CHARACTERIZATION OF UNCERTAINTY OF RESOURCES AND RESERVES: CASE STUDY ON THE ESCONDIDA AND ESCONDIDA NORTE COPPER DEPOSITS.

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ABSTRACT

The Escondida mining operation complex consist of two open pits feeding 4 processing plants at a total mining rate of 1 million metric tons per day. Successful completion of the business plan demands a good understanding of the uncertainty related to the mineral resources. The Annual Budget and the 5-year Mine Plan are developed from the Long Term Mineral Resource Model where the only indication of uncertainty on the mineral resources is provided by the Resource Categorization attached to each Long Term Model (LTM). The resource categories are developed globally, and are based on a general understanding of drill hole spacing and uncertainties related to the geologic and grade estimation models. Although the original intent of resource categorization systems is to provide an indication of global resource uncertainty, it is often used as a measure of local accuracy when developing mine plans. This is clearly bad practice, although quite common.

Conditional Simulation studies (CS) of metal deposits have become practical tools to develop models of uncertainty from which risk related to the mineral resources can be quantified. The adequacy of the current Resource Categorization method for properly describing the uncertainty related to the mineral resource was compared to the uncertainty model provided by a conditional simulation study recently carried out for both deposits. The resource categories as developed for the LTM are compared to the uncertainty described by the CS model. The availability of a distribution of values for each resource category instead of a single value, allows the calculation of confidence intervals for different cut off grades of tonnages, grade and contained metal.

Geological domains that controls copper grade distribution have been simulated along with TCu (total copper) and SCu (soluble copper) for both La Escondida and Escondida Norte deposits within the 5-year mine plan volume. The conditional simulation models provide a useful tool to validate the current categorization system as a descriptor of uncertainty on the mineral resource. The exercise was carried out comparing globally, by pushback, and by different production periods the uncertainty models from the conditional simulations to the uncertainty as described by the resource categorization system.

It was found that uncertainty within the Escondida 5-year mine plan is approximately +1.5 –1% with 90% confidence at all cut off grades. Uncertainty increases from FY05 through FY09, with ore tonnage more uncertain than copper grade.

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INTRODUCTION

The main objective of this work was to obtain a series of conditional simulation models for both the Escondida and the Escondida Norte deposits. These models were used to analyze different issues related to uncertainty and risk of resources and reserves.

Some of the applications derived from the simulation models involved a global uncertainty study for both deposits; a study on probability intervals derived from the simulations and how they support or relate to the resource classification schemes used; a change of support analysis comparing the dilution incorporated in the block model and the simulation models; derivation of optimum drill hole spacing based on different risk criteria; and risk studies related to pit optimization and mine scheduling, including yearly risk profiles based on the current mine plan.

To achieve the main objectives of this work, it was necessary to define the methodology to apply to both deposits, such that a reasonable geologic and grade representation can be obtained, given the current knowledge and data.

It is important to describe a joint space of uncertainty stemming from different sources of uncertainty, and in this case the geologic (estimation) domains and the Total (TCu) and Soluble Copper (SCu) variables were simulated. For the simulation of domains, a Sequential Indicator Simulation (SIS) with a local-varying mean was used, and a Sequential Gaussian Simulation (SGS) for grade simulation in the sulphide zones of the deposit. For those areas were SCu is important (above the Top-of-Sulphides surface), a simulation using the Stepwise Conditioning transformation was chosen (Leuangthong and Deutsch, 2003).

Due to space constraints, this paper summarizes only the conclusions of the study related to uncertainty of the resources and the risk of scheduled reserves not meeting the targets as stated in Escondida's 5-year Mine Plan.

METHODOLOGY

The method of choice for characterizing uncertainty is geostatistical conditional simulations. No detailed description of the techniques applied can be afforded here, so the reader is referred to some of the key references on the subject: Journel (1988), Journel and Deutsch (1998), Goovaerts (1997).

The simulated nodes for each variable should reproduce the histogram of the original data used in the simulation, in this case 15m TCu and SCu composite grades from the original drillhole data.

The simulated nodes were defined such that they are consistent with the resource block model, which is based on 25 x 25 x 15m blocks. The grade simulations were obtained on a 5 x 5 x 15m grid, while the nodes used in the geologic simulation were defined at 12.5 x 12.5 x 15m, in both cases with the same origin than the existing resource model. Thus, all simulated nodes can be averaged up straightforwardly into blocks coincidental with the resource model blocks.

Thirty simulations of geologic domains and 30 simulations of TCu and SCu grades were obtained for each deposit. Each simulated geologic domain was the basis for the grade simulation that corresponds to that domain. The simulated volume was such that it encompasses only the upcoming 5 year's production (according to the existing mine schedule at the time), and thus all uncertainty and risk analysis refers to the 5-year timeframe.

The specific steps used to develop the simulation models were:

1. Perform a categorical simulation of geologic attributes, using Sequential Indicator Simulation with a local varying mean (SIS-lvm). For both the Escondida and Escondida Norte deposits, the direct simulation of estimation/simulation domains (or Geologic Units, GUs) was preferred for practical reasons, since the estimation domains (GUs) are defined based on 4 variables (mineral type, lithology, alteration, and structural domains), and thus the simulation work world be much more involved. The simulated nodes were laid out on a 5 x 5 x 15m grid for both deposits. In both cases 15m down-the-hole composites were used, as 15m is the bench height used in the operation.

2. Total and Soluble Copper (TCu and SCu) were simulated using the stepwise conditioning transformation (Leuangthong and Deutsch, 2003), followed by an independent Sequential Gaussian Simulation (SGS) for each grade. The correlation between both was recovered with the stepwise back transform. This simulation was completed only for the material above the Top of Dominant Sulphides (TDS) surface, as simulated in the prior step. The grade simulation was completed on a 5 x 5 x15m grid.

