3D OREBODY MODELLING AND RESOURCE ESTIMATION OF THE JUCARO DEPOSIT, PINAR DEL RIO, CUBA

(MODELACIÓN 3D DE CUERPOS MINERALES Y ESTIMACIÓN DE LOS RECURSOS DEL YACIMIENTO JÚCARO, PINAR DEL RÍO, CUBA)

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ABSTRACT: The primary aim of this research was to model the Jucaro deposit and reevaluate its resources by taking into account the spatial variability of the mineralization and by complementing the existing geological, drilling and underground data with a computerized 3D model. The Jucaro deposit, located in the NE part of Pinar del Rio province, is hosted by the basaltic complex of the Encrucijada formation. The statistical analysis revealed the existence of a complex statistical population, which was split into two more or less homogeneous sub-populations: the mineralized zone and the hydrothermal alteration zone. The variography revealed no spatial structure in the plane of the deposit. The deposit was geometrically modelled using the perimeter and surface methods. The geological model provided a good 3D representation of the complex morphology of the mineralized zone and was used to apply geological control to the resource estimation. Based on the lenticular shape of the deposit the grid model was selected to calculate the mineral resources. Copper and sulphur grades were estimated using the inverse power of distance weighting technique. The total ore resource of the Jucaro deposit obtained from the grid resource model is slightly lower that the resource calculated by the conventional manual sectional methods.

Keywords: Variography, 3D Orebody modelling, grid model, Ore resource estimation.

RESUMEN: El objetivo principal de este trabajo es modelar el yacimiento Júcaro y re-evaluar sus recursos considerando la variabilidad espacial de la mineralización y conjugando la información geológica existente, los datos de perforación y laboreos con un modelo computarizado 3D. El yacimiento Júcaro que se localiza en la parte NE de la provincia de Pinar del Río, se encuentra hospedado en el complejo basáltico de la formación Encrucijada. El análisis estadístico reveló la existencia de una población estadística compleja, la cual fue dividida en 2 subpoblaciones más o menos homogéneas: la zona mineralizada y la zona de alteración hidrotermal. La variografía no reveló estructura espacial en el plano del depósito. Los métodos de superficie y de perímetro fueron utilizados para modelar geométricamente el yacimiento. El modelo geológico proporcionó una buena representación 3D de la compleja morfología de yacimiento y fue usado para aplicar control geológico a la estimación de los recursos. Sobre la base de la forma lenticular del depósito, el modelo de capa fue seleccionado para estimar los recursos. Las leyes de cobre y azufre fueron estimadas usando el método de inverso de la distancia. Los recursos totales arrojados por el modelo de capa para el yacimiento son algo menores que los recursos estimados por el método convencional de perfiles paralelos.

Palabras claves: Variografía, Modelación 3D de cuerpos minerales, Modelo de capa, Estimación de recursos minerales.

INTRODUCTION

The Bahia Honda region is well endowed with mineral deposits and mineral showings. The most important commodities are those of iron, asphaltite, bitumens and cupriferous pyrite, which are by far of the most economic value. Jucaro deposit is economically the most important deposit of the area. It is located in the northeastern part of the province of Pinar del Rio, approximately 12 km from Bahia Honda town. It was discovered during a prospecting and exploration campaign (1963-1965) executed in the Bahia Honda region. Since 1979, the mine has been in operation but nowadays it is about to close due to the decrease of the copper price in the World market. The deposit is hosted by the volcanic sedimentary sequence of Encrucijada formation.

The main objective of this paper is to describe and discuss the results obtained from the application of geostatistical methods and 3D geographic information system (Microlynx98) to the evaluation of Jucaro deposit and to compare the performance of the technique to manual calculation results. The mining software Microlynx98 was used throughout this study (Lynx mining systems).

