Grade Uncertainty Assessment for Sub-Vertical Vein Exploration Projects

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Summary

Initial Mineral Resources evaluation of deposits are commonly obtained using traditional estimation methods that yield deterministic tonnage and grade figures. However, it is in the early stages of exploration drilling when data is scarce and, consequently, the uncertainties about the volume, shape, and grades of the deposit are greatest and their evaluation most critical. This paper presents a probabilistic methodology to account for grade uncertainty in the evaluation of Mineral Resources of narrow sub-vertical veins. First, the available data is projected in a vertical plane to reduce the uncertainty related to core location. Second, the uncertainty in grades is characterized using the sequential Gaussian simulation algorithm. Finally, the resulting multiple simulated grade models are reported at different cut-offs. In this way, by considering the uncertainty in the grades, the Mineral Resource model provides a more comprehensive basis for further exploration and engineering decisions.

Keywords: Sequential Gaussian Simulation, Mineral Resources, Coordinate Transformations

Resumen

La evaluación de Recursos Minerales en las etapas tempranas de perforación es comúnmente efectuada por medio de métodos de estimación tradicionales que resultan en declaraciones determinísticas de tonelajes y leyes. Sin embargo, es en estas etapas tempranas cuando, debido a la escasez de datos, las incertidumbres relacionadas con el tonelaje, forma y la ley del depósito son más grandes y críticas para el desarrollo del proyecto. Este trabajo presenta una metodología probabilística para la evaluación de la incertidumbre de los Recursos Minerales de vetas angostas subverticales. Primero, los datos son proyectados en un plano vertical a fin de reducir la incertidumbre relacionada con la ubicación de los testigos. Luego, la incertidumbre de las leyes es caracterizada usando el algoritmo de Simulación Secuencial Gaussiana. Finalmente, las múltiples realizaciones de leyes son reportadas a diversas leyes de corte. De esta manera, al incorporar el rango de incertidumbre, el modelo de Recursos Minerales provee una base más amplia para decisiones sobre la exploración y desarrollo del proyecto.

Palabras Clave: Simulación Secuencial Gaussiana, Recursos Minerales, Transformación de Coordenadas

1. Introduction

Initial Mineral Resource estimates for narrow vein deposits are usually reported after a few tens of boreholes have intersected the vein structure. These estimates are obtained using traditional methods such as polygons and inverse distance interpolation on the basis that limited data do not permit the use of geostatistical methods such as kriging. However, it is in these early stages, when data is scarce, that uncertainties related to geometry, tonnage, and grades are the highest and most critical for further development of the project. Traditional estimation methods, including kriging, are deterministic methods that cannot deal appropriately with these uncertainties. Moreover, they may yield smooth and often biased models of the spatial distribution of grades (Journel and Kyriakidis, 2004).
Sequential Gaussian simulation (Journel and Huijbregts, 1978) yields multiple equiprobable realizations of grades and other mineral attributes at the same support as the informing data. These realizations not only honour the data values at their locations, but also the data histogram, and the spatial continuity imposed by the variogram model (Leuangthong et al, 2004).
This work develops a methodology for the application of Sequential Gaussian Simulation for assessing the grade uncertainty in narrow vein deposits. First, data is preprocessed by compositing the original samples at regular intervals; subsequently, the coordinates of the composites are transformed by projecting the plane of the vein to a vertical plane without loss of volume. Multiple realizations of grades are generated in the transformed coordinates using sequential Gaussian simulation. The multiple thickness and grade realizations are ranked and combined to characterize the range of joint grade-tonnage uncertainty, which is reported using statistical intervals and boxplots at different cut-off grades and compared with the results of conventional estimation methods. The simulated Mineral Resources models can be queried for the probability of exceeding certain metal content targets to support further exploration and engineering decisions.

2. Data Preprocessing and Analysis

The data used to illustrate the proposed methodology comes from one mineralised structure of a deposit conformed by various low-sulfidation epithermal veins. The coordinates and gold grades have been modified by undisclosed factors to protect the confidentiality of the original dataset.

2.1. Sample Compositing and Capping

For very narrow veins, this is when vein thickness does not exceed the minimum mining width or when there is a single sample per vein intercept, the sample accumulation approach should be adopted. This approach calls for the calculation of accumulations by multiplying the sample grade times the sample length. Estimation or simulation is performed using the accumulation values and the estimated or simulated, grades are obtained by dividing the accumulations by the estimated, or simulated, thickness (Deutsch, 1989).
For the present case study, however, the vein thickness ranges from 1 to 36 metres. Thus, the sample compositing approach is adopted since one or more samples can be taken from the vein intercepts, and because the minimum mining width allows for some selectivity in such wide vein structure. A compositing length of 1 metre was selected because it is the most common sampling length in the dataset and 90% of the samples are 1-metre long or less.
Capping of high grades is a common pre-processing step in the estimation of grades. For simulation, however, capping is not required as the aim is to characterize the full range of variability of the grades as informed by the available data. The smearing of high grades is not an issue in simulation, since simulated models reproduce the spatial variability and the proportions of grades at various cut-offs.

