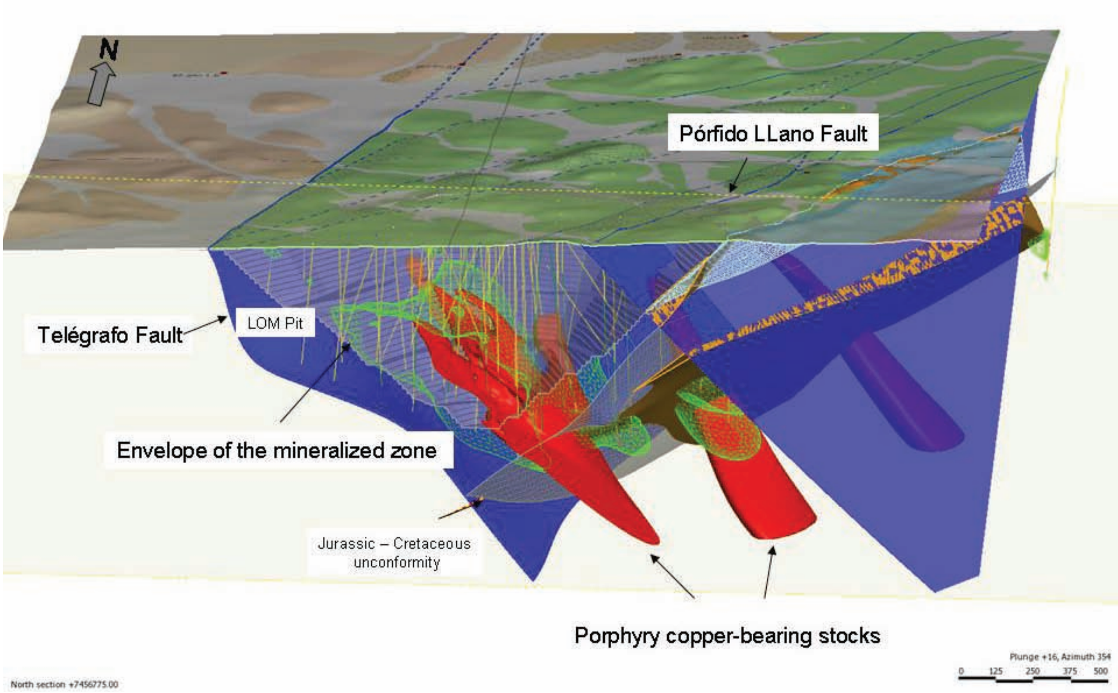

FIG 2 - Isometric view of the simplified geological model of Telégrafo project showing the relationship between the porphyry and copper (gold) mineralised zones.

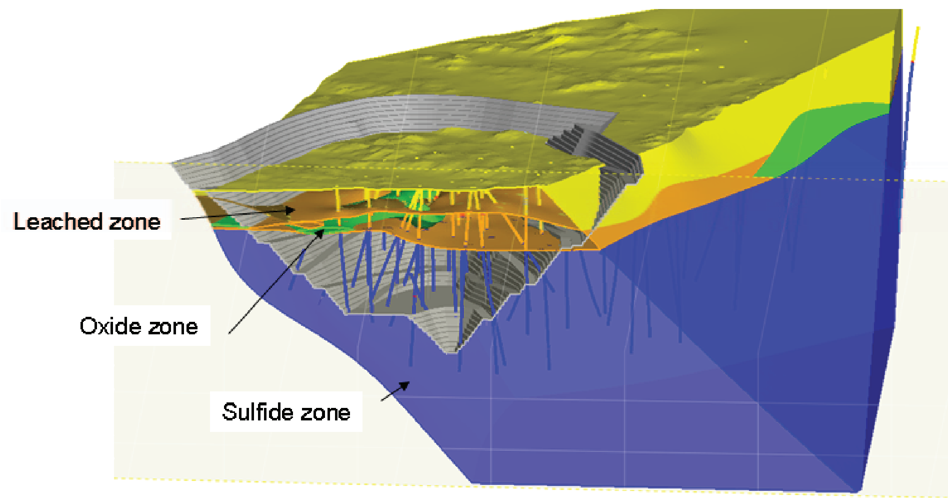

FIG 3 - Isometric view of the copper mineral zones at Telegrafo project showing the principal geological boundaries. The sulfides zone, the oxide zone and the leached zone.

