INDICATOR COKRIGING FOR CONSTRUCTION AND CONDITIONAL COSIMULATION FOR COMPARISON OF RESOURCES MODELS, QUETENA

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ABSTRACT

Quetena is a porphyry copper deposit located in the Chuquicamata district. The Oxide zone has an interesting economic potential for Codelco Norte. For this reason, the correct volume and characterisation of the copper solubility ratio is a critical factor for the Quetena project, presently in the conceptual (scoping) study stage.

Currently, the project has two available resource models. The first model has been built using a definition unit exclusively based on the geological mapping. This model was created by manual interpretation (deterministic). The second model uses a definition unit based on geological mapping, total copper (CuT) and soluble copper (CuS) contents, and solubility ratio (CuS/CuT). The spatial extent of the units was performed in a probabilistic way using indicator cokriging of the units. In both models, the total and soluble copper grades are estimated in geological units.

In order to compare the robustness of both models in relation to solubility ratio and indirect definition of the units, a global conditional cosimulation (using turning band) of the CuT and CuS grades was done on point support. For cosimulations 100 realisations were generated. At each node, the expected conditional solubility ratio was calculated at point support by averaging the solubility ratio (CuS/CuT) for each realisation. This solubility ratio has been compared within the two resources models: probabilistic and deterministic.

In this work, the advantages and disadvantages of using deterministic/probability models in an early stage of a mining project are presented. It is remarked that the probabilistic models are complementary and can provide a guide for the construction process of the traditional geological models in a more quick, precise and reliable way.

INTRODUCTION

Quetena is a porphyry copper deposit located in the Chuquicamata district. Quetena has been discovered in 2002, as a deposit close to Toki.

Division Codelco Norte (DCN) has resources over 17000 million tonnes with 0.52% total copper grades, the resources are mostly sulphides minerals. Codelco Norte will face the depletion of leachable ore reserves in the next decade, because Mina Sur and Radomiro Tomic will finish theirs oxides reserves, leaving hydrometallurgical plants available. For this reason, Oxides of Quetena project are strategic to continue with SX-EW production lines. In consequence, the correct volume and characterisation of oxides zones and copper solubility ratio are critical factors for feasibility of the project. In contrast, ore sulphides of project are not high priority by Codelco Norte because the mineralisation sulphides (chalcopyrite and bornite) have low leachable potential.

Currently, the project comes to pass from advanced exploration stage to scoping study. During last infill drill hole campaign 2008 have been drilled over 10000 meters of diamond core.

Historically, the Quetena project has presented problems with estimation proportion of the structural leached unit because low density of data, drill hole grid spaced over 100x100m.

The project developed two resource models. Geological units used as mineralisation controls for both models were minerals zones, these are associated with supergene processes. The first model has been built using a definition unit exclusively based on the geological mapping regardless grades. This model was created by manual interpretation (deterministic) on sections separated each 100 meters in direction North-South and plans each 30 levels. The second model (probabilistic) uses a definition unit based on geological mapping, Total Copper (CuT) and Soluble Copper (CuS) contents, and solubility ratio (CuS/CuT). The spatial extent of the units was performed in a probabilistic way using indicator cokriging of the units. In both models, the total and soluble copper grades are estimated on geological units.

Both models were constructed on based in the same database with two codes of units. A stochastic approach was applied with the goal to validate and compare the robustness of both models in relation to solubility ratio and indirect definition of the units. A global conditional cosimulation (using turning band) of the CuT and CuS grades were done on point support. For cosimulations 100 realisations were generated. At each node, the expected conditional solubility ratio was calculated at point support by averaging the solubility ratio (CuS/CuT) for each realisation. This solubility ratio has been compared within the two resources models: deterministic and probabilistic.

DATA INFORMATION

The current spacing between diamond core drill holes is in order of 100x100m. Quetena has over 36,000 metres of diamond drill hole with records geological mapping and grades analyses. The data base is based on support samples of 1.5 meters.

The Figure 1 shows in plan view, the drill holes traces separated between historical and last campaign.

