APPLICATION OF COKRIGING FOR GEOMETALLURGICAL MODELS OF LEACHING IN SULPHIDE RADOMIRO TOMIC PROJECT

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ABSTRACT

Radomiro Tomic (RT), Northern Chile, is a porphyry copper deposit that has been mined as oxide ore. Recently, Codelco Norte has focused on a new project to mine deep sulfide ore. This ore could to be sent to flotation or bio-leaching. With the goal of optimizing the mining plan sequence, a geometallurgical model has been developed to characterize and regionalize the performance of the bio-leaching process. A geometallurgical model for bio-leaching has been created using a two-layer approach. First, a set of geological sections is created using mapped distribution of sulfides, cokriging estimation of relative proportions of sulfide species and statistical analysis of soluble and total copper analysis. As a result we define two layers: One with secondary enrichment association and another with hypogene or primary mineralization. The two layers are further subdivided according to intensity of mineralization and species dominance, the mix of layers giving as a result a bioleaching unit. Finally, for each bioleaching unit, a cokriging is performed between total copper, soluble copper + ferric (30 minutes and 24 hours) obtaining as a result the ratio of soluble copper + ferric (24 hours) to total copper. This ratio is finally scaled to industrial levels.

This work is inspired in one principle born of the collaboration between CODELCO and Centre of Geostatistic of Paris Schools of Mines: "*Use massive amounts of simple, low cost tests that have correlation with scarce and costly metallurgical tests, in order to coregionalizer an cokriging on a local estimation basis, so the estimated results can be incorporated to mine planning*".

INTRODUCCION

Consideration of the spatial variability of metallurgical process performance has very important economical implications for the mining business. From our point of view, geometallurgy should seek to find controls on mineralisation that have an impact on process performance, e.g. Which variables (lithology, alteration, mineralogy, texture, liberation) control the performance a metallurgical process?

The next question is: Is it possible to regionalize copper recovery data from metallurgical tests? What is the spatial distribution of the variables that control process performance in the ore body? Some problems that must be faced are:

- The available data from tests is limited, and insufficient to do a proper assessment.
- Change of support between tests, selective mining unit and daily production.
- Samples for metallurgical tests may be composited from too different locations.
- Metallurgical variables or test results are not additive.
- The spatial models of the geological variables which control the metallurgical behaviour such as lithology, alteration, texture, liberation factor, surface properties and ore zones are not available or are not taken into account [2].
- And probably the greatest problem is the distrust wall between geologists, mining engineers, geostatistitians and metallurgical engineers in what is essentially a multidisciplinary effort.

In the mining industry, there are two frequently used approaches to apply metallurgical parameters in economic assessment: the first is assigning an average value to the metallurgical parameters for a given geological unit, the next usual way is to apply a regression fit to metallurgical process performance respect to feed grade [3].

This paper shows the application of cokriging: during construction of a geometallurgical model from RT sulphide leaching project and the indirect regionalisation of copper recovery of bioleaching from simple tests measures that have correlations using cokriging.

Problem

Radomiro Tomic, in Northern Chile, is a porphyry copper deposit that has been mined as oxide ore from the startup of operation. Recently, Codelco Norte has focused on a new project to mine sulphide ore, this project is in stage prefeasibility. This ore could be sent to conventional flotation or to a Bioleaching - Solvent Extraction process. With the goal of optimizing the mining sequence, a geometallurgical model has been developed to characterize and regionalize the copper recovery of the bio-leaching process.

Information available

The project area has information of drill core samples with support of 3 meters:

- ~47,000 samples with known total copper CuT.
- ~ 6000 soluble copper with ferric acid 24-hour shaker tests (CusFer24h) (cost US$ 25/un, time: 3 week).
- ~24,000 ferric acid 30-minute tests (CusFer30m) (cost US$ 5/un, time: 2 week).

- 74 bioleaching laboratory tests (cost by test US$ 3,000, time: 90 days)
- Drill core have detailed mapping of sulphide relative abundance (scale of 1:100).
- EW sections with interpretation of mineralogy domains.

Construction of Geometallurgical Sulphide Model

The geometallurgical model of sulphides has been developed in the two steps:

Bioleaching Units (UGBIOLIX): this step takes into account the 2D geological interpretation of mineralogy of copper-Iron sulphide based in the mapping of relative abundances in drill core; statistical analysis of relative sulphide abundances and their impact on soluble copper (CusFer24h) and total copper ratio.