2.2. Coordinate Transformation

The Cartesian system of coordinates is seldom the most adequate for characterizing Geological phenomena. Despite this, it is the only coordinate system used by most of the Mineral Resource modelling algorithms and software. Mineralisation in a vein follows non-linear and deformed vein geometry. Several solutions are available to deal with non-linear patterns of mineralization, such as unfolding algorithms and location-dependent variograms and distributions (Machuca-Mory and Deutsch, 2013)
Here we use a simpler approach: the straightening of the coordinates along one vertical plane (Rossi and Deutsch, 2013). This approach works well for sub-vertical (>70º dip) veins that are not heavily deformed. It can also deal with displacements induced by normal faults that are sub-perpendicular to the plane of the vein. The vein straightening transformation around the Y-axis is defined as follows:

$$y' = y_o - \bar{y} + c, \qquad (1)$$

With y' as the new straightened y coordinate, y_o as the original y coordinate, $\bar{y}$ as the y coordinate of the vein centreline, and c as an optional constant to translate the axis of the transformed coordinates to a convenient location. This transformation may require a prior rotation around the Z-axis if the vein strike is not parallel to the north-south or east-west directions.

Besides being simple, the benefits of using this coordinate straightening transformation include: (1) volumes are not distorted, (2) the uncertainty about core location in one of the axes is eliminated, (3) improved experimental variogram calculation, (4) a smaller block model is required for simulation, and (5) back-transformation is trivial.

2.3. Declustering

Sample declustering is commonly used to reduce the biases introduced by preferential sampling. Statistics that are more representative of the mineralisation are generated by incorporating the declustering weights. Cell declustering (Rossi and Deutsch, 2013) is the most popular method. However, declustering by polygons, nearest neighbours interpolation, or even kriging are more adequate methods for samples in vein deposits, since the volumes used to assign declustering weights can be truncated by the 3D boundaries of the vein. The polygonal method within the straightened vein volume was used for declustering the data in this case study.

2.4. Variography

Spatial continuity analysis was performed on normal score transformed grades in the straightened coordinate system. The fitted variogram model is comprised of three structures: (1) a 0.1 nugget effect, (2) an exponential short-range (50 metres) structure that is isotropic in the plane in the vein, and (3) an anisotropic long-range (300 and 190 metres) spherical structure with major axes ranges confined in the plane of the vein. Ranges perpendicular to the plane of the vein are 6 and 24 metres for the exponential and spherical structures, respectively.
Early exploration projects may suffer from insufficient data to produce well informed experimental variograms. In those cases, a variogram model of a similar and well-sampled deposit may be borrowed. In this case, however, the 702 composite samples within the vein structure allow for variograms that can be considered reliable enough for this study.

2.5. The Simulation Block Model

The volume support of simulated values must be similar to the sample support, thus a 1 metre by 1 metre by 1-metre cell size was chosen for the simulation model. Each cell was assigned with a code 1 if it is located within the volume of the vein in original coordinates, otherwise, the assigned cell code is 0.
The transformation of the original regular cell model into a straightened regular cell model is slightly different to expression (1). The cell model is straightened without overlap or loss of volume using the following formula:

$$y' = y_o - int(\bar{y}) + c, \quad (2)$$

where $int(\bar{y})$ is the nearest integer to the y coordinate of the vein centreline.
The straightened simulation block model contains 36.5 million cells, compared to 1,449 million 1-metre by 1-metre by 1-metre cells for a block model in original coordinates.

3. Grade Uncertainty Assessment

3.1. Simulation of Grades

Fifty realizations of gold grades were generated in the straightened block model using the program SGSIM of the GSlib geostatistical library (Deutsch and Journel, 1997). The search ranges and orientations used in the grade simulation correspond to full variogram model ranges and orientations. The declustered distribution of gold grades was used for normal scores transformation and back transformation. Simple kriging was used to condition the local distributions of grades, using up to 24 neighbouring data values and 12 previously simulated values.