The objectives are attained through the following steps:

- Generation of a digital database of the deposit
- Statistical and spatial analysis of copper and sulphur grades
- 3D orebody modelling
- Estimation of resources by complementing existing geological, drilling and underground data with a computerized 3D model

GEOLOGICAL SETTING OF THE REGION

The region is characterized by the profuse abundance of Cretaceous, Paleogene and Quaternary formations. The geological structure is complex and dominated by nappe tectonics. The area has been interpreted from different points of view. The rocks in the region are grouped in three sequences: Quaternary sequences, Rocks of the Upper Cretaceous Paleogene superimposed basin, Rocks of Cretaceous back arc basin (Cruz, 1993). The sequences of Cretaceous back arc basin are by far the most economically important as all the sulphide mineralization in the area is hosted by these rocks. It consists of three main formations: the Orozco Formation, the Quiñones Formation and the Encrucijada Formation.

The magmatic activity in the region is characterized by the presence of the ophiolite assemblage, which is represented by its four members: Metamorphosed ultramafic, Gabbro and cumulative, Diabasic, Basaltic with sediments.

GEOLOGY OF JUCARO DEPOSIT

The Jucaro deposit is hosted by the tholeiitic basaltic complex of Encrucijada Fm. The deposit is formed by two main orebodies (I and III) with minor bodies scattered around them. The bodies are lenticular in shape, the strike length is around 300-350 m, the thickness ranges from 1 to 40m, averaging 10m. The strike of the deposit area is NE (40°-60°) with a dip to the NW at the angle of 20°-70°. The deposit is tectonized by postmineral faulting that complicates the overall structure and morphology of the deposit. The main ore minerals present are pyrite, chalcopyrite, magnetite, hematite, marcasite, galena, arsenopyrite, and sphalerite. Quartz, Fe -rich chlorite, carbonates, sericite, and others are also associated with the mineralization. In the oxidized zone the following secondary minerals are also found: chalcosine, coveline, bornite, native copper and iron hydroxides. The country rocks are strongly altered, the predominant alterations are chloritization, hematization, sericitization and silicification. Three different type of ores have been described in the deposit: massive, disseminated and veinlet-disseminated, the last two being the most abundant. The massive ore is represented by chalcopyrite and occasionally by pyrite.

Genetically, Jucaro deposit is considered to be a Cyprus type volcanogenic massive sulphide deposit (Simon, 1986). However, the lack of stringer ore underlying the sulphide lenses and the very low grades of Pb, Zn and Ag, which have no economic importance are the major differences with respect to Cyprus type deposits located in other parts of the world. Both the grade and tonnage of Jucaro deposit are higher than the average grade (1.7% Cu) and tonnage (1.6 Mt) of this type of mineral deposit all over the world (Cox and Singer, 1986) therefore it can be considered as a modally size deposit.

DATA BASE

The data used in this work consist of the material gathered during the exploration and exploitation of the Jucaro
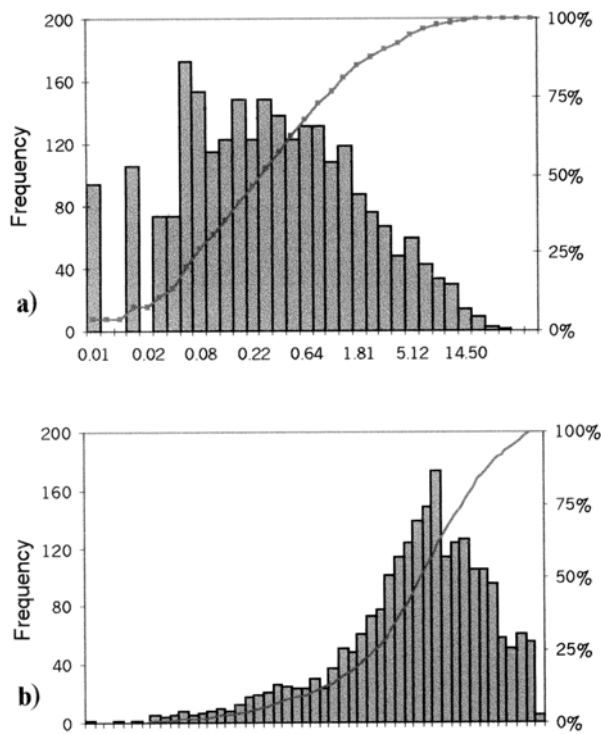