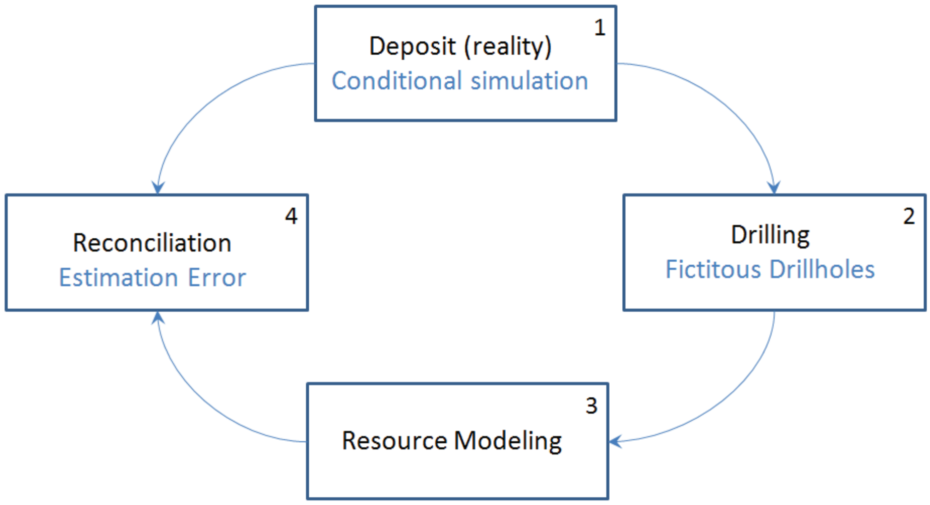

FIG 4 - Workflows of process showing the four main steps to calculate the estimation error for different sampling grid spacing.

The workflow of the procedure can be summarised as follows:

1. Generate 25 realisations of conditional simulations of the simplified geological units and copper grades using the available drill holes. Each realisation iteration is considered as a potential reality output in the following steps.
2. Generate 25 datasets of fictitious drill holes by sampling the conditional simulations of the deposit, recording the simulated geology and copper grades using different grid spacings.
3. Generate 25 geological models using the fictitious data sets obtained for different drill hole grid spacings, and estimate the copper grades inside the modelled geological units.
4. Calculate the tonnage, mean grade and metal content error associated with each drill hole spacing over different productions volumes.

It is important to note that, in this study, the 25 conditional simulations were created specifically in order to compare these simulations of the Telégrafo deposit with different drill hole grids and not to evaluate the variability associated with the current level of information.

The implementation details of each step are presented in the following sections.

Conditional simulation of geological units and copper grades

Using the available drill holes in the Telégrafo project, a set of 25 realisations or potential realities of the deposit were generated in a 1 × 1 × 0.3 km grid with nodes of 5 × 5 × 2 m. The selected study area is within a reference pit-shell (life-of-mine, or LOM) in order to contain the interface zone between oxides and sulfides.

Simulation of geological units

The procedure adopted to simulate the geological units is based on implicit boundary modelling (Carr *et al*, 2001; Henrion, Caumon and Cherpeau, 2010; McLennan and Deutsch, 2007) and Gaussian simulation (Chiles and Delfiner, 1999). The main reason to adopt this methodology is that implicit boundary modelling is the back-end core of the geological model software, Leapfrog, used by Antofagasta Minerals to model its deposits. The major strength of implicit modelling is that it includes more information about the sampling configuration, due to the fact that the geological unit of each sample implicitly includes the distance to nearest geological contact.

The simulation procedure is divided in two stages, the first is to simulate the sulfides interface, and the second the oxide and leached interfaces above the previously simulated interface. In both cases the following procedure is used:

1. Indicator codification of geological units: a binary variable is given to oxides, leached and sulfides.
2. Distance calculation to the nearest geological contact to each; assign a sign to the distance (positive when the indicator is equal to one and negative otherwise).
3. Normal score transformation of the calculated distances: the distance distribution is transformed into a Gaussian of zero mean and unit variances. It is important to keep the Gaussian value associated to the zero distance or contact between two units.
4. Perform the variography of transformed distances.
5. Generate Gaussian simulations of transformed distances using the sequential Gaussian simulation algorithm.
6. Truncate the distance-transformed simulations using the threshold-associated zero distance isosurface.

In this way a set of realisations of the geology of the deposit are generated. As an example, Figure 5 presents four realisations of the geological units in an eastwest profile showing the conditioning data.

Simulation of copper grades

The copper grade simulation was performed using sequential Gaussian simulations for each geological unit inside the simulated geological units obtained in the previous section. The workflow to obtain copper grade realisations is the following:

1. cell declustering of the drill hole data by geological unit,
2. normal score transformation of copper grades,
3. variography of transformed copper grades,
4. generate Gaussian realisations using the sequential Gaussian algorithm, and
5. back transform the simulated Gaussian values to the original copper grade scale.

Figure 6 presents two simulations of copper grades and its conditioning data in an eastwest profile.