3. Only Total Copper (TCu) grades were simulated below the TDS surface, using SGS, and on the same 5 x 5 x 15m grid. In all cases, (including Step 2 above), each grade simulation was conditioned to a categorical GU simulation obtained in Step 1. Thus, the final simulated grades incorporate a degree of uncertainty as described by the GU simulation.

4. The grade simulations were extensively validated, comparing histograms, basic statistics, and variogram models to the corresponding statistics of the 15m composites used in the simulation.

5. The grade simulations were reblocked to the same 25 x 25 x 15m blocks corresponding to the resource block model (in both deposits), such that a direct comparison between the resource block model grades and the simulated grades can be made.

6. In the case of the Escondida deposit, there are a large number of blast holes available for further validation. This was done by defining a surface 50m above the topographic surface available at the time of this study, which corresponded to the open pit status as of January 31, 2004. The blast holes were also averaged into the same 25 x 25 x 15m blocks, allowing for a comparison of the simulated grades vs. blast holes grades.

Categorical Simulations

At the Escondida deposit, a total of 5 GUs have been defined above the TDS, and another 13 GUs below the TDS. For Escondida Norte, 9 GUs have been defined, of which 3 are above the TDS, and thus required the simulation of SCu. As discussed above, the GUs are combinations of mineral types, lithology, alteration, and structural domain, which define different estimation (simulation) domains.

The simulation of discrete variables using SIS (Alabert, 1987, Journel, 1988) calls for the definition of the thresholds that define the different categories being simulated, in this case the GUs. The manner in which the categories are defined is irrelevant, since the simulated GU is based on randomly drawing a GU from the posterior cumulative distribution function obtained with multiple indicator kriging. In addition, the SIS applied in this study relied on a prior estimation of local means for all categories, which are in essence probability of occurrence, estimated for the same nodes being simulated. These local means are then used as conditioning information in the SIS, helping reduce artificial noise resulting from very small non-zero probabilities of occurrences for certain units. This is particularly important when the number of units being simulated is large, since it is likely that there will be several GUs at some nodes with small probabilities.

The indicator variograms for each GU, using the 15m composites, were fitted with anisotropic spherical models. For some of the enrichment units, the general continuity pattern is sub-horizontal, although one of the high supergene enrichment units in Escondida Norte shows a sub-vertical trend, assumed to reflect local structures. Except for some of the more volumetrically significant GUs, variability is generally high, particularly in the Southwest area of the Escondida deposit.

To obtain each of the 30 SIS simulations, a series of parameters need to be defined, similar to any estimation using kriging, and including search radii, orientation of search ellipsoid, the definition of octant search or not, the minimum and maximum number of composites and previously simulated nodes to be used, etc. The specifics of the implementation of the technique depend on the software used, in this case a modified SIS routine taken from GSLIB (Deustch and Journel, 1998).

Validation of the Categorical Simulations

In the case of categorical simulations, it is expected that the simulated values reproduce the proportions of each GU, and also reproduce reasonably well the corresponding indicator variogram model.

Figure 1 shows the histogram of the proportions of simulated values for simulations No. 10 and 23, along with the proportions of the resource block model. Note that in this case the proportions of the 15m composites and the resource block model are very similar, because, by construction, the composites were tagged with the interpreted geologic variables. Figure 2 shows the same comparison for Escondida Norte. In general, the proportions of the simulated GU are fairly well reproduced, although there are some units (such as Escondida's GU 1, 6, and 17, or Escondida Norte's GU 3 and 4) where there is a relative volumetric deficit, and which happen to be generally good grade units. Although the differences are only in the order of 2 to 3% relative, which is considered reasonable, this is consequential for the overall prediction of material above cutoff, and at the time warranted further investigation.

As an example of the indicator variogram checks, Figure 3 shows the indicator variogram resulting from the simulated nodes for GU 6 (Escondida), along with the indicator variogram model used in the simulation, corresponding to two of the principal directions of anisotropy, azimuths 150º and 240º. In both cases, the variograms correspond to the horizontal plane. Observe how the simulated nodes reproduce fairly well the variogram model, implying that the spatial variability and distribution of the GUs are well reproduced.

Figure 4 shows Escondida's Bench 2875 comparing the Resource Model GUs (left) and two simulations (Nos. 10 and 23) center and right, respectively. In general, the spatial patterns of the GUs are reproduced very nicely, with the most notable differences near contacts, as expected. Similar conclusions can be reached from Figure 5, which shows the same comparison for Bench 3020 at Escondida Norte.

