Geostatistical Determination of Production Uncertainty: Application to Pogo Gold Project

Jason A. McLennan[1], Clayton V. Deutsch[1], Jack DiMarchi[2] and Peter Rolley[2]

[1]University of Alberta
[2]Teck Cominco Limited

Abstract

Geological uncertainty is an unavoidable characteristic of all mining projects since only limited information is available from sampling. Mine planning and development decisions with significant economic consequences are made when the geological heterogeneity is inherently uncertain. Geostatistical simulation is preferred over kriging because the methodology provides alternative property realizations that can be combined into a model of geological uncertainty. Geological uncertainty can be transferred into production uncertainty, which can help characterize the economic risk of the project.

This paper presents a case study for the Pogo property, being prepared for development near Fairbanks, Alaska. The exact dimensions, grades and production predictions have been modified; however, the methodology is illustrative. The geostatistical methodology consists of (1) assembling the relevant drillhole data and establishing a suitable coordinate system, (2) calculating the target distribution, (3) creating a model of spatial correlation, (4) generating multiple realizations at a small scale and (5) linearly averaging all the realizations to the chosen selective mining unit (SMU) support size. The geostatistical model is then used to calculate production uncertainty.

Introduction

Mine planning is conventionally based on block estimates created from some flavor of kriging. The classical application of kriging to mine planning is discussed in Journel and Huijbregts (1978). However, kriging results often either trade too-smooth estimates for local accuracy or conditional bias for global accuracy; this is described in Isaaks (1999) and Davis as the kriging oxymoron. Conditional simulation is recently becoming preferred over kriging due to improved heterogeneity characterization, joint uncertainty quantification and conditional unbiasedness. The implementation and documentation of geostatistical workflows contribute to the credibility and use of conditional simulation for mine planning challenges.

Exploration drillholes help delineate the geological properties of an ore deposit; however; in between drillhole samples, the geology is impossible to exactly predict. That is, it is impossible to establish the true distribution of geological properties (for example, attribute grades) until the deposit is recovered at the end of the mine life. Geological uncertainty is, therefore, an unavoidable element of making mine planning decisions.

The purpose of a geostatistical study is to quantify geological uncertainty and transfer it to production uncertainty (Deutsch, 2000). Geostatistical simulation allows alternative realizations of the geology to be created. The variation from realization to realization is combined into a model of geological uncertainty. Geological uncertainty is then transferable to several forms of production uncertainty that can assist mine planning and development decisions.

There are many sources of production uncertainty such as the geostatistical model parameters themselves, scale up from high resolution to the selective mining unit (SMU) resolution, economic forecasts and so on. Nevertheless, for most applications, the most significant contribution to production uncertainty is the uncertainty in the reserve, which is fluctuation between several possible geological parameter realizations created from geostatistical simulation.

This paper documents a study to quantify geological uncertainty using geostatistics and then transfer the geological uncertainty into a corresponding model of production uncertainty. The main steps of the geostatistical procedure are (1) assemble the relevant drillhole data and establish a suitable coordinate system, (2) calculate the target distribution, (3) create a model of spatial correlation, (4) generate multiple realizations at a small scale and (5) linearly average all the realizations to the SMU support size. The geostatistical model is then used to calculate production uncertainty.

Determination of production uncertainty using geostatistics essentially quantifies the economic risk associated to extracting an inherently uncertain reserve. The gross revenue forecasts for a mining project's cash flow model depend almost entirely on the model of the attribute/s grades. However; there is uncertainty in the grades and, therefore, there is uncertainty in the project revenues. Geostatistical simulation quantifies the uncertainty in the grades and transfers it into uncertainty in gross revenue forecasts. This aids mine planning decisions.

Pogo Project

The Pogo deposit is a plutonic gold system. The claims are underlain by high-grade gneisses of the Yukon-Tanana terrane, which have been locally intruded by granitic rocks (Rhys, 2003). Gold mineralization occurs within several shallow dipping tabular auriferous shear hosted gold-quartz veins. The most significant economic vein system is known as L1. Post-mineralization faulting structurally deformed L1 into several unconnected gold populations with significant vertical and lateral mismatch.