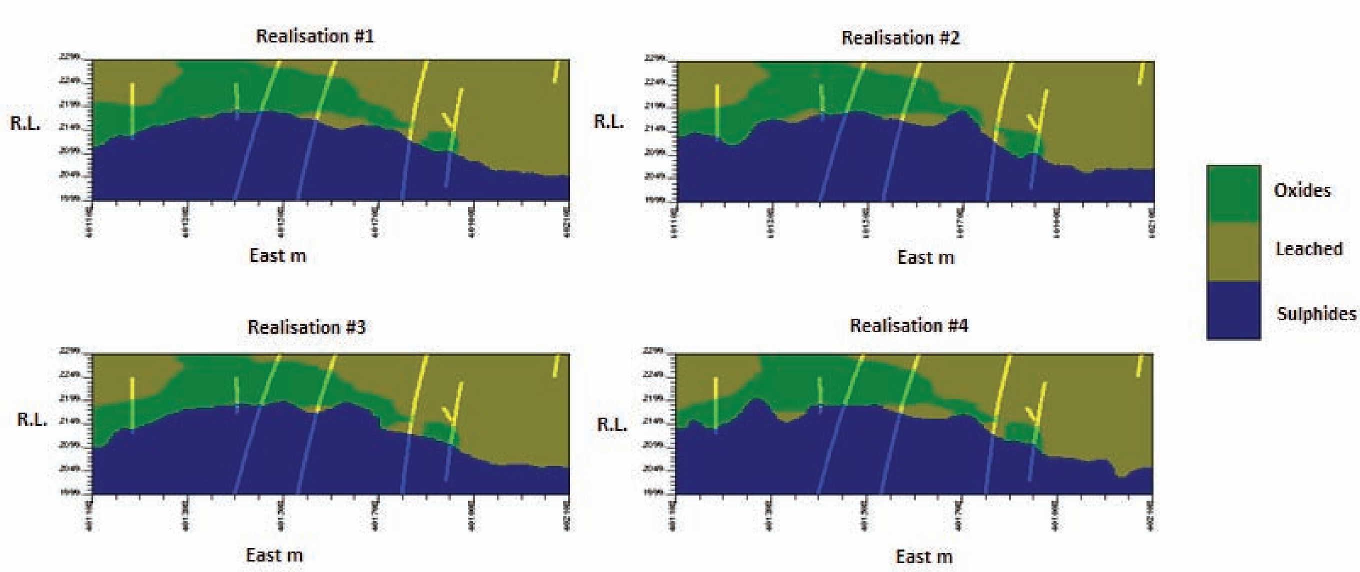

FIG 5 - East-west profiles of the geological model showing four possible realisations (simulations) of the copper mineral zone model.

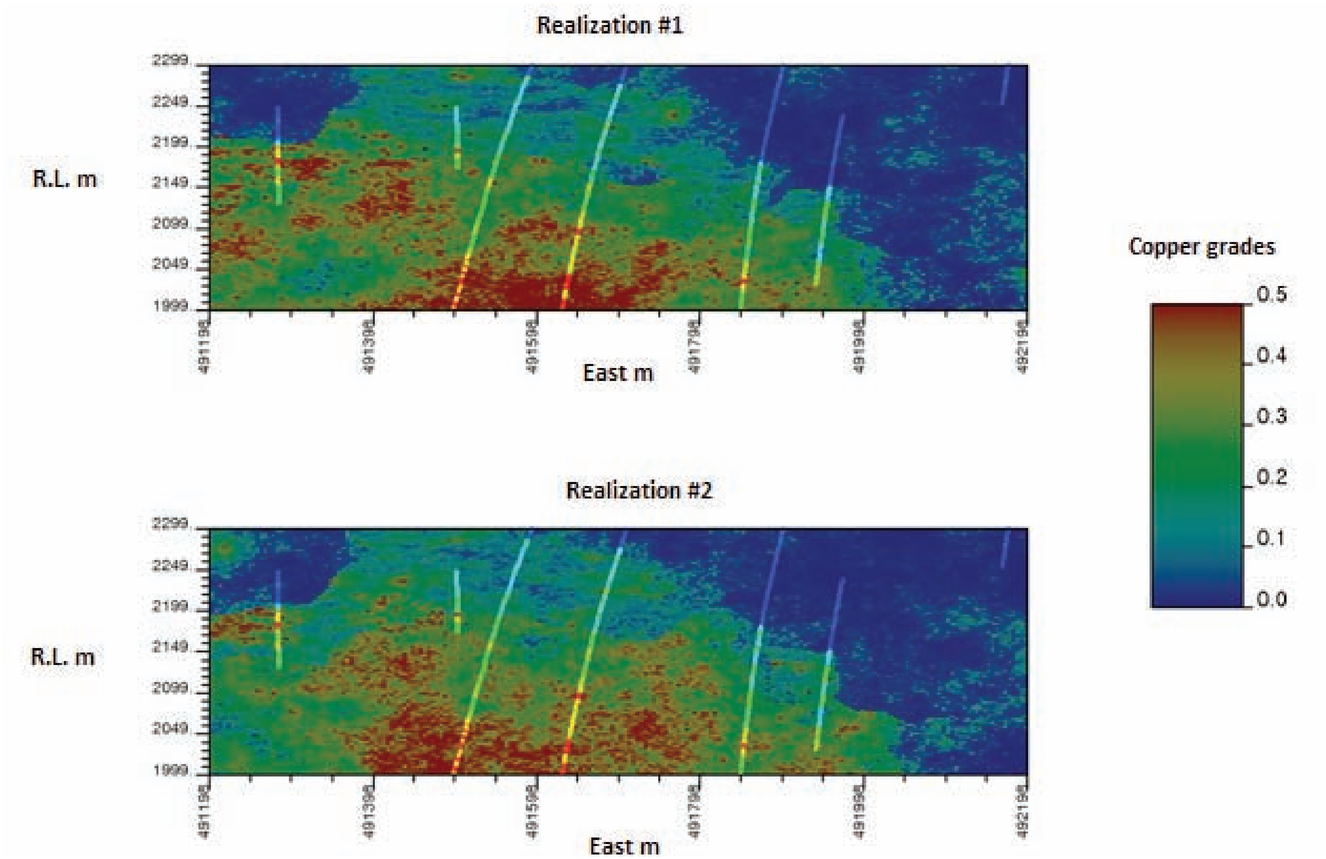

FIG 6 - East-west profile: two realisations of copper grades and conditioning data showing two possible realisations (simulations) of the copper grade.