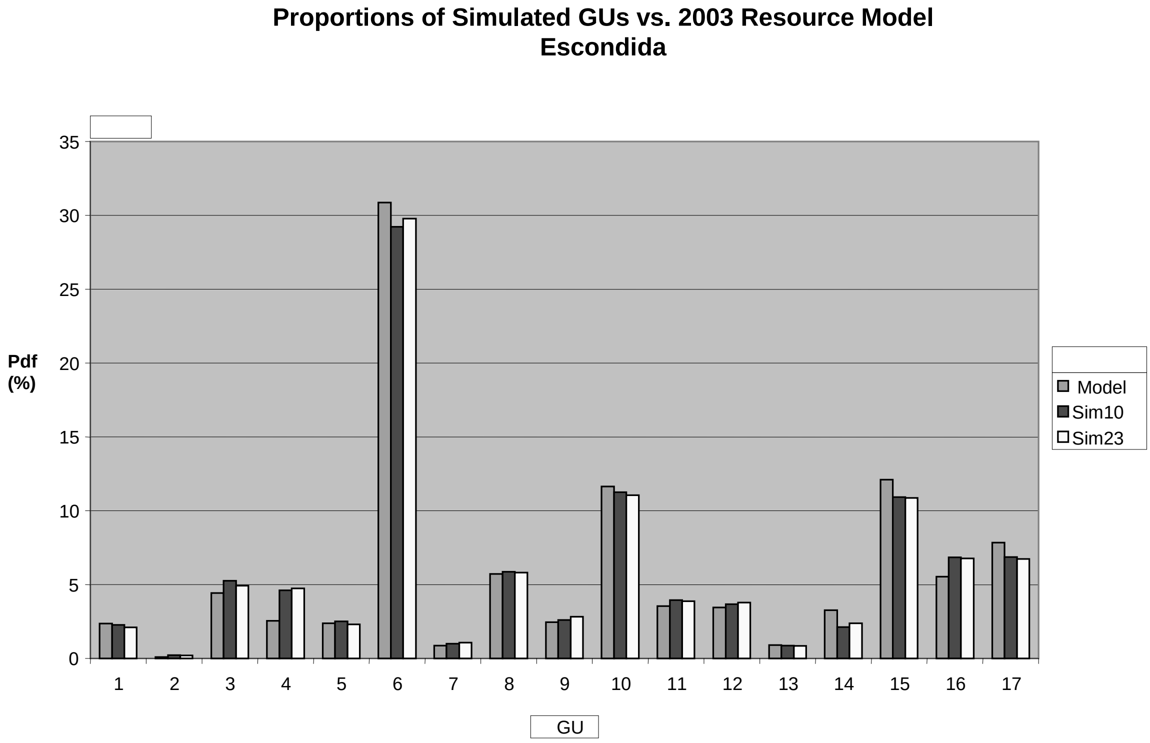

Figure 1: Proportions of simulated GUs (Sims 10 and 23) vs. October 2003 Resource Model, Escondida.

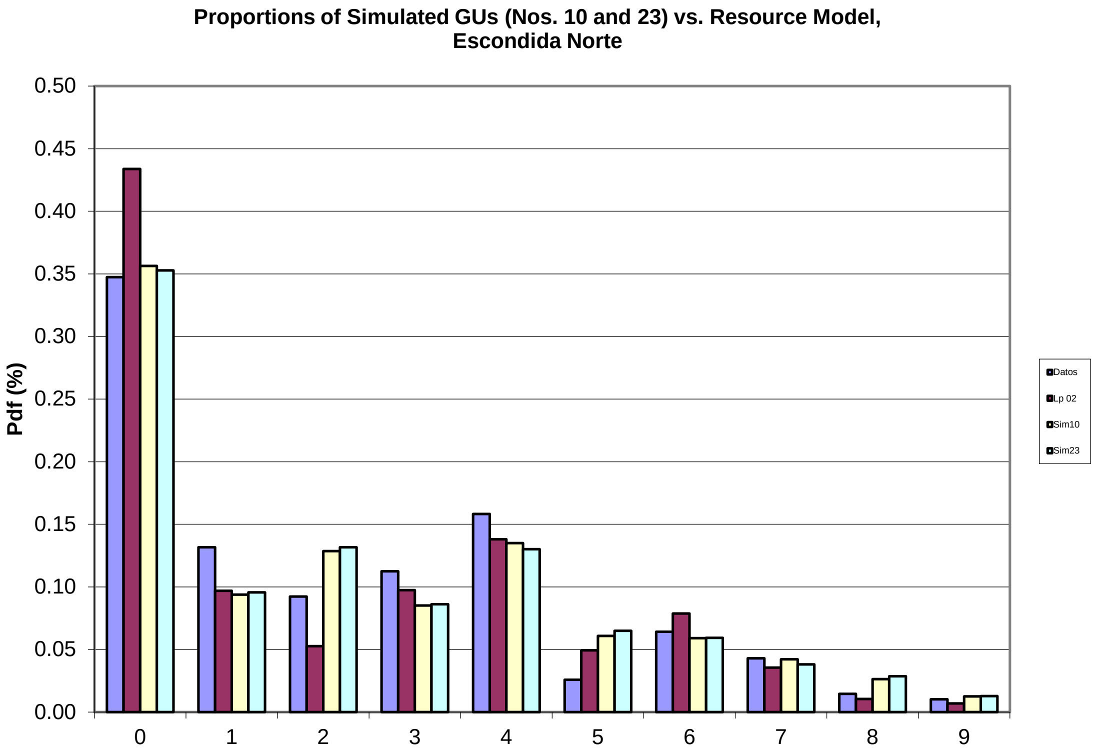

Figure 2: Proportions of simulated GUs (Sims 10 and 23) vs. Resource Model, Escondida Norte.