A cokriging of relative abundance of copper-iron suphides was done to simplify the original interpretation of minerals zones and to help interpretation and 3D coherence. The results are two layers that are further subdivided according to intensity of mineralization, of species dominance and impact in ratio CusFer24h/CuT. One layer represents an early mineralization event (relative abundance of hypogenes minerals: bornite, chalcopyrite and pyrite), and the second layer gives count the supergene mineralization event (relative abundance of chalcocite and covellite). Finally the mix of these two layers gives as a result the bioleaching units.

Cokriging CusFer24h, CusFer30m and CuT: The bioleach test results have a non-linear correlation with the ratio CusFer24h/CuT. The bioleach tests are only 74. For this reason, the ratio will be important in indirectly predicting copper recovery. The ratio and recovery are not additive variables, and so these are not possible to estimate by kriging directly. The cokriging geostatistical (heterotopic case) method was used to estimate CusFer24h and CuT using also CusFer30m in each bioleaching unit. After this the ratio CusFer24/CuT was calculated in each block. The cokriging is the generalization multivariable of the kriging [4]. In general, this technique is used when there is a correlation lineal between variables. The more frequent applications are in the following: the estimation must maintain relations between variables (Example: $Z_1(x\ ) + Z_2(x\ ) + Z_3(x\ ) = 1$) or where sampling density are different by variables.

Units Bioleaching (Ugbiolix)

Mineralogy of sulphides

The geology of Radomiro Tomic ore has a strong structural control of the mineralization with zones of early alteration (potassic intense and background potassic) overprinted by late alteration (pyritic quartz/sericite). The lithology is homogeneous in the ore deposit. The sulphide mineralization overlay shows strong and week chalcocite/covellite enrichment, bornite dominant bn/cp mineralization, chalcopyrite dominant cp/bn mineralization and chalcopyrite only sulphide mineralization, Figure 1.

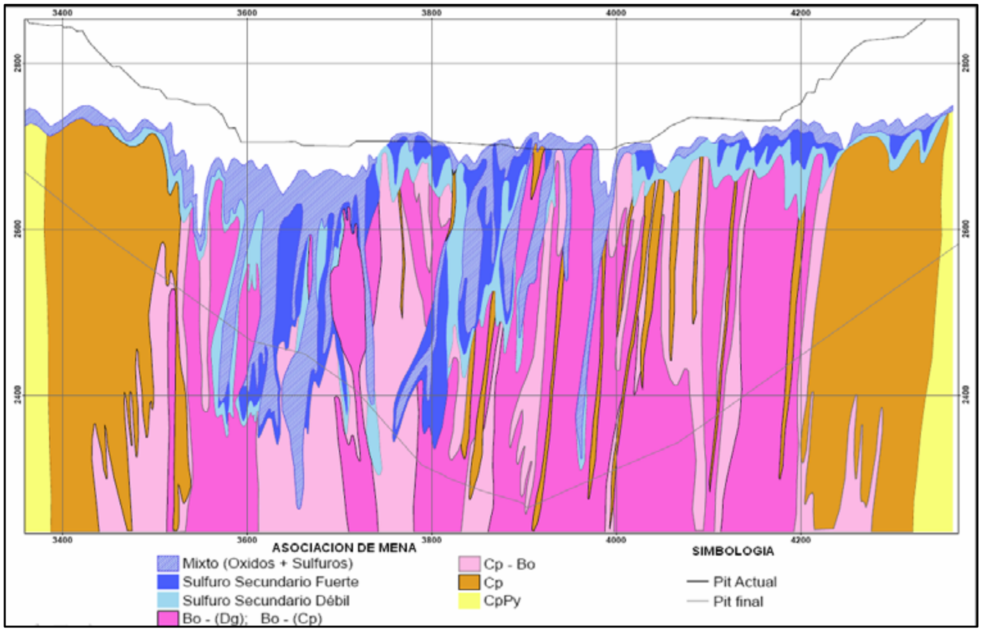

Figure 1: Domains of Minerals Sulphides of Copper and Iron in section EW

The ratio CusFer24h/CuT is uncorrelated with total copper grade, Figure 2. The main control of this ratio is the relative abundance of chalcopyrite or chalcocite. Chalcopyrite is the less soluble mineral and chalcocite the most soluble of copper sulphides.