FICTITIOUS DRILL HOLE SAMPLING

The conditional simulation of grades and geological units were sampled using four, square, drill hole grid meshes on 200 m, 100 m, 50 m and 25 m spacings. In order to obtain more realistic results, the azimuth and dip distribution of the fictitious drill holes were simulated to replicate the original drill hole orientations. It is important to note that for each grid spacing, both geology and copper grades for every realisation is recorded. As an example, Figure 7 presents two fictitious drill hole spacings for a particular geological simulation of the deposit.

Resource modelling using fictitious drill hole sampling

Modelling the geological units

For each realisation and drill hole grid spacing, a geological model is generated using the implicit boundary approach and the fictitious data. Due to the large amount of data, the option to use Leapfrog was not possible; therefore an alternative procedure analogous to the simulation of geological units was adopted.

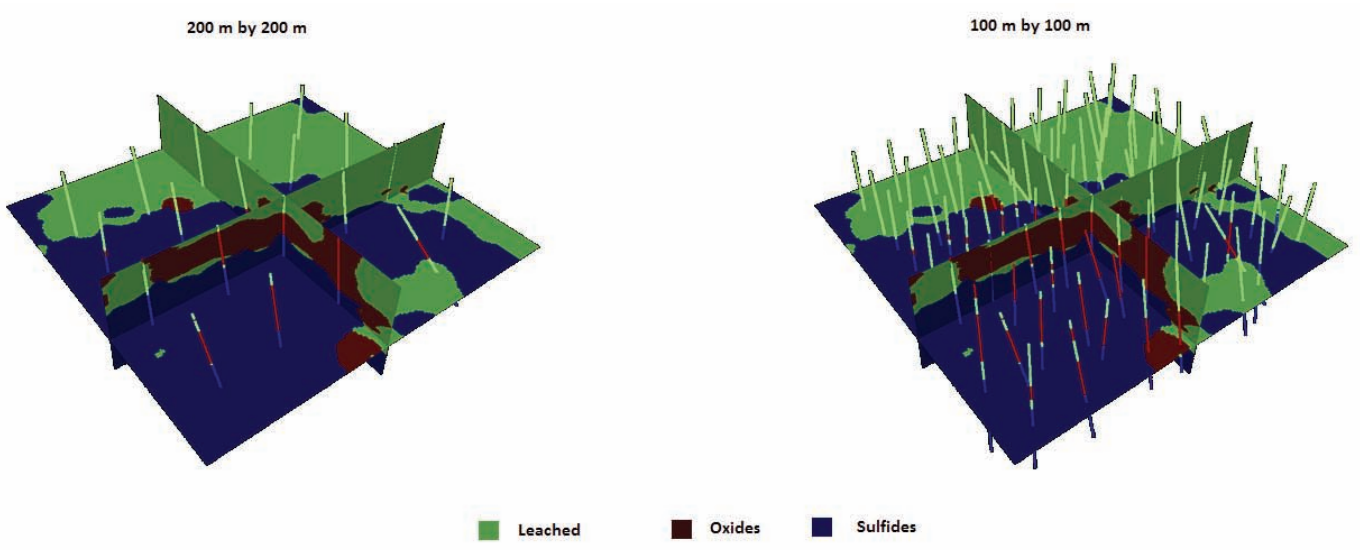

FIG 7 - Fictitious drill holes spacing and geology simulation of the deposit showing minerals zones models based on drill spacing of 200 m × 200 m and 100 m × 100 m.

For each fictitious drill hole data set, the first step was to model the sulfide interface, and then the oxide and leached unit above the previously modelled interface. In both cases the modelling process was done as follows:

1. Calculate the distance to the nearest geological contact for each sample and assign a sign to the distance (positive sign when the indicator of the unit is equal to one and negative otherwise).
2. The variography of the original samples was assumed, given that variogram modelling of the distances for every realisation and grid spacing would have been too time consuming.
3. Interpolation of the distance using kriging for the sulfide interface, and simple kriging in order to not extrapolate the oxides unit. This is performed over the same simulation grid.
4. Truncate the interpolated distance zero distance threshold in order to get the geological model.

To illustrate the result, Figures 8 and 9 present in section and plan the target realisation (unknown reality) and the geological models depicted from the fictitious drill holes. For each grid spacing, it is possible to appreciate how the geological model becomes similar to the target realisation as the information level increases.