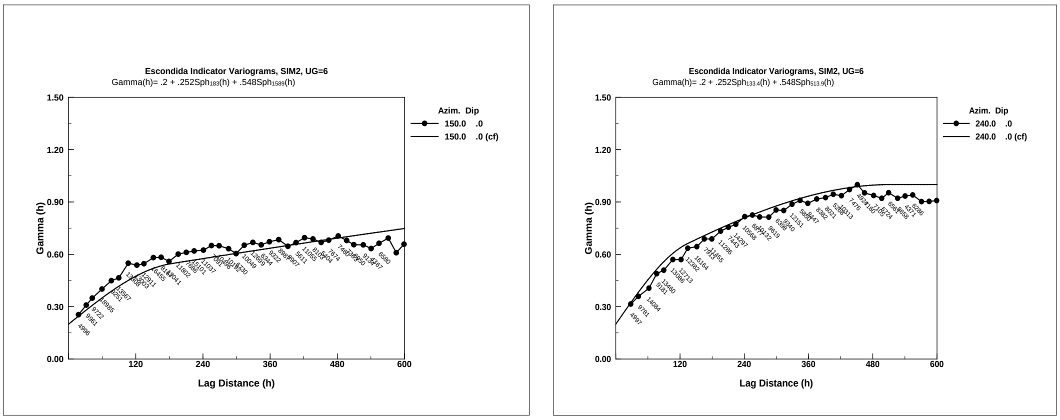

Figure 3: Indicator Variogram, GU 6, Escondida, Simulation 2, with spherical model used to simulate, Azimuth 150°, Dip 0° (left), and Azimuth 240°, Dip 0°.

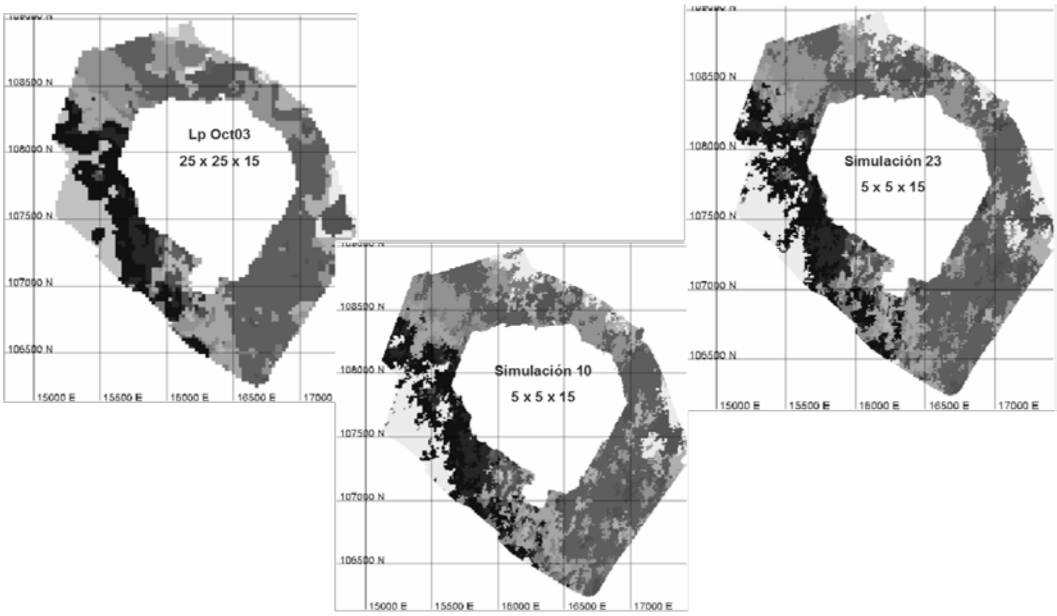

Figure 4: GUs Resource Model and Sims No. 10 and 23, Bench 2875, Escondida.

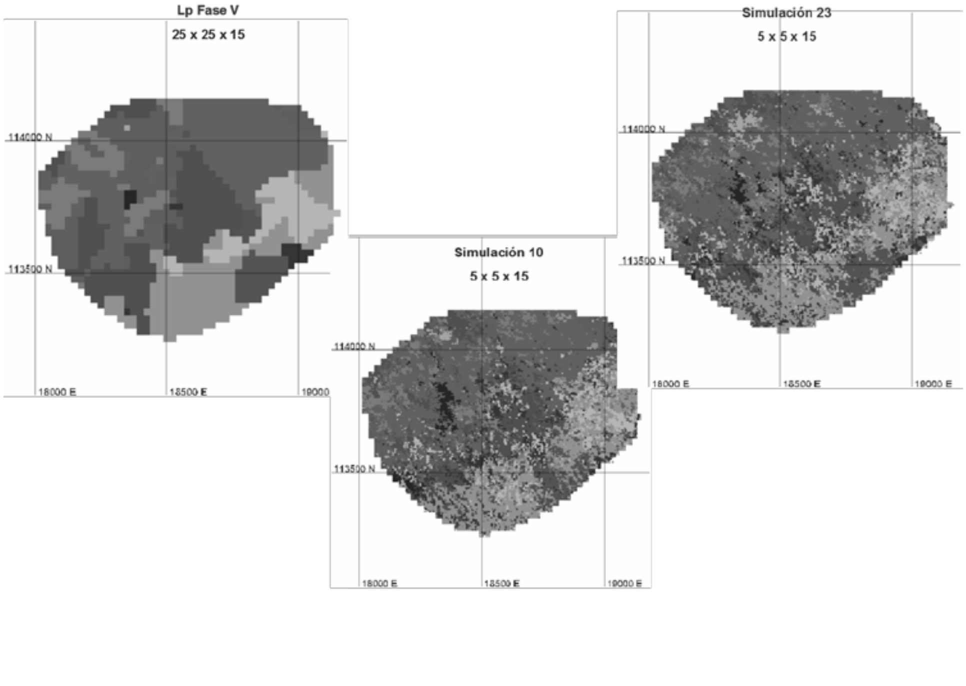

Figure 5: GUs Resource Model and Sims No. 10 and 23, Bench 3020, Escondida Norte.