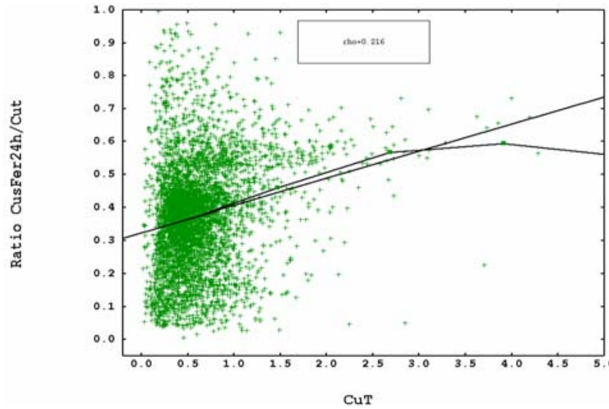

Figure 2: CuT vs Ratio CusFer24h/CuT

Criteria of classification for construction Bioleaching Units

To define the influence of geology on bioleaching, an analysis was conducted on the relationship between extraction achieved using the ratio CusFer24h/CuT and the mapping mineralogy of the samples used in these tests. It was found that three mineralogical combinations were significant:

- Chalcocite + covellite + digenite (Cc+Dg+Cv): the digenite has been added to the supergene (Cc+Cv) minerals, because it is not easy to distinguish from chalcocite during mapping and it is not abundant in the deposit. In addition, digenite and chalcocite have the same recovery in bioleaching process.
- Chalcopyrite + pyrite (Cp+Py): both minerals are found in the ore margins.
- Bornite (Bo).

Mineralogical information available from the drill hole database was used to calculate the percentage of the three mineralogical combinations, Cc+Dg+Cv, Cp+Py, and Bo, within each sample. The relationship between these mineralogical combinations of sulphides and copper ratio CusFer24h/CuT (potential extraction) was plotted on a ternary diagram (Figure 3). Contour plots show how extraction varies depending on the intensity relative of sulphides.

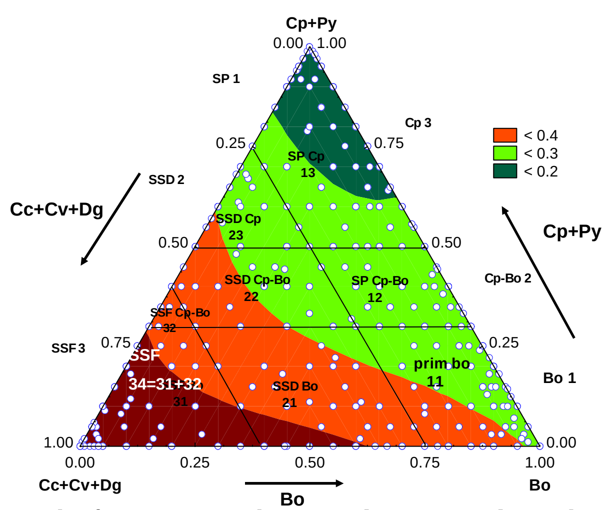

Figure 3: Ternary Graph of ratio CusFe24h/CuT and mapping relationships of relative of sulphides

Codelco has classified two criteria of geologic controls that represent supergene and hypogene mineralization events:

Criteria 1- supergene layer: Controls reflecting the percentage of secondary sulphides, from which three material types were defined (left axis on Figure 3):

- Strong Secondary Sulphide (Sulfuro Secundario Fuerte SSF): Cc+Dg+Cv > 65%
- Weak Secondary sulphide (Sulfuro Secundario Débil SSD) : 25% < Cc+Dg+Cv < 65%
- Primary Sulphide (SP): Cc+Dg+Cv < 25%

Criteria 2 - hypogene layer: Controls reflecting higher bornite content near the centre of the deposit and higher chalcopyrite content on the periphery, from which three material types were also defined (right axis on Figure 3):

- Chalcopirite (Cp-Py): Cp+Py > 50%
- Chalcopirite Bornite (Cp-Bo): 30% < Cp+Py < 50%
- Bornite (Bo): Cp+Py < 30%

Cokriging of sulphide relative intensity

The tree variables from the ternary graph have the property that their sum is 100%, then these can be cokriged in the block model. The percentages were then estimated for each block in the deposit by co-kriging of the sample percentages. The proportions estimated of Cc+Cv+ Dg and Cp+Py were painted with the previous criteria and used as guide for 3D modeling. Figure 4 shows the same section as Figure 1, with classification criteria of Cp+Py.