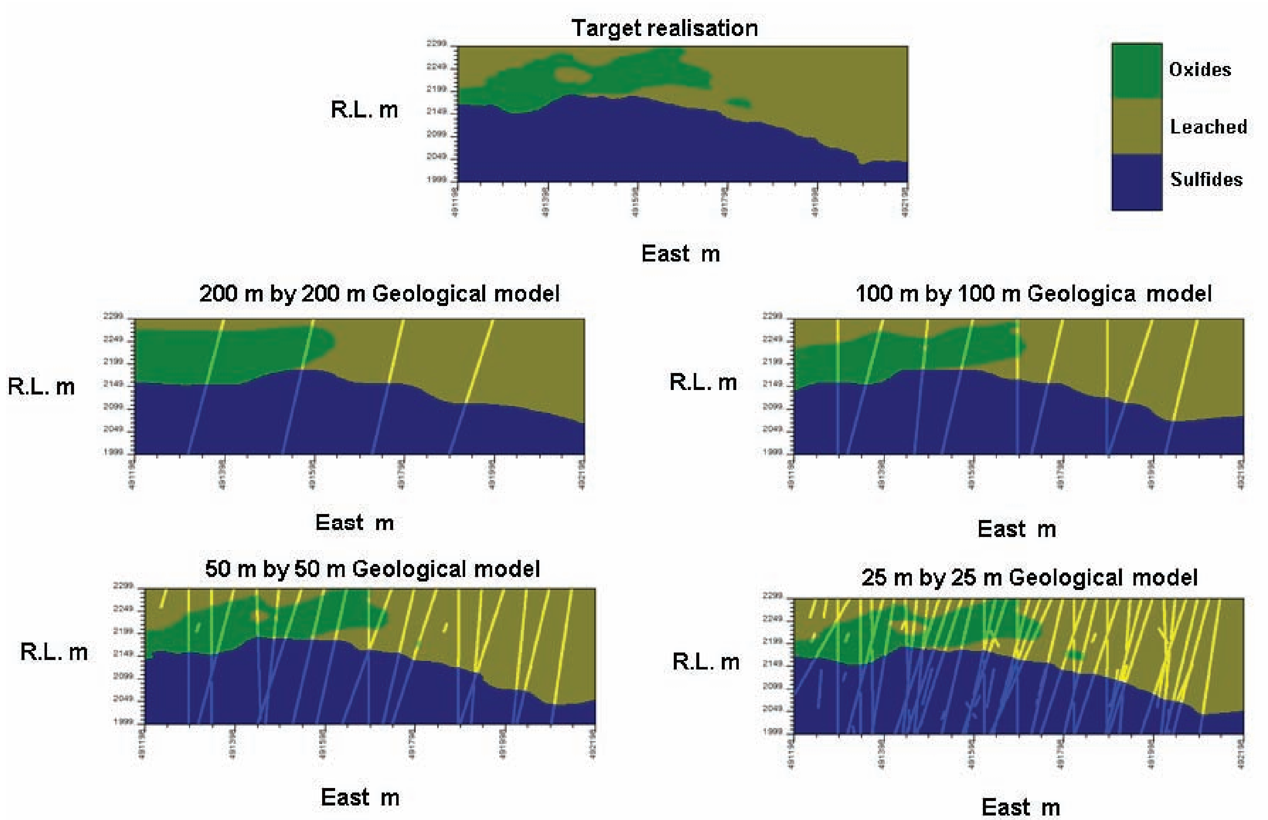

FIG 8 - Sections of target realisation (unknown reality) versus geological models from fictitious drill holes showing the variations of the geological model respect to different sampling grids.