TCu and SCu Grade Simulations

For those units for which SCu is significant (oxides, partial leach, and sulphide/oxide mixed mineralization), it is important to consider the correlation of SCu and TCu at the time of simulation. To this end, the stepwise conditioning transformation (SCT) was used to preserve the relationship between the two grade variables. The method is based on transforming the two variables to the Gaussian space such that they can be independently simulated (using SGS), and then recovering the relationship for the simulated values at the time of back transforming the data to the original space. The SCT method is applied such that the chemical relationship SCu ≤ TCu is preserved, which meant that it is convenient in some cases to simulate the variable Insoluble Cu (ICu), which is the difference between TCu and SCu. The details of the extensive Exploratory Data Analysis and the required transformations are not described here because of space limitations.

For those units below the TDS, only TCu was simulated, using the same SGS technique. The details of the method can be found in Isaaks (1990), and Deustch and Journel (1998), and are not described in detail here. It is important to recall that in all cases a GU simulation was used to condition each of the 30 grade simulations, which implies that each grade simulation incorporates a different GU model, and thus the resulting uncertainty model carries a measure of geologic uncertainty.

To obtain the simulations, similar to the categorical simulations and in addition to using the Gaussian variogram models, several important parameters had to be defined, such as search radii, minimum and maximum number of composites and previously simulated nodes to be used, octant searches, etc. These parameters could have a significant impact in the final uncertainty model, and so careful consideration must be given to the available choices. For more details on this subject, see for example Rossi (2003).

Validation of the TCu and SCu simulations

As before, histograms, basic statistics, and Gaussian variogram models, as well as TCu correlogram models, were checked to confirm that the simulations result in a reasonable reproduction of input statistics.

Figure 6 shows the comparison of histograms and basic statistics for GU 10, 15m composites vs. Simulation No. 10, Escondida. This is shown as an example only, considering that there are some 390 such comparisons (30 simulations and 13 GUs). In general, the reproduction of basic statistics is considered acceptable, within the expected ergodic variability.

Figure 7 shows the correlogram obtained from Simulation No. 2 for GU 3, with the model obtained from the 15m composites for TCu. The two directions shown correspond approximately to the main directions of anisotropy; the reproduction of the TCu correlogram is quite acceptable.

Figure 8 shows the simulated TCu for Bench 3020 on a 25 x 25 x 15m (simulations No 10 and 23), along with the estimated grades from the resource block model. There are some significant differences indicated by the simulated models, but later validated with further infill drilling. At the time of this study, mining at Escondida Norte had not started, so the only available information was from drill holes, in most cases fairly widely spaced.

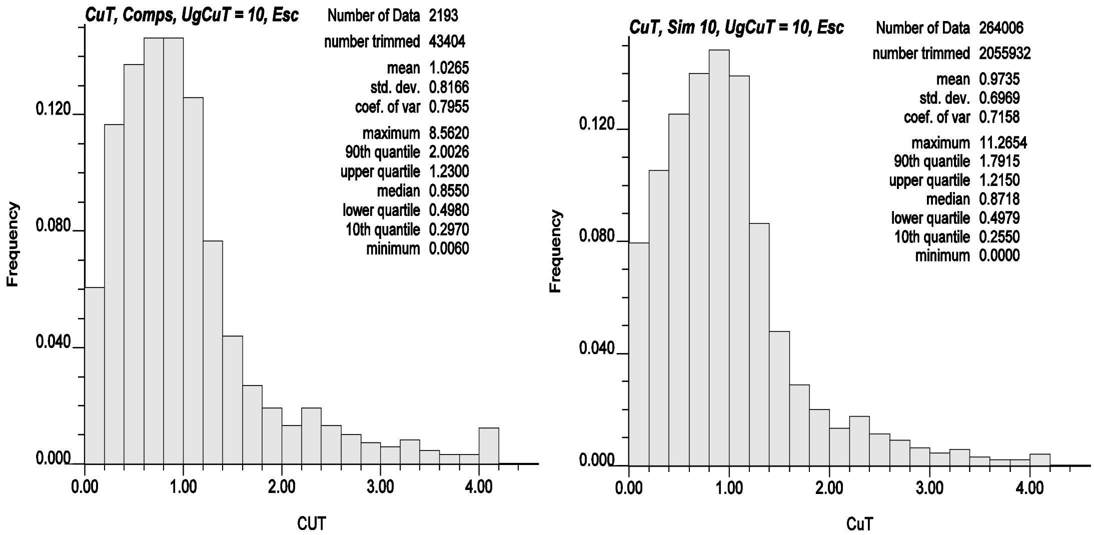

Figure 6: Histograms and basic statistics, 15m composites and Simulation No. 10, GU 10, Escondida.

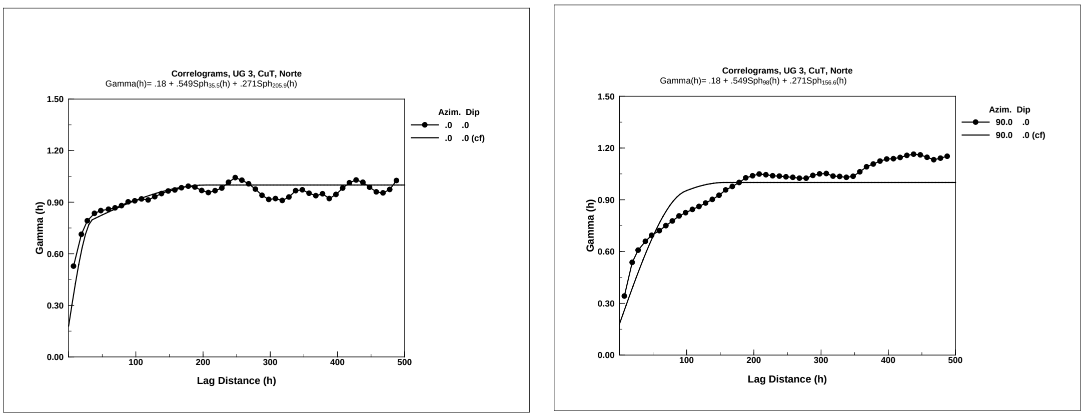

Figure 7: TCu Correlogram, GU 3, Simulation No. 2 and original model, Escondida Norte, azimuth 0°, Dip 0° (left), and azimuth 90°, Dip 0° (right).