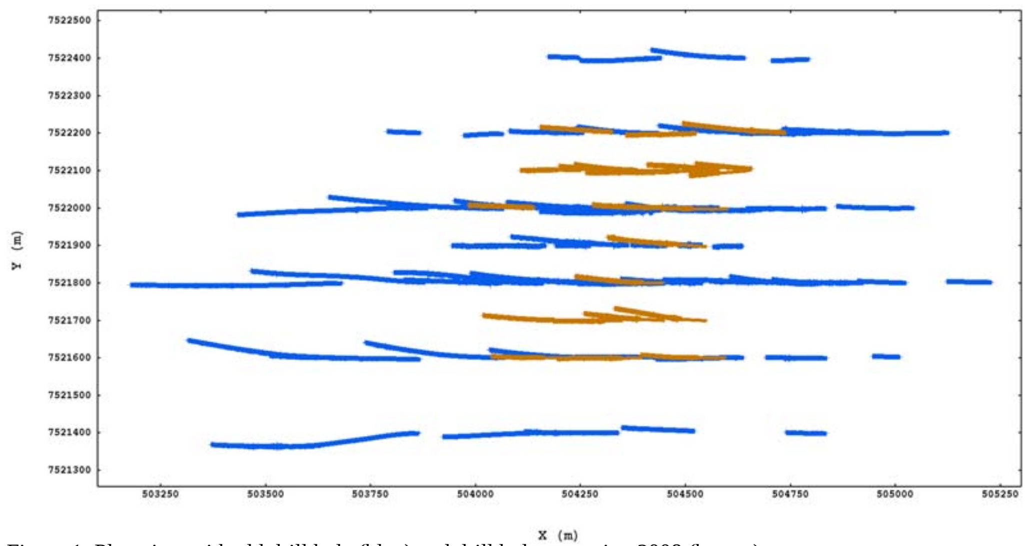

Figure 1: Plan view with old drill hole (blue) and drill hole campaign 2008 (brown)

GEOLOGY AND UNITS

Quetena has a gravel overburden of 100 meters of thickness on average. The mineralisation was emplaced by means on tonalitic porphyry and host rocks (composed by tonalites and andesites mainly) also were mineralised.

Oxides Zones Units

Both approaches (probabilistic and deterministic) model the same oxides units, but theses were defined with different geological attributes:

- **Green Oxides (OXV):** This unit is characterised by high presence of chrysocolla, malachite, seudomalachite and atacamite and a low abundance of black oxides. This unit should have control over the distributions of high total copper grade and high solubility ratio (Cus/CuT).
- **Black Oxides (OXN):** unit with abundance of copper wad, copper black oxides, tenorite and others. This unit is located around of green oxides units. Also, this unit has an important presence of limonite. The solubility of black oxides is medium, explained by the presence of minerals with low leaching kinetics.
- **Leach (LIX):** this unit is characterised by presence of disseminated limonite and structurally controlled limonite. **Structural leached** are associated to faults, dykes or high permeable zones, where fluid were channelled, alterating and leaching the mineralisation, producing iron oxides and removing copper oxides. Mineralisation with content copper is scarce. This unit presents low solubility ratio.
- **Mixes (MIX):** this unit represents the coexistence of sulphides and oxides mineralisation i.e. it is possible to find sulphides mineralisation with presence of oxides minerals. The solubility ratio is low in this unit.

The green oxides are in the centre of the ore body surrounded by black oxides. These units are crossed by structural leach and the amount of limonite increases to the outer part of the deposit.

The historical information of geologic mapping presents quality deficiencies in the logging and consequently in the oxides zones classification among green oxides, black oxides, leached and mixed. The characterisation visual of oxides minerals is complex, this requires good training and experience for to distinguish oxides minerals.

METHODOLOGY

For the project two resources models have been developed:

Deterministic model: The first model was built with recoded units based exclusively on geological mapping without consideration of total and soluble copper grades. The model was created by the plan view interpretation of mapped information using a set of control sections, after that plan view interpretations are modelled and finally extruded (traditional way). After this, the model was estimated using ordinary kriging for total copper and soluble copper grades for each unit and finally reblocked to 25x25x15 m.

Probabilistic model: The second model uses a different recode of units approach based on geological mapping, total copper (CuT) and soluble copper (CuS) contents, and the solubility ratio (CuS/CuT). The spatial extension of the units was made in a probabilistic way using indicator cokriging (ICK) of the units. The indicator cokriging provides proportions or probabilities for each unit in each block. Then CuT and CuS grades estimation were done for each unit. Finally, the proportions and grades were weighted to obtain total copper and soluble copper grades estimation. Then the final block model was reblocked to 15x15x15 m.

Indicator cokriging has advantages for the models where the units have border effect or in the case of nested units in relation to the independent indicator kriging [1]. Simple and cross indicator variograms of four units are shown in Figure 2.