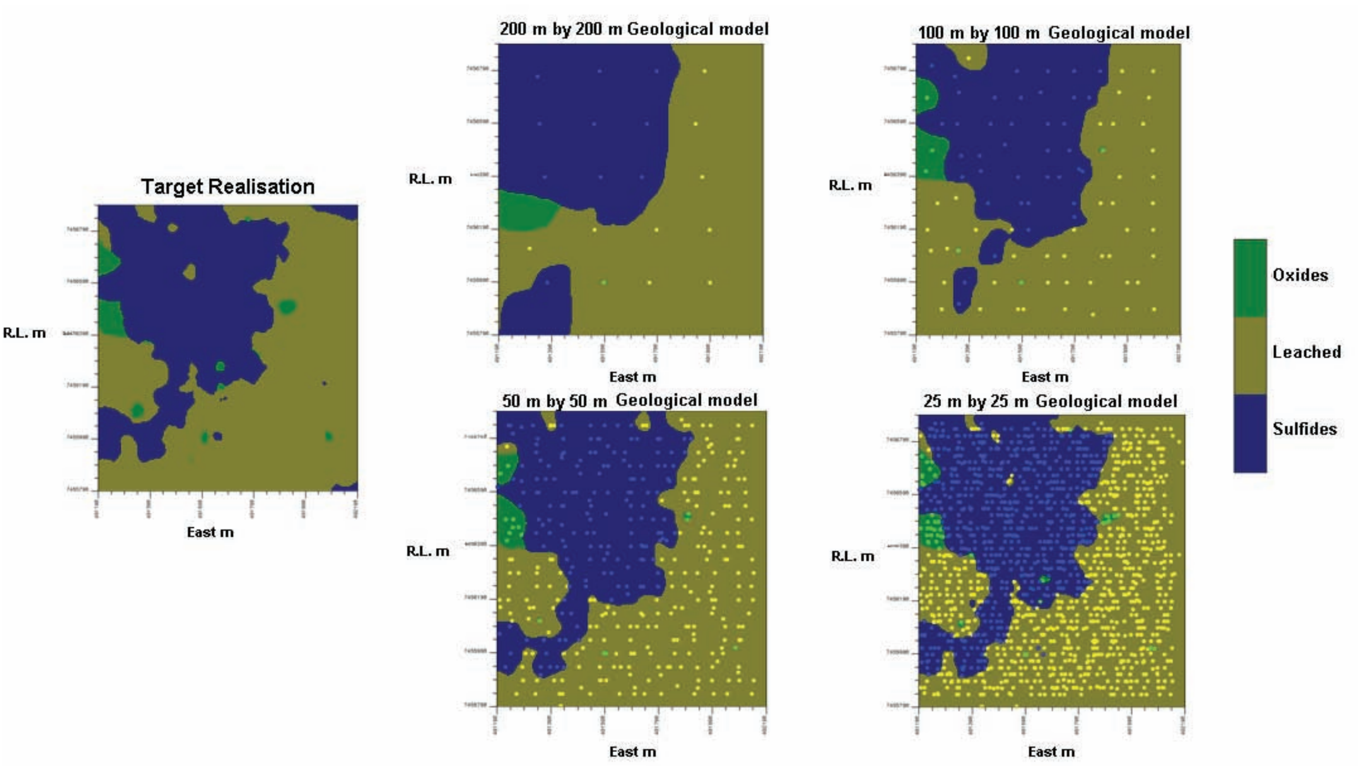

FIG 9 - Plans of target realisation (unknown reality) versus geological models from fictitious drill holes showing the variations of the geological model respect to different sampling grids.

Estimation of copper grades

The estimation of copper grades was performed using ordinary kriging with estimation parameters as close as possible to the ones used by Antofagasta Minerals to estimate the current official model. The exception comes from the search ellipsoids that are modified depending on the grid spacing to be evaluated.

The variogram models of each unit are derived from the original data samples, to avoid variogram modelling for each grid spacing and realisation.

The estimation is performed at block support of 20 m × 20 m × 16 m by geological unit. This is done by weighting the estimated copper grades for each unit by their volume percentage for every block.

Figure 10 presents the copper grade target realisation and the estimated copper grade models using the fictitious drill holes, analogous to the geology as the information increase the estimated model are close to the target realisation.

COMPUTING ESTIMATION ERROR

Through these exercises, we have been able to generate a set of 25 random outputs of the deposit that are equi-probable realisations. For each realisation, there are four estimation models of tonnage and grade related to meshes spaced at 200 m × 200 m, 100 m × 100 m, 50 m × 50 m and 25 m × 25 m. Therefore, we can calculate the estimation error of each mesh and also obtain a distribution curve of errors. Obviously we can see on sections and/or plans the matching between the models and the original (Figures 8 and 9).

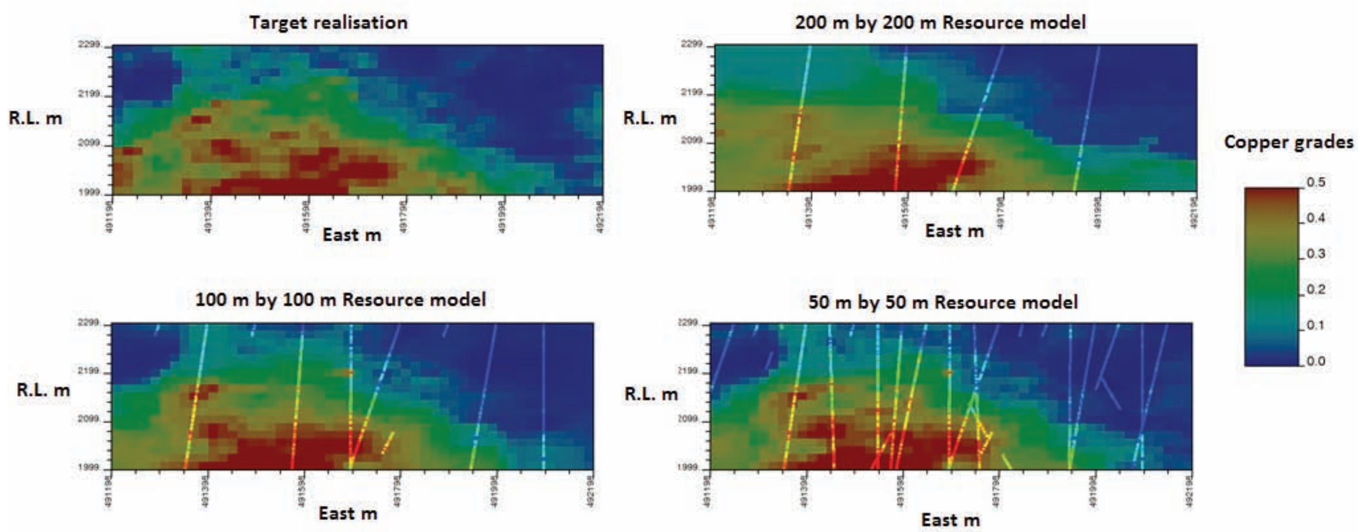

FIG 10 - Sections of the copper grades target realisation and the estimated copper grade models using fictitious drill holes showing the variations of the copper grades respect to different sampling grids.