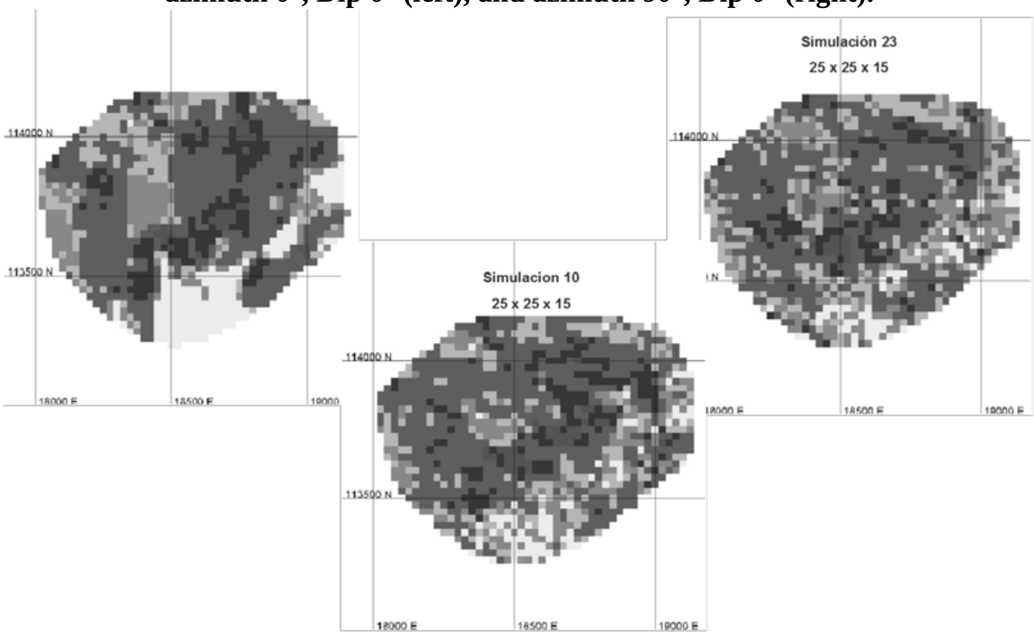

Figure 8: Resource Model and Simulations No 10 and 23, TCu on 25 x 25 x 15m blocks, Bench 3020, TCu, Escondida Norte.

RESULTS AND DISCUSSION

Conditional simulation studies have become the most useful tool to develop uncertainty models and assess risk. The most contributor to overall uncertainty in resource models is the geologic model, in this case the GU model used in both Escondida and Escondida Norte. The relative abundance and spatial distribution of the GUs determine, to a large extent, the predicted tonnage above cutoff available to be recovered.

For this same reason, uncertainty around the definition and spatial distribution of the GUs play a significant role in resource classification. The uncertainty model developed from the conditional simulations allows for a better understanding of effectiveness of the current resource classification system to capture relevant uncertainty.

Resource classification is typically a function of, among other aspects, geologic variability and availability of drill hole information to describe that variability. It is generally expected that those areas within the deposit with more drill hole information be better known, and therefore evidence less variability from one conditional simulation to another. Therefore, the uncertainty model derived from the conditional simulations can be related to resource classification schemes, and it is particularly relevant to do so by geologic domain (GU).

Assessment of the existing Resource Classification Scheme

Probability intervals based on the 30 simulations were constructed using the distribution's 95th and 5th percentiles, and referred to the average simulated value, as follows:

$$\textbf{Probability Interval } (PI_{90})(\%) = [(100 \times (P_{95} - avg) / avg);(100 \times (P_5 - avg) / avg)] \quad \textbf{(1)}$$

Probability intervals were calculated for several TCu cutoffs of interest using Eq. (1), and are presented in Figure 9 for the 5 year production as the date of the study. It should be noted that this and the following Figures show a total deviation (PI_{90}) as a sum of negative and positive variations, giving the overall expected deviations.

From Figure 9, it can be seen, for example, that the simulation model predicts that there is a 90% probability of the estimated TCu grade being within ±1.7% (relative) for the next 5 years of production (globally).

In the case of the tonnage and metal above cutoff, the expected variations with respect to the predicted values go from 1.7 to approximately 3%. Again, this variability is for the complete, global volume representing the 5-year mine plan, and with no consideration for resource categories.

The equivalent uncertainty values for a single year of the plan (FY05) are shown in Figure 10. Note that, for FY05, the uncertainty by cutoff profile is similar, but the expected relative deviations are higher, with a fairly constant 2.7% relative for TCu grade, and an increase in variability from 3 to 5.5% for different cutoffs for both tonnage and metal content. This is to be expected, since the 1-year volume is significantly smaller.

Also, but not shown here, the uncertainty for the subsequent annual increments of the mine plan (FY06 onwards) showed a gradual increase in expected variations, which is reasonable given that there is, in general, less information available to estimate grade and tonnages above cutoff further out in the future.