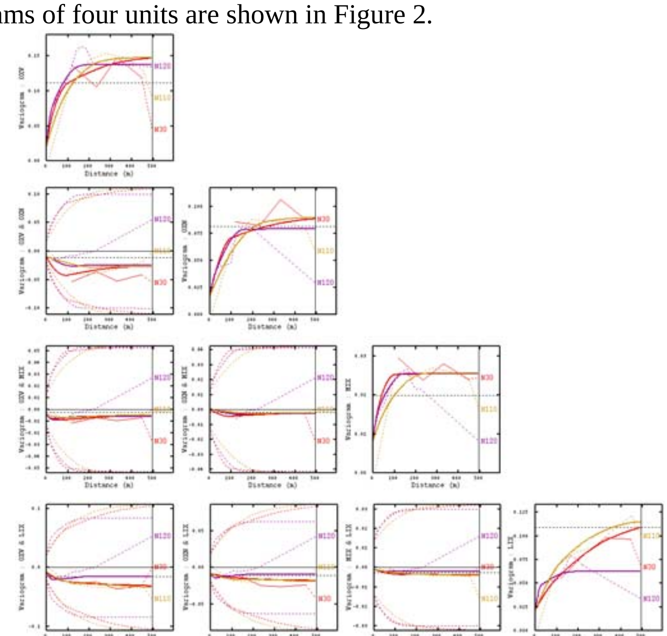

Figure 2: Direct and cross indicator variograms

Figure 3 presents a perspective view of the green oxides proportions (co)estimated by ICK.

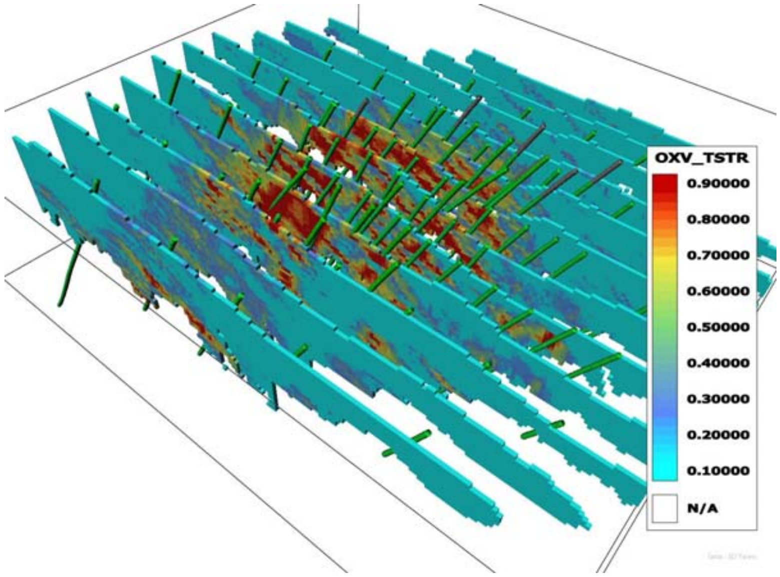

Figure 3: Isometric view, probability or proportions of green oxides and drill hole data

Comparison with Solubility Ratio Calculated from Cosimulation of CuT and CuS

The robustness both models was compared with respect to a global estimation of spatial distribution of solubility ratio by indirectly way. Solubility ratio was calculated in each block by means of conditional simulation, this allows comparing indirectly of definition of the units. A conditional gaussian cosimulation (using turning band [2]) of the grades CuT and CuS was done to punctual support without considering the geological units. For cosimulation 100 realisations were generated. At each node, the expected conditional solubility ratio was calculated at point support by averaging the solubility ratio (CuS/CuT) for each realisation: this is the conditional expectation estimator [3].This solubility ratio has been compared to both resource models available.

The cosimulation was done with all zone oxides limited between top rock - gravel contact and in the bottom with limited sulphides presence.

The scatter plot total copper and soluble copper have good correlation in raw and normal score transformation.

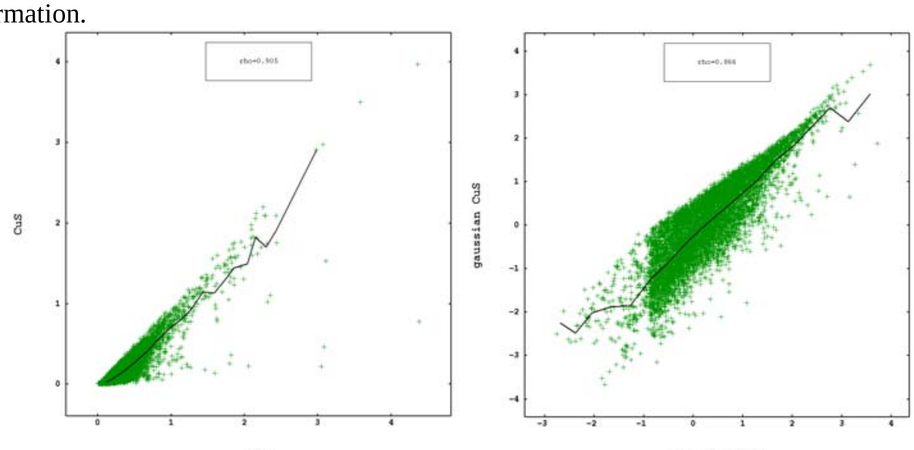

Figure 4: Scatter plot of CuT and CuS on composites 1.5 m with conditional expectation curve (CuS/CuT) on raw data and normal score transformation.