Using this approach, we have calculated the estimation errors associated with the Telégrafo annual production (support). To do this, we conducted a 'mining reconciliation' between the simulated models and the resource models related to the different drill hole mesh sizes within the LOM pit-shell. To adjust the reconciliation to a specific volume or tonnage, we selected the required number of mining benches inside the pit equal to one year of production (ore to mill = 97 000 tonnes per day → 35 Mt/a).

Through consideration of the re-blocked simulated models and the estimated models as defined by different drill hole grids, the following approach was used to calculate the estimation error:

1. definition of a validation zone related to a yearly production volume of approximately 35 Mts for sulfides and 25 Mt for oxides in the interface between both units;
2. definition of a validation zone associated to sulfides below the interface zone with the same tonnage as the previous zone;
3. definition of separation materials by copper grade cut-offs and geological units (Table 1); and
4. compute average grade, tonnage and metal content by material for both estimated models and re-blocked simulations respectively, and process as done in a conciliation approach.

TABLE 1

Definition of ore materials by copper grade cut-offs and geological units showing the main characteristics in terms of ore type and cut-off grade.

Material	Geological unit	Cut-off grade
Oxides	Oxides	Cut ≥ 0.1%
Sulfides	Sulfides	Cut ≥ 0.15%
Waste	Leached, oxides or sulfides below the cut-off grade	

RESULT AND DISCUSSION

We can discuss the result as visual check and the distribution of error by mesh.

Visual check

It is evident that the realisation No 1 on the plan view 2158 (Figure 9) that the 200 m × 200 m mesh appears to be still too wide to permit a model close to 'reality'. The 100 m × 100 m mesh shows a good fit, with the 50 m × 50 m mesh showing a still-better fit (Figure 9). However, a closer mesh, for example 25 m × 25 m, appears redundant and does not gain a better fit or accuracy.

Estimation error by sampling mesh

The distribution of estimation errors refers to the ore type and size of mesh, and confirms the above discussion. To show this we have taken as an example the case of primary ore (Figure 11). Inside of annual support the spread of error is greater for the 200 m x 200 m mesh than smaller meshes (100 m × 100 m or 50 m × 50 m). Additionally, we can see a bias in the 200 m × 200 m mesh. Also the range of error is ± eight per cent for a 100 m × 100 m mesh and ± five per cent for the 50 m × 50 m mesh. However, the number of drill holes needed to pass from the highest to lowest mesh complies with the law of diminishing returns as the number of drill hole is increased by at least 50 per cent, which translates to a very high additional cost but only associates with only a marginal increase in confidence.

The expected error for the different materials and drill hole spacing is presented in Figure 12. This error is higher for the oxides than the sulfides in every sampling grid. Also the error is related to the geological variability into the interface zone between both units. The expected error for the sulfides below the interface zone (deep sulfides) decreases, because the geological boundary factor is no longer active and only leading to express the variability of copper grades.