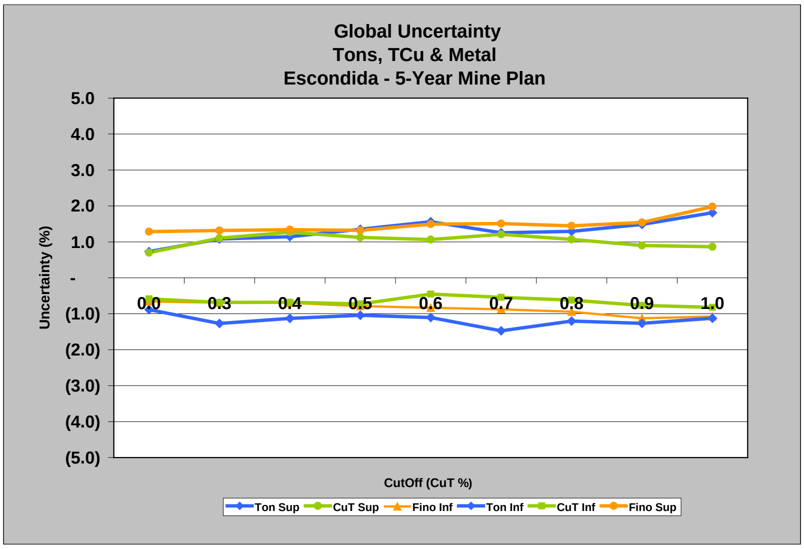

Figure 9: Global uncertainty, 5-year production plan (FY05-FY09).

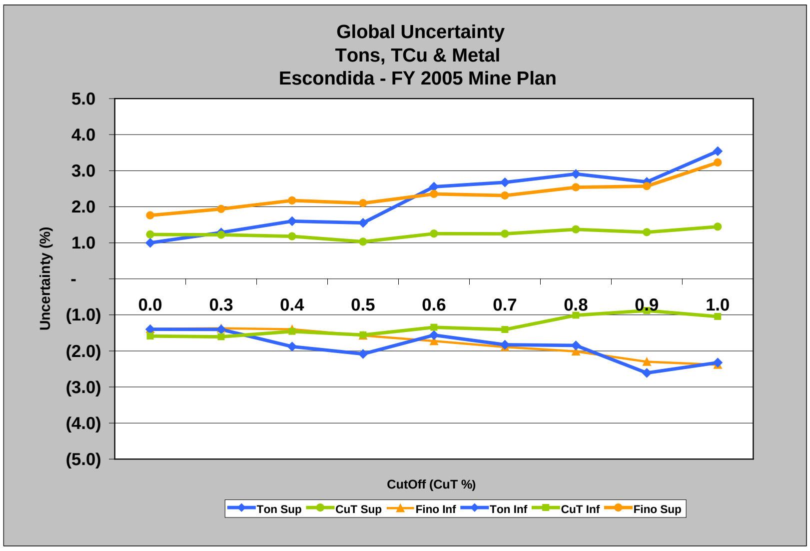

Figure 10: Predicted uncertainty for a single year (FY05) of the production plan.

Analysis by Resource Categories

When introducing resource categories into the analysis, it can be seen that there is a significant difference between measured and the other categories as defined in the Resource Model. Figure 11 compares the uncertainty model for the global tonnage and metal content (in full lines) with that portion of the resource that has been classified as measured (in dash lines). As expected, the increased confidence in the measured resources is reflected in the corresponding Probability Intervals, at about 1.8% and 2.6%. In the case of the indicated resources, the uncertainty jumps significantly, to about 5% for TCu (at all cutoffs), and between 9 and 23% relative for tonnages, the larger uncertainty at 1% TCu cutoff. The graphics are not shown here for lack of space.

Analyzing measured resources by Fiscal Year evidence that there are different degrees of measured resources, see Figure 12. Although for tonnage there is little uncertainty change from one year to the next, TCu grade is much more uncertain in later years; for example, from FY05 to FY06, grade uncertainty jumps from 2.5 to 4.5% relative, which is directly translated in contained metal. Therefore, just because the resource is classified as measured, it cannot be assumed that the uncertainty will be the same in all areas or mining periods. Similar conclusions can be obtained for the indicated resource class, not shown here.

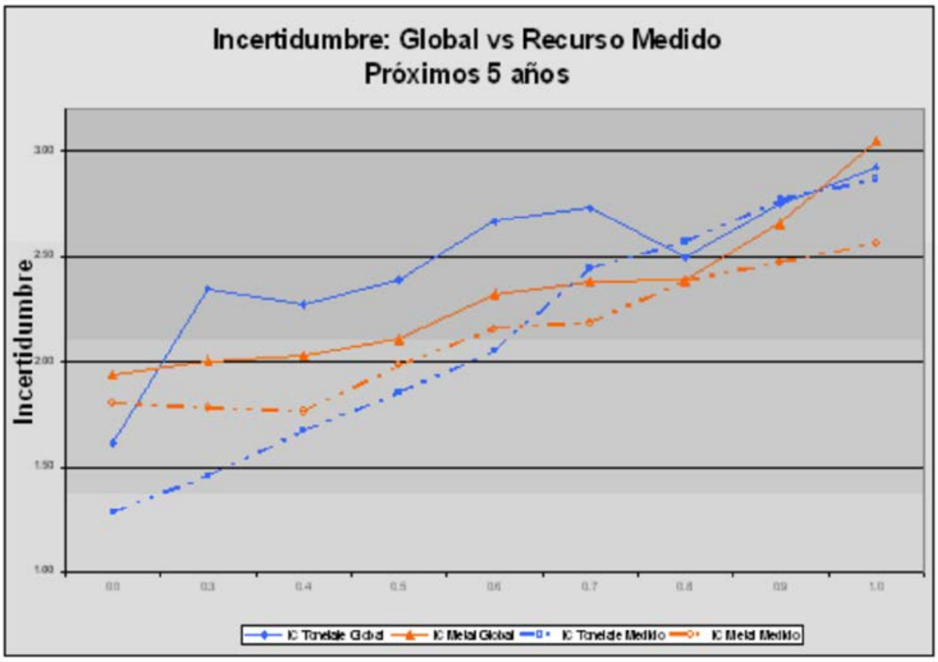

Figure 11: Comparison, Global Uncertainty vs. Measured Resources, Tonnage and Metal.