The Pogo project is a potential underground gold mine operation in Fairbanks, Alaska. The project is currently in the feasibility and permitting phase with operations expected to begin in late 2005. Gold grade is the geological attribute of interest. Surface and underground drilling campaigns were implemented to delineate the deposit. There are 281 drillholes and 1,471 assays available to help determine the spatial distribution of gold grades.

As part of the feasibility study, the gross revenue forecasts are required. These directly affect the cash flow model and economic viability of the project. A theoretical production schedule was previously constructed and is available for the study. It provides the 3-Dimensional location, tons and time for mining each SMU in the deposit. The basic idea is to estimate the gold grades at the SMU scale and merge this model into the production schedule. This allows access to profiles of the gold grade, tons and revenue versus time for the project.

Initially, a kriging scheme was implemented to estimate the gold grades and estimate the production revenues. However, there is uncertainty in the gold grades that requires uncertainty in the project revenue forecasts. Recently, a simulation study was launched to check the kriging results and incorporate the inherent gold grade uncertainty into the revenue forecasts. The emphasis of the study is creating several possible gold grade models using geostatistical simulation. These possible gold grade models are then used to calculate corresponding possible revenue profiles. The fluctuation between revenue profiles is a representation of production uncertainty that is a result of extracting an uncertain reserve.

Methodology

GSLIB is used for geostatistical modeling. The locations, grades and revenue forecasts have been modified; however, the methodology is illustrative and can be used in virtually any mining setting.

Multiple geostatistical realizations of the gold grades are created at the SMU scale and used to calculate corresponding realizations of the revenue forecasts. The main steps of the geostatistical procedure are (1) assemble the relevant drillhole data and establish a suitable coordinate system, (2) calculate the target distribution, (3) create a model of spatial correlation, (4) generate multiple realizations at a small scale and (5) linearly average all the realizations to the SMU support size.

Geostatistical calculations such as variography, estimation, and model scaling should be done within the deposit's original geological structure. Alternative coordinate systems are often calculated to restore the deposit's existing structure to its original structure before major structural deformations. For Pogo, a flattened vertical coordinate system is calculated to restore the vertical mismatches that resulted from post-mineralization faulting. The geostatistical procedure is performed in this flattened space then mapped back to preserve the existing geological structure in the final model.

The geostatistical model provides the uncertainty in the gold grades and is used to calculate uncertainty in the revenue forecasts. The transfer of geological uncertainty to production uncertainty is possible by merging the gold grade realizations into the production schedule. That is, the grades in the geostatistical model are mapped to the closest 3-D location in the production schedule. This gives an estimate of the gold grade being mined at any time. According to various time scales such as days, weeks, months, quarters and years, the SMUs to be extracted are flagged; within the flagged SMUs, the gold grades are averaged and the tons are added.

Production uncertainty is presented by plotting the gold grade, tonnage and revenue versus time. The gold grade simulations are summarized by plotting the p-90 and p-10 realization curves, that is, where the probability of the gold grade exceeding is 10% and 90%, respectively. The p-90 and p-10 revenue curves are calculated by multiplying the p-90 and p-10 gold grade curves, respectively, by the tonnage curve and an assumed gold price. The simulation results are compared with results from a conventional kriging estimation scheme.

Application

The 1,471 L1 drillhole data are used for the example. The locations and grades have been modified; however, the methodology is illustrative. There are 1,471 gold assay data with four variables for each data point: *X* – easting location, *Y* – northing location, *Zrel* – elevation location, and *Au* – gold grade. The data are reformatted into an ASCII file compatible with GSLIB.