3.2. Validation and Post-Processing of the Realizations

The 50 simulated models were trimmed by the vein code, keeping only the values within the veins. Still, in the straightened coordinates, the simulation results were validated by checking the reproduction of the declustered histogram and normal scores variogram model.
The coordinates were subsequently back-transformed using the expression

$$y_o = y' + int(\bar{y}) - c, \quad (3)$$

and upscaled to the SMU size of 24 metres by 6 metres by 12 metres. The percentages of vein and waste rock material were calculated for the upscaled blocks.
For each upscaled realization, the tonnage, average grade and gold content above cut-off were calculated. Using boxplots, Figure 1 illustrates the spread of uncertainty in the gold content of the 50 realizations at different cut-offs. For comparison, the estimated gold content obtained from models created using inverse distance to a power of three

(ID3), and ordinary kriging (OK) are also plotted. For low cut-offs up to 1.50 Au g/t, estimated ID3 and OK models provide results that are very close to the average of the distribution of uncertainty in gold ounces. Relative to the average of the simulations, ID3 tends to over-estimate the gold content at cut-offs greater than 1.50 Au g/t. The overestimation obtained from kriging is less pronounced at these higher cut-offs, and even under-estimate the gold content at high cut-offs above 4.00 Au g/t.

4. Discussion and Conclusions

Geostatistical Simulation methods are regarded as sophisticated approaches that can be used only when data is abundant enough. Here we have shown how geostatistical simulation can be used even in the early stages of exploration for characterizing the grade uncertainty of the deposit. Simulation is not affected by the over-smoothing of estimated grades and can reproduce the correct tonnage above cut-offs, it can be used to validate estimated models and to provide globally accurate assessments of the Mineral Resources. Finally, although there are no fixed prescriptions for acceptable uncertainty thresholds in the Mineral Resources at different stages of a project, the spread of uncertainty resulting from the ensemble of simulated models can be used to obtain quantitative measures of uncertainty related to different production volumes or time periods, accompanied by probabilistic confidence estimates (CIM, 2019).

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Illustrations

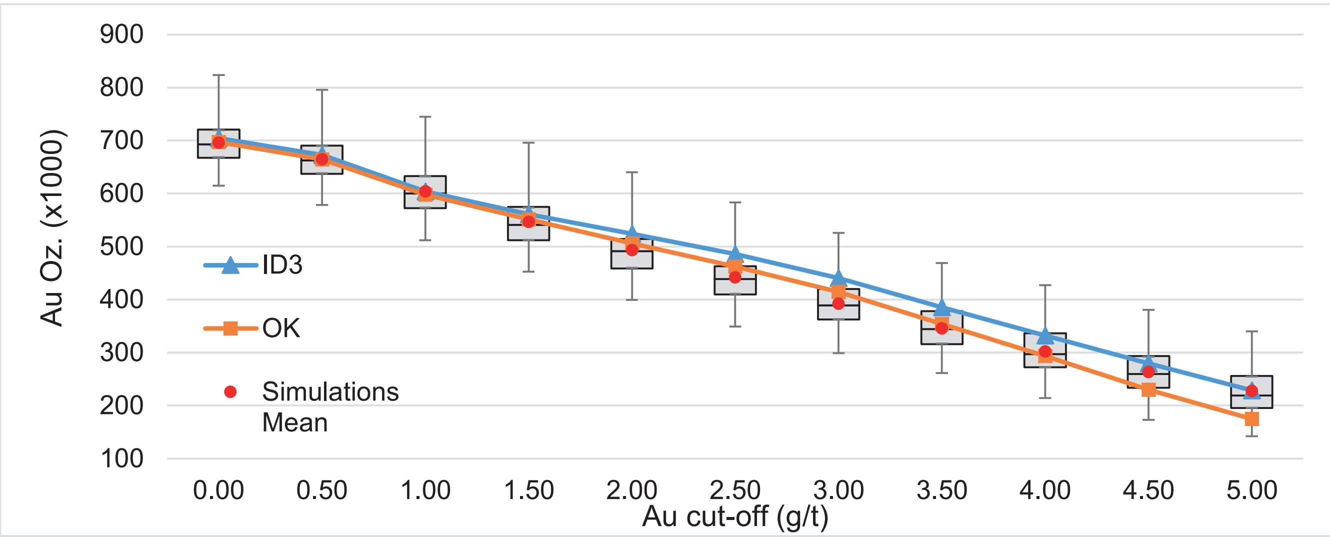

Figure 1: Gold Ounces above cut-off grade for inverse distance to a power of 3 (ID3) and ordinary kriging (OK) estimates compared to the uncertainty distribution based on 50 simulated realizations of gold.