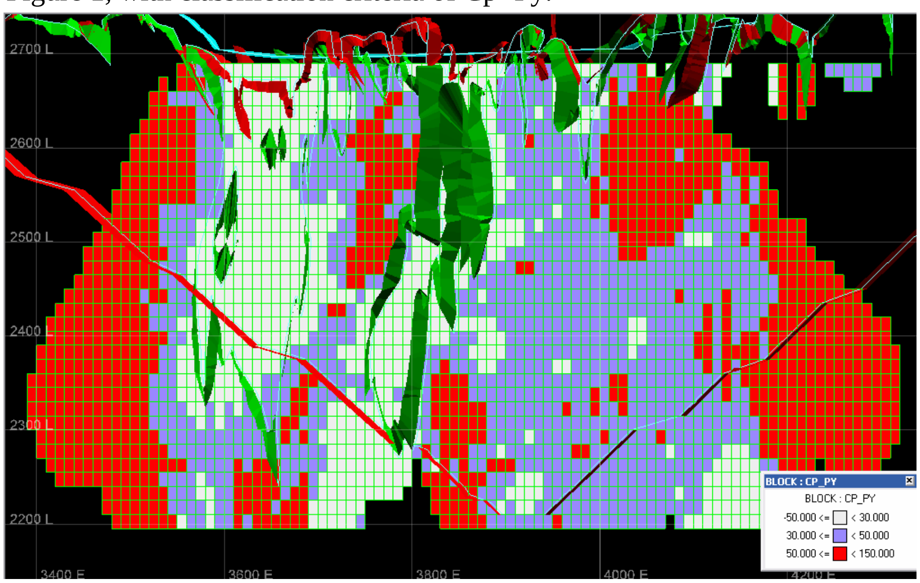

Figure 4: Section view, Cokriging Cp+Py painted like classification criteria

As a result of the previous analysis the supergene layer and hypogene layer, were interpreted in all the deposit Figure 5.

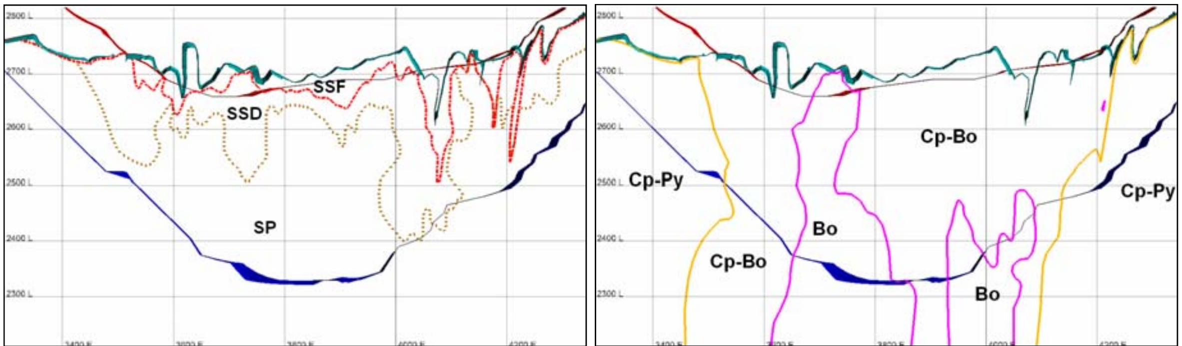

Figure 5: Section view, open pit (present and final) and top of sulphide. Left: Supergene layer or late minerals classification (Cc+Cv+Dg) , right: hypogene layer or early mineralization (Cp+Py).

Definitio of Bioleaching Units(UG BIOLIX)

The intersection of these two layers results in the definition of eight different geological units (UGBIOLIX) which are named, numbered and displayed in polygons on Figure 3. A statistical analysis was done of the bioleach sample solubility within and between combinations of geological units. On the basis of these studies the numbers of units are reduced from eight to six defined as shown on Table 1 and Figure 6.