Figure 1. Histograms of transformated grade of the Jucaro deposit: a) copper; b)sulphur.

deposit. The Jucaro dataset comprises 116 surface drillholes (40 of them intercept Orebody III) and 66 underground drillholes (41 intercept Orebody III). The main sections are at 50 m regularly spaced and the drillhole spacing along sections is 50m. The underground drillholes were bored from the second mine level (-25m) and were designed to evaluate the resource between the second and the third levels. The average core recovery is 75%. A total of 1564 samples were collected from the 81 holes. The sample interval is approximately 1m. The number of samples gathered in each drillhole is variable and depends on the thickness of the mineralized zone.
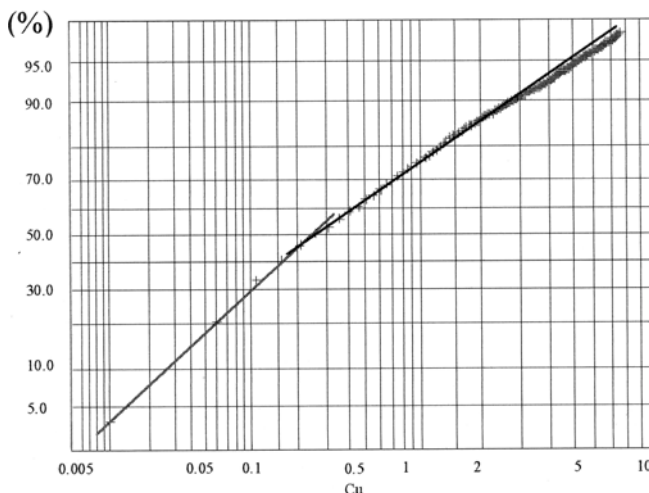

Figure 2. Cu (%) cumulative frequency curve.

DATA COMPOSITING

Sample compositing is a process whereby drillholes are divided into intervals that are different to the original field sample intervals. For each new interval, the numerical sample values are computed as the mean of the values of the original field sample intervals, weighted by their original length. There are several different methods of sample compositing: downhole (collar), bench and geological. For this project, geological compositing was selected in order to restrict the regularization process within the mineralized zone. The composite interval (1 m) was chosen on the basis of average sample length (0.98 m) and minimum mining thickness of 1m. The composite data are used for the volume modelling and structural analysis.

EXPLORATORY DATA ANALYSIS AND VARIOGRPHY

A sound exploratory data analysis, aimed at revealing the characteristics and relations between data, is the necessary first step in any evaluation exercise. It includes the calculation of descriptive statistics, the construction of histograms and cumulative frequency curves, which give illumination into the type of the statistical distribution of data, the identification of the presence of complex populations, which may represent different geological zones, and the identification of outliers (Whateley and Harvey, 1994) . Both the raw data and composite data of copper and sulphur were used for the statistical analysis. The structural analysis was carried out using only the composite data of the two elements. As the results of the raw data are very similar to the composite one, only the statistics of the composite data is presented.

The histograms of untransformed Cu and S grades illustrate that the data are strongly skewed. The histograms and probability plots of the transformed data are rather symmetric although the marked changes from one class to another, and the presence of inflexion points (breaks) in the cumulative frequency curves, indicate the mixing of several populations (multimodality) (fig. 1). A detailed study of the cumulative frequency curve of Ln (Cu) for the deposit is presented in figure 2. The break of the distributions at 0.3% Cu (Jucaro deposit and Orebody I) and 0.5% Cu (Orebody III) gives ground for the subdivision of the data into two more or less homogeneous populations; in addition 0.3% and 0.5% Cu are two of the cutoff grades used in the mine to outline the outer limits of the deposit. In our case 0.32% Cu is used to delimit the extension of mineralization. The first population (Cu >0.32%) comprises the mineralized zone and the second one is the hydrothermal alteration zone that surrounds the high-grade zone. Consequently, the further analysis is focused only on the mineralized zone.