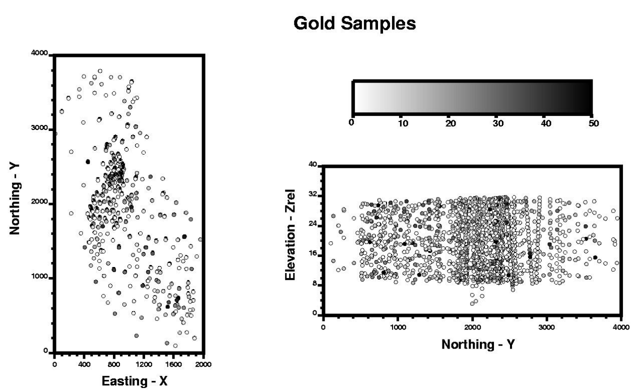

Figure 1: An *X-Y* plan view and *Y-Zrel* cross sectional view of the 1,471 gold assay locations in L1. The assays are also shaded according to gold grade.

Figure 1 shows the location and grade of all the gold samples in plan and cross section (*Zrel – Y*) view. The study area spans 2000m in the *X* direction by 4000m in the *Y* direction by 40m in the *Zrel* direction. The vertical coordinate *Zrel* is distance away from an imposed centerline assumed to be at a constant elevation benchmark of 20m; the extents of *Zrel* in the geostatistical model are from 0 to 40m.

Figure 2 shows a histogram of gold grades. The distribution of raw gold grades is positively skewed with a mean and variance of 8.67 and 113.0, respectively. Preferential sampling in the high grade areas requires use of declustering to obtain the target distribution. This target distribution is also shown in Figure 2 with a noticeably reduced mean and variance of 8.48 and 106.50, respectively.

Variography was performed using the normal score values of the raw gold grades. Experimental horizontal and vertical variograms are calculated and fitted with a final variogram model. Aerial variography is direction-independent or omni-directional, that is, the variogram is virtually the same for any azimuth.

Figure 3 illustrates the final 3-D variogram model fitted to the horizontal and vertical directions simultaneously.

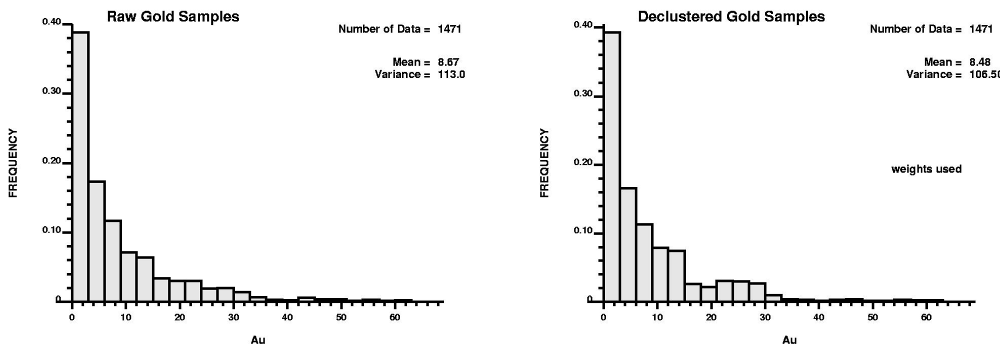

Figure 2: The raw and declustered distribution of gold grades. The declustered distribution is the target distribution and has mean and variance parameters of 8.48 and 106.50, respectively.