Table 1: Name and description of Units Bioleach (UGBIOLIX)

Name - Number	Description
SP Cp-Py - 13	Primary Sulphide - Chalcopyrite - Pyrite
SP Cp-Bo - 12	Primary Sulphide - Chalcopyrite - Bornite
SP-SSD_Bo - 11-12	Primary and Weak Secondary Sulphide - Bornite
SSD_Cp - 23	Weak Secondary Sulphide - Chalcopyrite
SSD_Cp-Bo 22	Weak Secondary Sulphide - Chalcopyrite - Bornite
SSF	Strong Secondary Sulphide

The mineralogy of boleaching test has been validated with 600 samples analyzed with QEMSCAN.

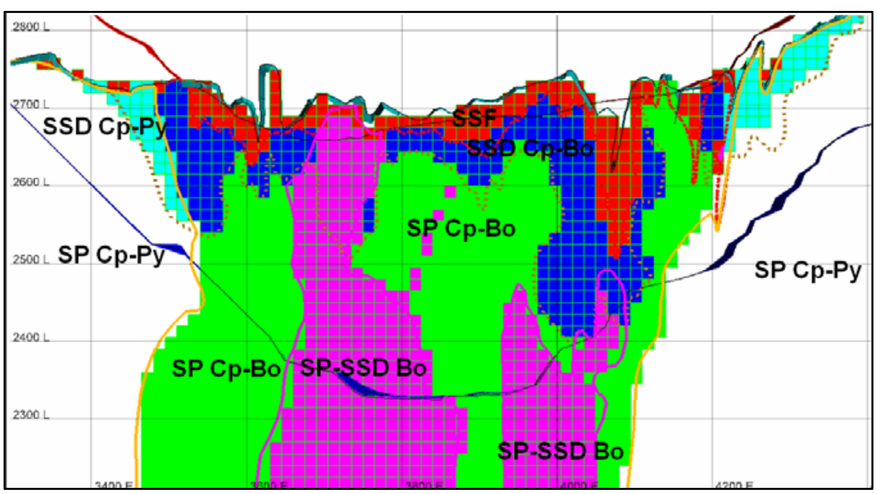

Figure 6: Section view Units Bioleaching

Cokriging of CusFer24H, CusFer30M and CuT

Relation recovery test bioleach and ratio CusFer24h/CuT

There is a strong non-linear correlation between recovery of bioleaching tests and CusFe24h/CuT test results Figure 7. Because of the small size of the bioleaching test dataset, a decision was made to develop a deposit model in which the bioleach solubilities would be those expected from a 24 hour shake test. Ultimately there will be a need to modify these CusFe24h estimates of copper solubility to obtain estimates of what extraction will be on a commercial scale. The data needed to complete this conversion are not yet available.

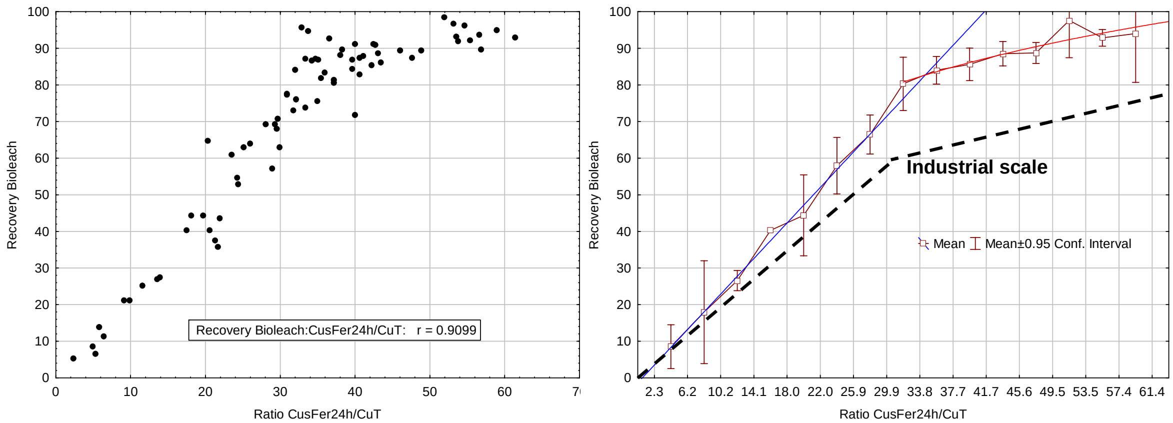

Figure 7: Scatter and mean plot of bioleaching test recovery vs ratio CusFer24/CuT

Application of cokriging Ordinary CusFer24h, CusFer30m and CuT

The statistics of CusFer24h, CusFer30m and CuT are shown in Table 2. The average of CusFer30m is less than the average of CusFer24h, this is explained by the effect of the time.