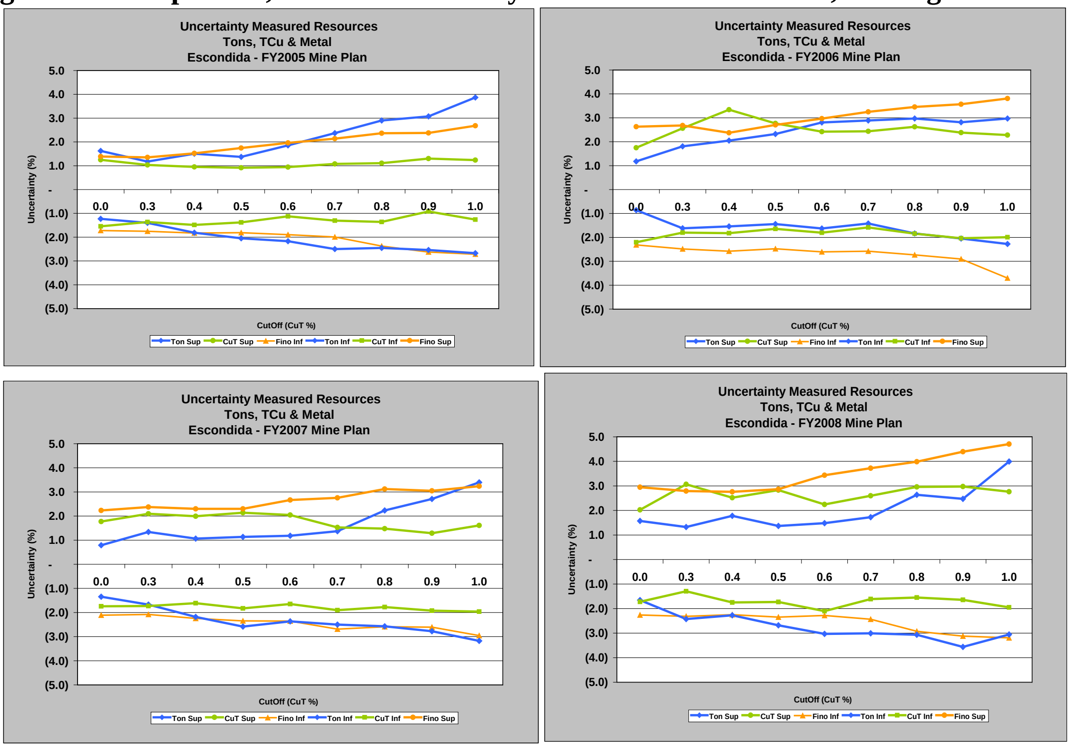

Figure 12: Uncertainty for Measured Sulphide Resources, FY05-FY08.

SUMMARY AND CONCLUSIONS

This paper has briefly discussed one of several applications of the uncertainty model developed for the Escondida and Escondida Norte deposits, relating to a description of the overall uncertainty as it relates to specific volume and resource categories. The analysis of resource classification was made according to the following characteristics:

- All comparisons are made based on 25 x 25 x 15m blocks, the same used in the resource model, which implies that this is the minimum resolution of the comparison.

- Since resource classification is a global qualitative model of uncertainty, the most relevant comparisons were made for the next 5 years production, by mine areas, by yearly production according to the mine schedule, and by resource classification. Although not all comparisons are shown here, in all cases 90% probability intervals (PI) were obtained from the simulations for each of these volumes and periods.

The conditional simulation models provide the PI in each case, from which a ranking according to levels of uncertainty can be made. These PI were also contrasted with the "acceptable" levels of uncertainty according to Mine Management, which were defined as ±5% for measured, ±10% for indicated, and ±20% for inferred resource, all considering a yearly volume. Thus, the uncertainty models resulting from the simulations provide guidance as to which volumes require further drilling, and which are in acceptable according to management's risk tolerance.

In conclusion, the evaluation of the uncertainty using conditional simulations resulted in a better understanding of the expected variations with respect to predicted values, as well as an evaluation of the existing resource classification method. The following is a summary of the main results:

- Within the volume corresponding to 5 years production (FY05-FY09) the 90% probability interval is:
  - Grade: +/- 1.7%.
  - Tonnage: +/- 3%.
  - Contained Metal: +/- 3%.

- For the Fiscal Year Fiscal 2005 the 90% PI was:
  - Grade: +/- 2.4%.
  - Tonnage: +/- 4.8%.
  - Contained Metal: +/- 4.1%.

- For the Fiscal Year Fiscal 2006 the 90% PI was:
  - Grade: +/- 4.0%.
  - Tonnage: +/- 4.3%.
  - Contained Metal: +/- 5.8%.

- The uncertainty on the indicated resources is ten times higher than the uncertainty on the measured resources, although they represent only 10% of the total production in Fiscal Years 2005-2009.

- The current resource classification method can be improved by considering not only the drill hole available and the spatial continuity of the estimation domains used, but also the area in the deposit being classified.

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