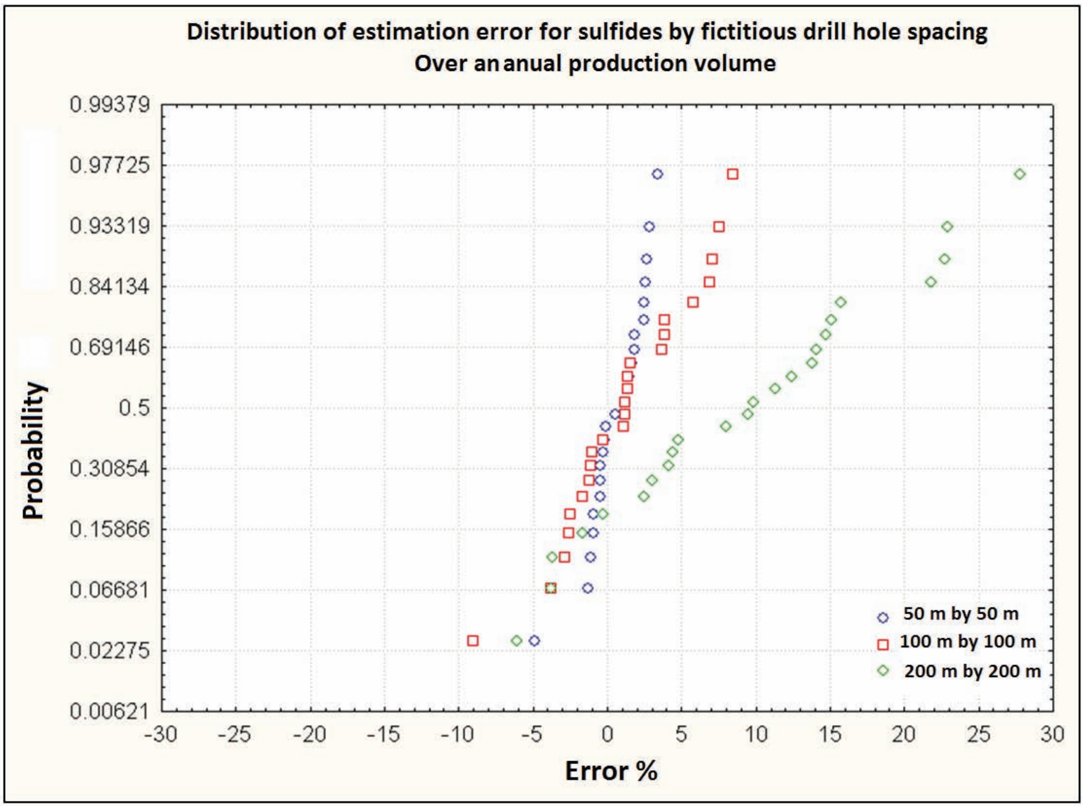

FIG 11 - Distribution of estimation error for primary ore showing the accuracy and precision of the estimated models based on different fictitious drilling spacing grids.

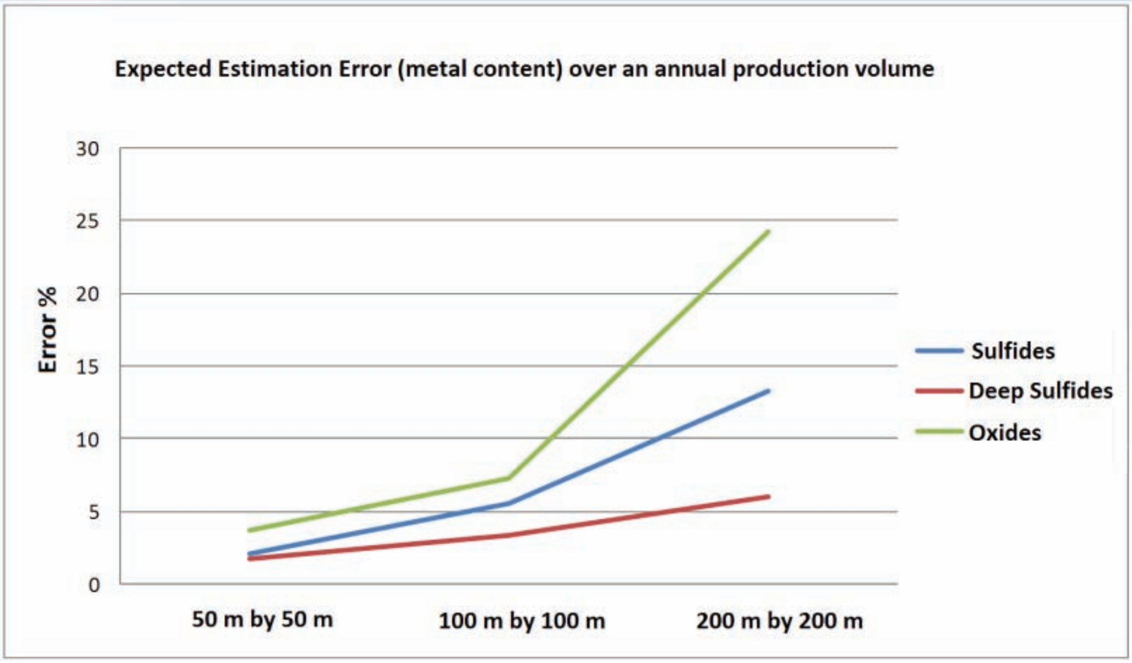

FIG 12 - Expected estimation error (metal content) over annual volume as function of drilling spacing grids showing different behaviour for sulfides ore, deep sulfides ore and oxide ore.

With these outputs we can define the optimal spacing of mesh sampling for each class of mineral resource: measured, indicated and inferred. Additionally an optimisation of the drilling budget can been made, potentially allowing for a re-assignment of infill drilling budgets to other programs related to geotechnical, geometallurgical and hydrogeological studies that are also critical for to project.

CONCLUSIONS

To quantify the estimation errors in the Telégrafo porphyry copper deposit, we have successfully applied the techniques for implicit geological modelling and conditional simulations. With these tools it has been possible to generate 25 random outputs of the deposit and resource models for four different sampling meshes.

The reconciliation between the original model and the resource model related to different sampling meshes has enabled us to obtain distribution of estimation error for each sampling mesh. This has been used to support a resource classification criterion for Telégrafo and define the potential benefits (and associated cost) if the number of drill holes is increased. We have succeeded in defining the optimal thresholds for drill holes grids in relation to the desired mineral resource categories.

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