The summary statistics of the mineralized zone are shown in Table I. The histograms and the probability plots of the mineralized zone itself depict more symmetric histograms of the transformed data and the cumulative frequency curves approximate a straight line, although some

Table 1. Descriptive statistics for copper and sulphur based on the composite data of te mineralized zone

Parameters	Jucaro Deposit	
	Cu(%)	S(%)
No of samples	1220	1159
Minimum	0.02	0.10
Maximum	22.82	47.59
Mean	1.92	14.06
Variance	6.71	105.66
St. error of mean	0.07	0.30
Skewness	3.34	1.18
Kurtosis	15.06	0.83
Coef. of Variation	1.35	0.73
Geom. Mean	1.09	10.44
Log variance	1.04	0.76
Log estim. of mean	1.85	15.23

inflection points are again present. The existence of different types of ore (disseminated, massive, etc) within the deposit may explain the breaks in the probability plot. However, these probable subpopulations do not prove to be spatially coherent, are mixed in many places and are not easily separable. Therefore, it was decided not to split further the mineralized zone.

The raw data of the mineralized zone for the whole Jucaro deposit is used for the correlation analysis. As both Cu and S are lognormally distributed, the log-transformed values were plotted to construct the scattergram. The correlation coefficient is 0.48, indicating a very weak relationship between Cu grade and S grade. This is typical for Cyprus type deposits where pyrite is the most abundant mineral. The calculated coefficient is significant at 99% confidence level.

STRUCTURAL ANALYSIS

The aim of this study is to analyze and quantify the spatial variability of mineralization, and to identify the main directions of continuity through the production and modelling of variograms. A variogram, a measure of spatial variability, is the key to any geostatistical study (Deutsch and Journel, 1998). Since the data for geostatistical analysis should be drawn from a geologically homogeneous population, several attempts were made to split the mineralized zone into different single subpopulations on the basis of histograms and cumulative frequency curves. The entire attempt to separate the mineralized population at different cutoffs (1.5% and 4% Cu) failed, as the subpopulations do not prove to have any spatial integrity. In other words different ore types are mixed up all over the deposit and it is not possible to separate them at core sample scale.
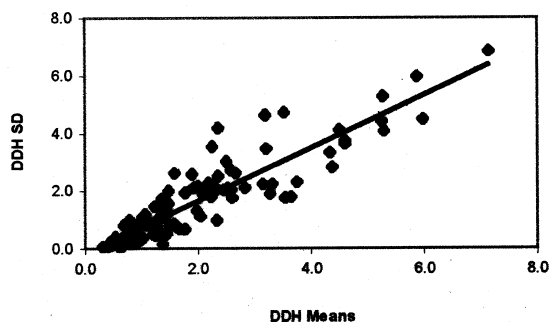
Figure 3. Scatterplot of local means *versus*. local standard deviations.

As the data are lognormally distributed, copper grade was checked for the presence of the proportional effect (relationship between the local mean and the local standard deviation). The scatterplot of the mean and the standard deviation for each drillhole (Fig. 3) confirms that a proportional effect exists. The relationship is linear and the correlation coefficient is equal to 0.92. The relative variograms were used throughout this study in order to take account of the presence of the described effect (Isaaks and Srivastava, 1989).

Three directional variograms were calculated: N-S (Downdip-180°), E-W (along the strike-90°) and downhole. These directions refer to the transformed coordinate system. The analysis was carried out for the whole deposit and for each separate orebody. The lag spacing was selected on the basis of the average drillhole spacing (50m for the whole deposit and Orebody III and 25 m for Orebody I); the downhole variogram was calculated using a lag of 1m (composite sample length) and an angular tolerance of 30°.