Table 2: Statistic of CuT, CusFer30m and CusFer24h, cases all samples and samples with 3 measures

	All sample			Sample with 3 measure		
VARIABLE	N	Mean	Std. Dev	N	Mean	Std. Dev
CuT	47559	0.58	0.50	3863	0.61	0.40
CusFer30m	24299	0.20	0.26	3863	0.20	0.21
CusFer24h	4909	0.25	0.25	3863	0.24	0.24

The variables CusFer24h, CusFer30m and CuT have a good linear correlation. Figure 8 shows the scatter plot of all samples where at least two measures are available. The same good correlation is conserved between the variables for each bioleaching unit. The correlation matrix for cases where the sample has all 3 measures is shown in Table 3.

Table 3: Correlation matrix of CuT, CusFer30m and CusFer24h, cases samples with 3 measures

VARIABLE	CuT	CusFer30m	CusFer24h
CuT	1	0.83	0.83
CusFer30m	0.83	1	0.95
CusFer24h	0.83	0.95	1

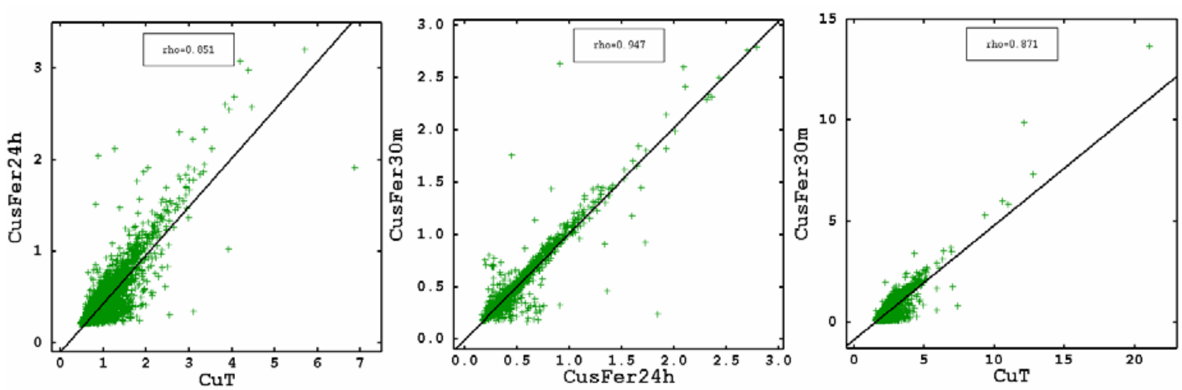

Figure 8: Scatter plot, Left CusFer24h vs CuT, Centre CusFer24h vs CusFer30m and Right CusFer30m vs CuT

Three block values were estimated by cokriging: CuT, CusFer30m, and CusFer24h. Each estimate is a linear combination of the sample values surrounding the block. If we want to estimate $Z_1^*(x)$ by cokriging using 3 variables, we can use the following notations:

$$Z_1^*(x) = \sum_i \lambda_{1i\alpha} Z_1(x_{i\alpha}) + \sum_i \lambda_{2i\alpha} Z_2(x_{i\alpha}) + \sum_i \lambda_{3i\alpha} Z_3(x_{i\alpha})$$

Where

$Z_1(x_{i\alpha})$: i sample of CusFe24h in region α; $\lambda_{1i\alpha}$: weigth of i sample variable Z_1, in region α

$Z_2(x_{i\alpha})$: i sample of CusFe30m in region α; $\lambda_{2i\alpha}$: weigth of i sample variable Z_2, in region α

$Z_3(x_{i\alpha})$: i sample of CuT in region α; $\lambda_{3i\alpha}$: weigth of i sample variable Z_3, in region α

In order to guarantee the unbiased condition, the following conditions must be met:

$$\sum_i \lambda_{1i\alpha} = 1 \qquad \sum_i \lambda_{2i\alpha} = 0 \qquad \sum_i \lambda_{3i\alpha} = 0$$

The cokriging minimize the error variance. The equation lineal system is constructed on base the simple variogram and cross variogram and for each condition weights sum one lagrange multipliers is added. The results of cokriging are the weights that minimize the error variance [7].