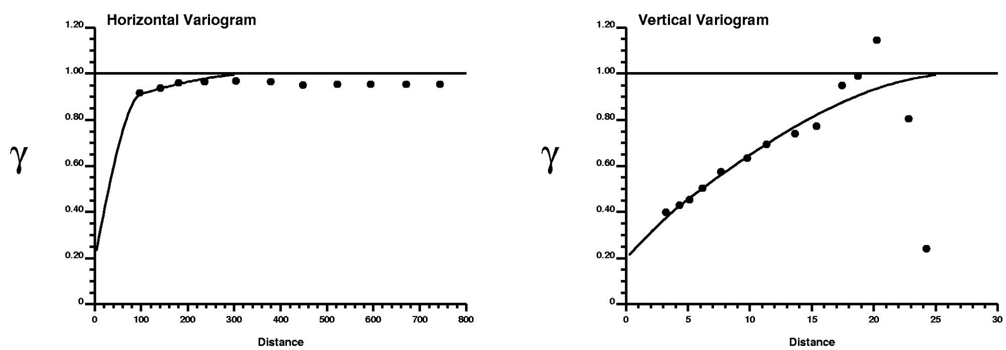

Figure 3: The horizontal and vertical gold variogram. The model variogram is shown as dark lines over top the calculated experimental points in the horizontal and vertical directions.

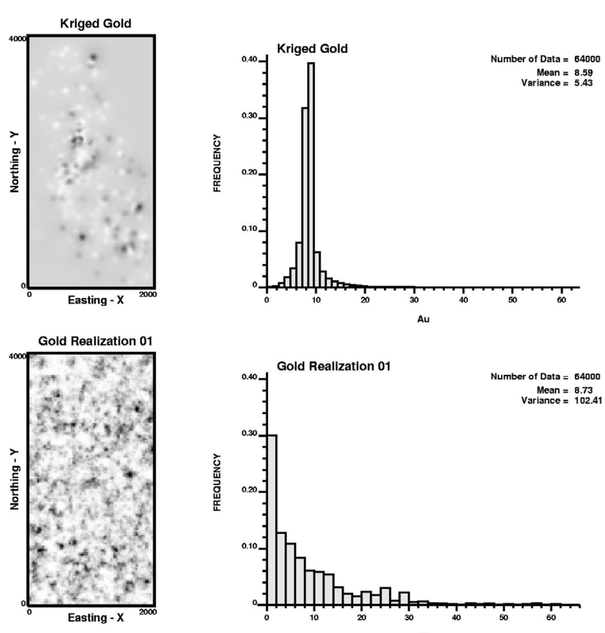

Figure 4: The distribution of gold grades is illustrated in an *X-Y* cross sectional view and histogram for the kriging and simulation scheme implementations.

The gold grades are estimated using kriging and simulation. Both estimation algorithms use the 1,471 gold assays (Figure 1), the target distribution of gold (Figure 2), and the 3-D gold variogram model (Figure 3) as conditioning information. The SMU measures 25m x 25m x 8m in the *X*, *Y*, and *Z* directions, respectively. For the simulation, 25 realizations were constructed at a fine scale then linearly averaged up to the SMU scale. Figure 4 shows a central *X-Y* section and histogram of the gold grades for the simple kriging results and the first realization of the simulation. The histograms are plotted at the same scale as Figure 2 and the same grey scale in Figure 1 is used for easy comparison. Note, the kriged estimates are too smooth. The variance of the kriged estimates is 5.43 versus the target 106.5. The simulated realizations better reproduce the target variability (102.41 versus 106.50, respectively).

The 25 gold grade realizations and the kriged gold grade model are mapped to the locations in the production schedule. The grades are averaged according to a stope time frame. Average gold grades are calculated from the SMUs inside each stope of the deposit and plotted against the time each stope is scheduled for extraction. The tons are summed within each stope and plotted against the same timeline. This is repeated for all 25 realizations and the kriged gold grade. A constant gold commodity price is assumed and the revenue is calculated as the product of gold grade, tons and price.

Figure 5 shows profiles of the estimated gold grade, tons and gross revenue with time. The gold grade profile curves are the geological uncertainty and the revenue profile curves are the production uncertainty. The simulation results are summarized with dark lines representing the p-90 and p-10 values where the probability of exceeding is 10% and 90%, respectively. The kriging results are shown as shaded lines. Note, the kriged profile is always enclosed below the p-90 and above the p-10 curves. The probability of exceeding a particular revenue at a particular time is immediately attainable from the production uncertainty. For instance, the probability of exceeding the kriged grade at any time is equal to the proportion of simulated realizations that exceed the kriged revenue.