The relative experimental variograms with fitted models for copper grades in the Jucaro deposits are shown in figure 4. The downhole variograms for both elements revealed a clear spatial structure with a range of about 6m. On the other hand, the variograms calculated in the plane of the orebody showed no spatial correlation. They behave as a pure nugget effect. The spatial structure on the plane of the deposit, if it exists, might have a range smaller than the drillhole spacing (25 m), so a spherical model with a range of 15m was chosen to model the empirical variograms.

An indicator approach has been used to enhance the existing spatial correlation and to deal with the erratic nature of the directional variograms in the deposit (Carr, 1995). The copper grade was transformed using an indicator function i (x,z), which is based on the grade of a sample point z(x) and on a selected indicator cutoff grade (COG).

$$i (x, z)= \begin{cases} 1, \text{ if } z(x) > COG \\ 0, \text{ if } z(x) < COG \end{cases}$$

Indicator COGs of 1.5% and 4% copper were selected based on the analysis of the probability plots. After several trials the 4% COG was discarded as it failed to produce any interpretable structure. The same spatial relationship is expressed by the downhole variogram; the other
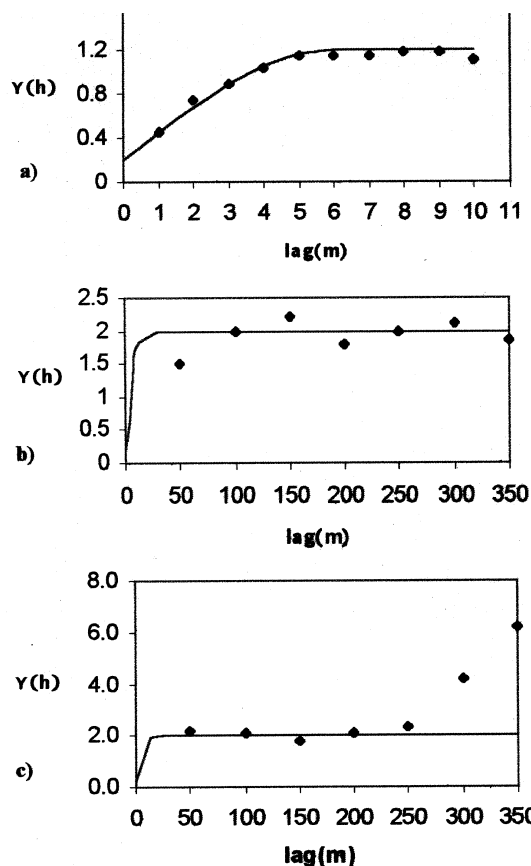

Figure 4. Relative variograms for copper in the Jucaro deposit.
a) Downhole variogram
b) Directional variogram (180°)
c) Directional variogram (90°)

two directional variograms did not produce any improvement in this study. The indicator variograms for Orebody I and III fail to reveal any spatial autocorrelation in the plane of the orebodies; however they are more stable and amenable to interpretation. The indicator approach confirmed the absence of a spatial relation between samples in both the dip and strike directions.

The results of the variography are consistent with the observed high variability of copper and sulphur grades in the Jucaro mine, which is caused by the complex tectonic distortion of the deposit. It is believed that the original spatial continuity of the mineralization was destroyed by the postmineralization faulting.