The advantage of cokriging is that it recognizes the correlations between the three copper values and it uses all available data [6]. In addition cokriging gives three copper estimates which, being based on the same sample values, can be used to calculate percentage solubility from the ratio of soluble copper over total copper.

Three dimensional estimation of block total copper (CuT) and soluble copper (CusFer30m and CusFer24h) was done using cokriging of the sample CuT, CusFer30m and CusFer24h. Block estimation of copper solubility took into account all samples for which at least one CuT, CusFer24h or CusFer30m value was available in the same unit bioleaching. The ratio CusFer24h/CuT was calculated from the grade estimated by cokriging, the results in one section are shown in Figure 9.

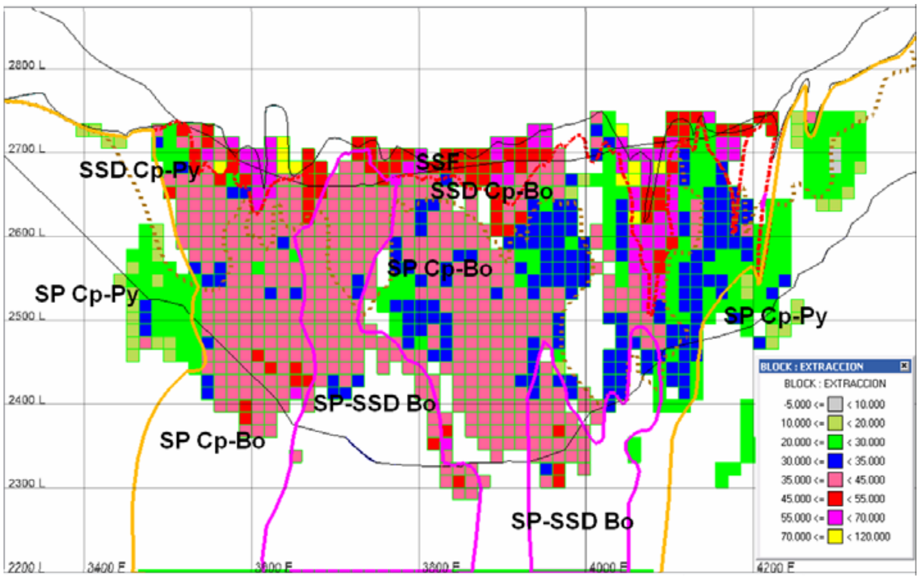

Figure 9 – Ratio CusFer24h/CuT calculated from cokriging estimation of CuT, CusFer30m and CusFer24h

CONCLUSIONS

The application the cokriging in early stage of modelling and interpretation helped geologists in modelling the 3D tend of minerals zones of copper and iron sulphides.

The geometallurgical model units have been built on the basis of mineralogical mapping of drill core.

There is a non-linear correlation between recovery of bioleach tests and ratio CusFer24h/CuT. Ordinary cokriging allows having a block estimation of copper solubility taking into account all samples for which at least one CuT, CusFe24h or CusFe30m has been measured.

While the present model is correct from a conceptual point of view, this model must be validated at a pilot scale or in mine operation.

This geometallurgical model opens the opportunity to do better trade offs between flotation or bioleaching process optimizing mine planning, giving a better alternative than the traditional approach.

This work is inspired in one principle born of the collaboration between CODELCO and Centre of Geostatistic of Paris Schools of Mines: *"Use massive amounts of simple, low cost tests that have correlation with scarce and costly metallurgical tests, in order to coregionalizer an cokriging on a local estimation basis, so the estimated results can be incorporated to mine planning"*. Another example application of this concept could be to use uniaxial compressive strength geotechnical tests for work index estimation. This could improve the mine sequence planning integration work index [1].

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NOMENCLATURE

CuT	total copper grade
CusFer30m	test of soluble copper with attack of acid ferric in 30 minute shaker test
CusFer24h	test of soluble copper of acid ferric in 24 hours shaker test
UGBIOLIX	Geological Bioleaching Units

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