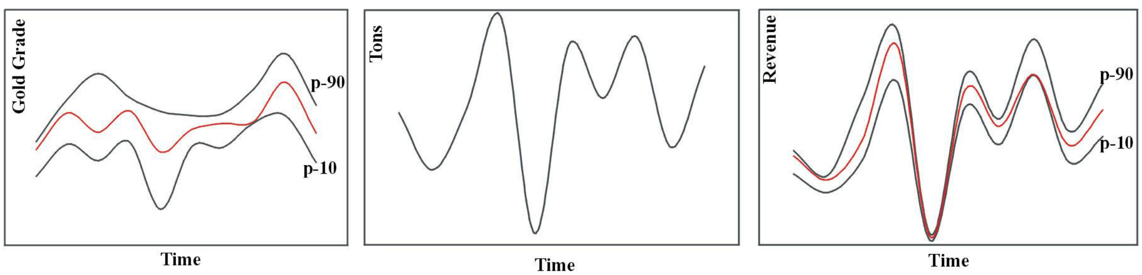

Figure 5: Geological uncertainty is the profile of possible gold grades with time (left) and production uncertainty is the profile of possible revenue forecasts (right). The transfer of geological to production uncertainty is made by multiplying grade, tons and gold price together.

Discussion and Conclusion

The revenue profiles generated in Figure 5 are important economic indicators of the project venture and can be utilized to assist mine planning development decisions. Areas of future concern such as extreme low grades at particular times are easily identifiable. Also, the timing and location of areas in the deposit with large uncertainty can be identified and investigated further. An automatic procedure could easily be implemented to iterate the production sequence so that a specific amount of gold is recovered over a specific time increment within the mine life. For instance, the early years of the production schedule could be customized for high-grading to quickly recover the project's initial capital investment.

Additional drilling would allow improved mine planning decisions. The value of additional drilling is that it would reduce the uncertainty in gold grade and revenue. In terms of Figure 5, additional drilling would close the gap between the p-90 and p-10 gold grade and revenue curves. In this way, the economic risk of the project can be better characterized. However, this improvement in mine planning must be balanced against the time and monetary cost of acquiring more drillhole data. The methodology could easily be modified to quantify the reduction in geological and production uncertainty with additional drillhole data.

Although gold grade is likely the most significant contributor to production uncertainty, the effect of uncertainty in the architectural and commodity price also contributes to uncertainty in the revenue forecasts. The architectural uncertainty could easily be incorporated by geostatistically modeling gold thickness using a similar methodology. The thickness would be multiplied by density and the SMU area to calculate multiple realizations of the tonnage. Practically, gold price is not a constant over the project life as assumed in this study; rather; it prescribes to uncertain fluctuations. These fluctuations can also easily be incorporated into the revenue profile realizations. The result of incorporating such additional uncertainties would result in an inflation of the final production uncertainty.

Simulation is performed due to its ability to better reproduce the heterogeneity of the gold grade variable. The histogram and variogram parameters are reproduced in expected value using simulation whereas they are not using kriging. Moreover, simulation provides access to joint uncertainty, that is, simulation provides a local distribution of possible gold grades for each SMU in the model whereas kriging provides only one value. The uncertainty in the grades is represented by these local conditional distribution functions (ccdf's) and can be used to calculate the uncertainty in production variables. For Pogo, the uncertainty in gross revenue forecasts is quantified based on the uncertainty in the gold grades.

Mine planning decisions with significant economic consequences are made based primarily on the project cash flow. And revenue forecasts are a significant component of the project cash flow. Moreover, the attribute grade heterogeneity and uncertainty are directly linked to the revenue forecasts and their uncertainty. Finally, geological uncertainty is captured by the geostatistical methods. The transfer of geological uncertainty to production uncertainty is straightforward.

Acknowledgements

This study was completed through cooperation between Teck – Pogo Inc. and the University of Alberta. Also, the authors thank Teck Cominco Ltd. for publication permission.

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