GEOLOGICAL AND RESOURCE MODELLING

This step deals with the creation of geometric and resource (volumetric) models of the Jucaro deposit. The geometric model represents the spatial location and the morphology of the orebodies and is then used to control the resource modelling. Several different methods are described in literature for the 3D geological characterization of mineralized bodies (Sides, 1997; Orlic, 1997). In this case, the automatic boundary-fitting methods (surface method) and manual boundary-fitting methods (perimeter method) were used for the modelling. The surface method is a surface based approach where the geological sur-

faces (hanging wall and footwall) are automatically derived from a set of points representing intersection of drillholes with the limits of mineralization. Surfaces are initially represented as a series of non-overlapping triangles joining the known data points (triangulated irregular network). A triangulated volume model that matches the dimensions of the surface triangles is then generated between the surfaces.

The perimeter method is a section-based approach where the outline of mineralization (perimeters) is digitized on a series of parallel transverse geological sections and subsequently linked between sections in order to obtain a 3D model of geology. The steps involved in the creation of the geological model are described below:

Geological section arrangement

The primary source of information for the interpretation of the deposit outline is the drillhole data observations. These are displayed in an appropriate format on a set of transverse parallel geological sections that coincide with the original exploration drilling sections. A total of nineteen cross sections (11 main sections and 8 intermediate sections) was arranged perpendicular to the strike of the deposit, which trends NE (40°-60°).

Hangingwall and footwall surface model creation

The next stage of modelling was the generation of a simple geological model using a surface based approach. This first step required some editing of the database in order to simplify the interpretation so as to eliminate the bifurcation of the mineralization. These bifurcations cause serious problems during the automatic extraction of the hangingwall and the footwall.

Subsequently the automatic extraction of the hangingwall and footwall was undertaken. This function creates a string file containing points, which reside on a specified surface, from the intersection points of the surfaces with the drillholes. The hangingwall and footwall surfaces, represented by points alone, are triangulated thus fully defining the surface. The topography of the deposit was represented using the same approach, the only difference being that the spot heights were derived directly from the drillhole collars and then triangulated to model the topographical surface.

The triangulated hangingwall and footwall were cut by a series of parallel cross sections (25m apart) allowing the calculation of the volume contained between them. The result of this operation is a perimeter file containing the outlines of the orebodies on each section. As the generated sections are not a perfect representation of the mineralization, they are only used as a guide in the next step.

Perimeter digitizing and solid model

In this stage, the geology of the deposit is interactively interpreted on the screen of the computer. The procedure used is as follows (Houlding, 1994). First one of the geological sections is displayed on the background and the corresponding section with the outline of the orebody is also added to it. Then the limit (0.32% Cu) of the ore zone is digitized in such a way as to enclose as much high grade as possible. Although sometimes it was also necessary to include some low-grade areas in order to ensure the continuity of the orebody. Each orebody present in the geological section is digitized as a separate perimeter, which is assigned a name, a code (representing the geological unit to which the polygon belongs) and the z-plane coordinate. This step is repeated for all the geological sections through the deposit.

Once all the perimeters have been digitized, they are merged with the samples in the database in such a way that all samples that fall within a geological perimeter, are tagged with the geological code of the perimeter defined in the geological table. The primary use of this approach is to apply geological control to the grade interpolation so that the grade of any model element is estimated using only samples pertaining to the same orebody.

The next stage is the generation of a 3D solid model of the deposit from the previously digitized sections through wireframing. The wireframing process involves creating a series of triangles that link perimeters from section to section. This can be interactively controlled by manually digitizing corresponding strategic points (inflection points) in successive sections. The wireframes of Orebodies I and III (fig. 5) show the complex morphology of the Jucaro deposit. The 3D solid model can then be used to control the resource estimation of the deposit.
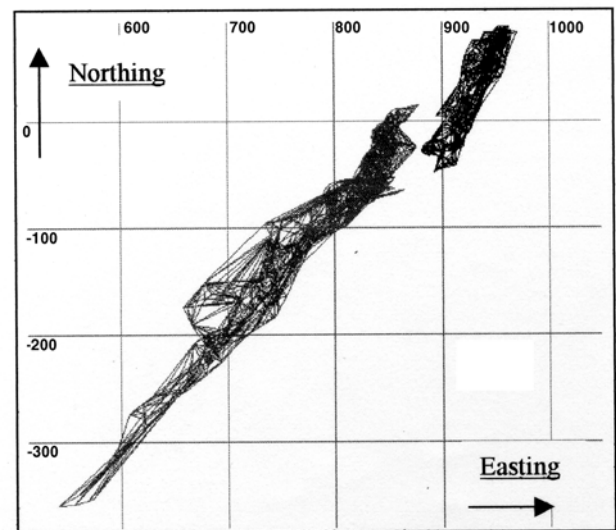