The variograms of normal score transformation of CuT and CuS are shown in Figure 5. There is no evidence of anisotropy due to the low density of information, and to avoid an artificial preferential trend, an omnidirectional variogram for CuT and CuS were calculated.

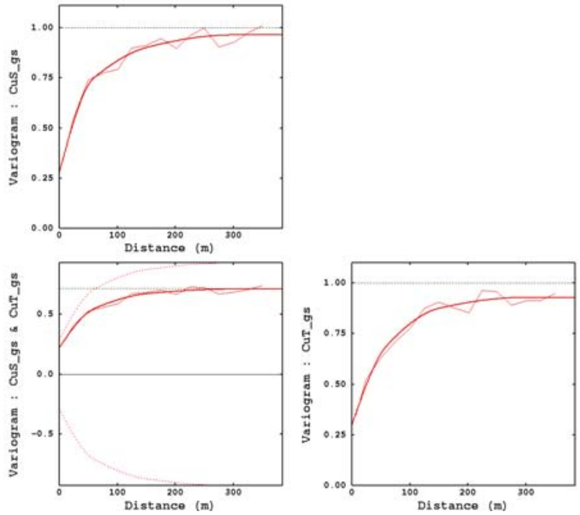

Figure 5: Bivariate experimental and modelled variograms of Gaussian transformation CuS and CuT

RESOURCES

Both estimations have very similar resources. Some observations are possible to do:

- The probabilistic model presents more metal copper for the cutoff grade 0.35% CuT than the deterministic model; this is explained by a mixture of units in latter one.
- Indicator cokriging model presents more tonnage in cutoffs lower than 0.25% CuT in relation to the traditional model. This difference can be explained, because the coestimation of units was done using only drill hole samples without a border limit i.e. the indicator cokriging was extrapolated in the domain. Artificial point control may be added in the waste zone at the outer part of the deposit to avoid the extrapolation of low grades. The relative metal copper of two models is shown in Figure 6.

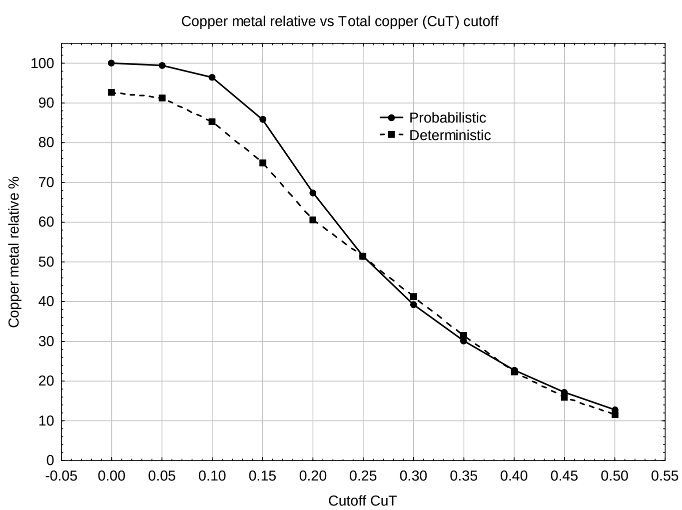

Figure 6: Copper metal relative vs. total copper cutoff of both models

COMPARISON SOLUBILITY RATIO CALCULATED FROM COSIMULATIONS

The results of the cosimulation of CuT and CuS reflect the global trends of the spatial distribution of the solubility ratio (high and low values zones). The cosimulation was done over the oxides domains without accounting for the geological units (Figure 7), the following aspects can be stated:

- The cosimulated solubility map shows a better match with the units of the probabilistic model. The Green oxides unit of the probabilistic model presents a similar shape to the high solubility zone, whereas the black oxides unit is associated to medium solubility ratio around green oxides.
- For the deterministic model, the green oxides are present over the whole domain with a wide range of solubility ratio, mixing high and low solubility ratios.
- The solubility approach exhibits a North-South trend caused by a structural leach unit that is present in the deterministic model. The probabilistic model does not reflect that unit.
- The conditional cosimulation does not directly consider the relation order (CuS<CuT) of the cosimulated variables. For this reason is possible to find cosimulated grades where the soluble copper is greater than the total copper, situation without physical sense. That mainly happens in the outer part of the deposit associated to low grade zones. A conditional cosimulation approach that considers variable constrains should be studied and developed.
- The high solubility zone could be used as guidance for the 2D manual interpretation of the green oxides unit, reducing the time and complexity of the 2D interpretation and consequently the 3D construction.
- Solubility ratio can be obtained by the independent cosimulations of CuT and CuS grades for each geological unit, and then comparing and reviewing the definition consistence of each unit.

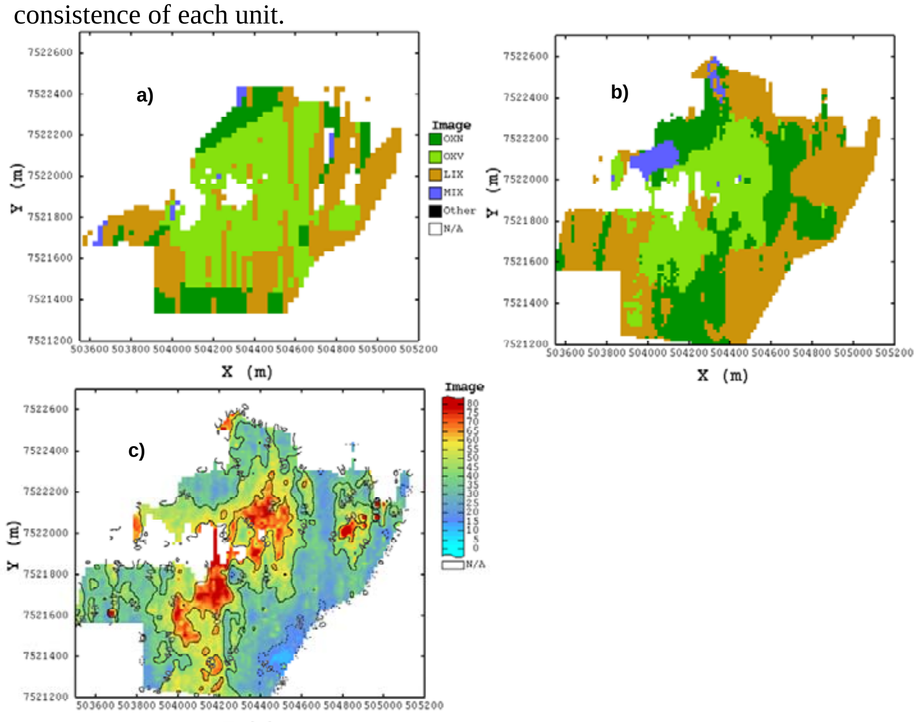

Figure 7: Level 2125 a) deterministic model units, b) probabilistic model units and c) solubility ratio map from cosimulation of CuT and CuS with isocurve.

CONCLUSIONS

The solubility ratio calculated using cosimulation of CuT and CuS provides a global picture of the trends of the high and low solubility zones and generally shows a better match to the probabilistic model. To improve these results, the solubility ratio could be calculated by each geological unit using the data at each domain. The results of this work indicate that the deterministic and probabilistic models provide very similar copper metal resources from a global point of view.

The probabilistic models are especially adequate when the geology of the deposit exhibits a simple geometry and when the decisions about the project are global without a highly detailed level. The generation of the probabilistic models is faster than the traditional way, with the consequent cost decreasing, which allows us to make decisions in the early stage of the project. Also, the construction process is fully reproducible, auditable and easily modified or updated in function of new data or a new geological concept.

In addition, the probabilistic models can be used as guidance for the geologist to perform the geological interpretation, in this the case of study the mineral domains.

There are several available methods to build a probabilistic model of geological domains such as indicator kriging, indicator cokriging or truncated gaussian kriging [4]. The key aspect is choosing the more suitable method depending on the geological setting of the deposit.

However, the probabilistic models are not the panacea; a purely data-driven numerical modelling could provide an incomplete or unreal picture of the deposit because there is a lot of geological knowledge beyond the sample data that should be considered and incorporated in the probabilistic approach. The incorporation of that knowledge could be achieved by adding some control points and by sampling the available geological interpretation [5].

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NOMENCLATURE

CuT	total copper grade
CuS	soluble copper grade
OXV	green oxides
OXN	black oxides
LIX	leached
MIX	mixed
ICK	indicator cokriging

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