Figure 5. Wireframe model of Jucaro deposit on vertical section normal to strike.

Hangingwall and footwall surface model creation

The next stage involves the creation of the hangingwall and footwall surface models. This step is very similar to the above-described one with the only difference being that the string files are derived directly from the digitized

perimeters and are then triangulated to end up with the surface model. Later these geometric models are used to set up spatial and geological control for subsequent estimation to constrain the mineralization in the grid model.

Resource modelling

As explained above the grid model was selected for the resource modelling of Jucaro deposit based on the lenticular shape of the mineralized lenses. The gridded seam model consists of cells, which are rectangular prisms with the same cross-sectional area but varying height. The cell size (Siz_N, Siz_E) was determined as 20% of the average drillhole spacing and the heights (Siz_L) are calculated from the hangingwall and footwall elevations at each cell of the grid model (Lynx mining system)

Estimation of model cell values

At this stage the copper and sulphur grades are estimated for each cell using one of the interpolation tools available (Bonham-Carter, 1994). As the cupriferous mineralization in the Jucaro deposit has no spatial continuity, it was decided to reject Kriging and to use inverse distance instead.

The inverse power of distance weighting technique applies a weighting factor, which is the inverse of the distance between each sample and the cell centroid, raised to the power 'n', where 'n' usually varies between 1 and 3. Only samples falling within a specified volume are used in the interpolation (Annels, 1991).

The following parameters were used to execute the interpolation process:

Size and orientation of the search ellipsoid. As the structural analysis revealed no spatial correlation in the plane of the orebodies, the search radii were selected intuitively on the basis of drillhole spacing. The x, y, z search radii are 60 m, 60m and 20m for Orebody III, and 30m, 30m, 20m were used for Orebody I. The search ellipsoid was rotated 40° around the east axis in such a
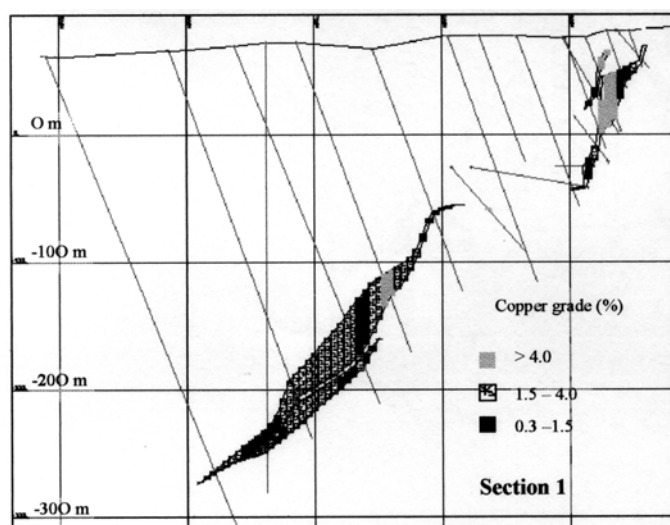

Figure 5. Cell estimated Cu (%) plotted on a verttical cross section.

way that the z search axis becomes normal to the plane of the orebody.

Number of samples used. The minimum and maximum number of samples required for the estimation process were set as 2 and 10 respectively.

Grid model resources report

The results of the resource modelling can be displayed in section and plan. A summary of the estimated values of copper and sulphur grades was produced in tabular format. It includes the ore tonnage, copper and sulphur grades and contained copper and sulphur. The tabulation was set up as rows (level), columns (sulphur) and pages (easting). The results of the model were also exported as a delimited text file for the generation of grade -tonnage curves.

Copper and sulphur grades distribution

The estimation results of copper and sulphur grades in each cell of the grid model are displayed in color-coded cross sections and longitudinal sections. Three intervals were selected to show the spatial pattern of estimated grades within the deposit. Figure 6. depicts the estimated copper grade of each cell in section S1 (1100E), the copper grade changes irregularly in the horizontal direction with alternation of zones with different copper values. However, in sections S3, S0 and S2 the grade is less variable and ranges from 0.3 to 1.5%. It is clear that the richer areas are surrounded by zones of lower grade and are located in the fringes of orebodies.

GRADE - TONNAGE CURVES

The plotting of grade-tonnage curves is a very important step in resource estimation as the curves depict at a glance exactly how much ore exists above a certain cutoff and how the change of cutoff grade affects the tonnage, the grade and the contained metal. In this study, grade tonnage curves have been computed to help in the understanding and assessment of the results obtained from the grid model. A cutoff of 0.32% Cu was used to define the extension of mineralization thus the curves relate only to resources available at cutoffs grade above 0.32% Cu.

COMPARISON WITH MANUAL RESOURCE ESTIMATES

The resources of Jucaro deposit were manually calculated using the conventional sectional method during the exploration campaign of Orebody III (Escobar, 1973). The deposit was outlined by employing a cutoff grade of 0.5% Cu and a minimum mining thickness of 1m. In this study, a cutoff grade of 0.32% Cu and a minimum mining thickness of 1m were used for delimiting the extension of mineralization.

The resource results of the grid model are not completely comparable with manual ones. Firstly all the data generated during the underground exploration and exploitation of the deposit have been incorporated in the database, and therefore a larger database was used in this

project. Secondly the morphology of the deposit was simplified in order to facilitate the automatic generation of the hangingwall and the footwall surfaces and thirdly some small mineralized lenses, which also contribute to the total Jucaro deposit resource were neglected, as they are confined in one geological section.

The comparison of the results indicates that the total tonnage of the deposit is 8% lower than the manual one. On the other hand, the average sulphur grade obtained from the grid model is 14% lower while the copper grade is slightly higher. The difference in tonnage may be explained by the simplification of the real shape of the deposit in order to meet the requirements of the software used.

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions and recommendations can be drawn concerning the orebody modelling and ore resource estimation of the Jucaro deposit

1. In spite of the complex geometry and high spatial variability of mineralization the 2D/3D GIS modelling technique proved to be suitable for evaluation of the sulphide orebodies forming the Jucaro deposit.
2. The statistical analysis shows that both copper and sulphur grades conform to lognormal populations in the mineralized zone although the cumulative probability plots give some evidence for statistically complex populations. On the basis of the statistical analysis, cutoff grades in the range of 0.3-0.5% Cu seem to be the most appropriate in defining the extension of the mineralization in the deposit. The correlation analysis revealed a weak linear relationship between Cu and S.
3. The geology model of the deposit provided a good 3D representation of the morphology of the mineralized zone, which allowed the resource estimates to be constrained through the application of geological control.
4. The structural analysis indicates that the sulphide mineralization has no spatial continuity in the plane of the orebody, however a short-range spatial structure is revealed in the vertical direction. This is consistent with the observed high variability of sulphur and copper grades in the deposit.
5. Based on the above conclusion the geostatistical technique (Kriging) is not suitable to estimate the Cu and S grades thus inverse power of distance weighting (IPDW) interpolation seems to be the most viable technique to deal with the characteristics of the mineralization.
6. The total in situ resource is slightly lower than the manually calculated one.
7. Performance of reconciliation study using the production data of Orebody I, which is already mined out, in order to check and validate the reserve estimation procedures used in this study.

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