A CASE STUDY USING INDICATOR KRIGING — THE MOUNT MORGAN GOLD-COPPER DEPOSIT, QUEENSLAND

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Abstract

In August 1882, the Morgan brothers recognised a mineral deposit, now known as the Mount Morgan Gold-Copper Deposit. The final production figures for the mine were 250 tonnes of gold and 360,000 tonnes of copper from 50 million tonnes of ore, making the average grades 4.99g/t gold and 0.72% copper.

A three dimensional grade model was made of the pre-mined gold distribution within the Main Pipe mineralisation between the Slide Fault (to the west) and the Andesite Dyke (to the east), and bound to the south by the South Dyke.

Indicator kriging provided a method for estimating the grade in the strongly skewed gold distribution, without the problems of smearing of the high grades as seen in linear techniques. The application of indicator kriging using grade thresholds based on the declustered sample decile values was shown to be a poor application of indicator kriging, but was greatly improved by modifying grade thresholds above the median so that the amount of contained metal was evenly distributed between these classes.

The pre-mined resource estimate for this portion of the Main Pipe mineralisation using a 2g/t lower selection limit was 3,526,800 tonnes with an average grade of 11.98g/t, equivalent to 42.25 tonnes gold.

***Key Words**: geostatistics, non-linear grade estimation, indicator kriging.*

Introduction

The Mount Morgan Mine in central Queensland was for many years described as the greatest gold mine on earth with grades as high as 2000 ounces per tonne. The aim of the study was to prepare a detailed three dimensional computer model of the grade distribution within a select area of the Mount Morgan deposit (pre-mining), and to compare some different estimation techniques. Indicator kriging was used to estimate the grades in this paper.

The study area is a section of the Main Pipe mineralisation between the Andesite Dyke and the Slide Fault, and north of the South Dyke (Figure 1). The northern, lower and upper boundaries are those of the known data.

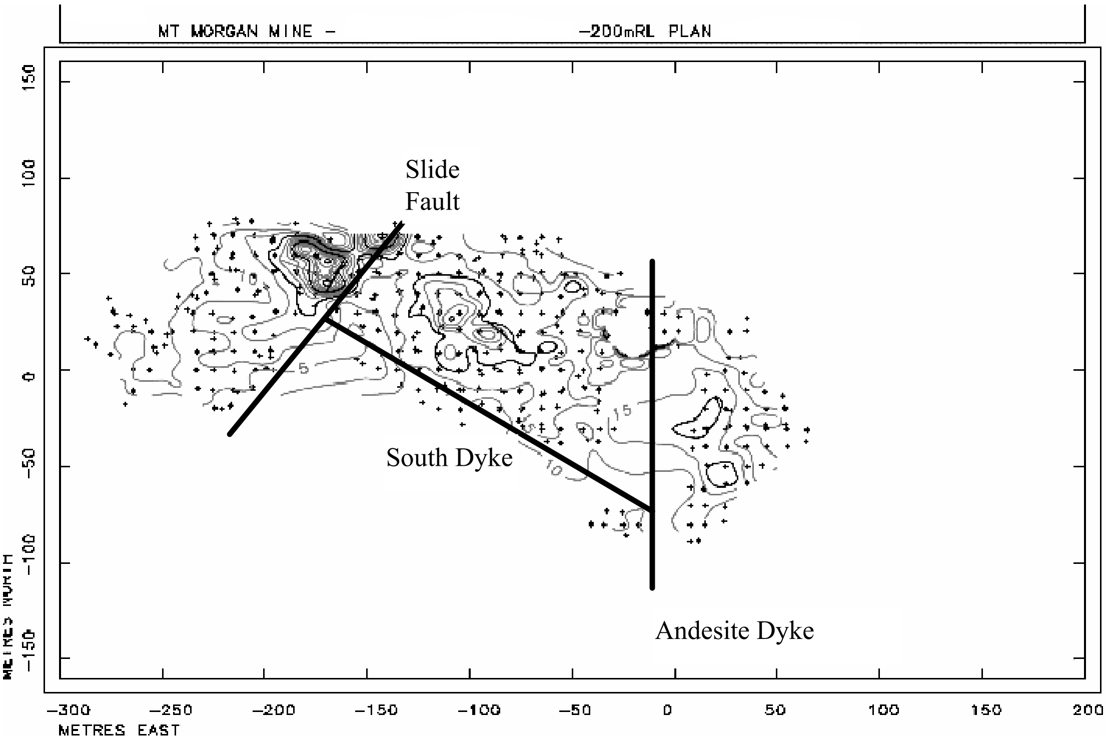

Figure 1 Location of the Study Area in relation to the major geological features within the Mt Morgan deposit.

The Main Pipe mineralisation was a concentrically zoned sub-horizontal pipe-like orebody (Jones and Golding, 1994), with the highest grades in the centre of the pipe. At the western end of the study area, there is a narrow vertical high grade gold shoot. The aim of the study was to prepare a detailed three dimensional computer model of the grade distribution within a select area of the Mount Morgan deposit (pre-mining). The model itself was used to investigate the three dimensional grade distribution of the deposit relating it to the recorded geology using computer visualisation.

In order to do this, a three dimensional computer model of the distribution of metal within the study area was prepared, and indicator kriging was used for grade estimation. A comparative study using two different methods of determining grade thresholds in the study was also performed.

Indicator kriging, as proposed by Journel (1982), has been a well accepted technique by the geostatistical community for dealing with skewed distributions and extreme values. It is a non-parametric estimation procedure, is not based on the data fitting a particular statistical distribution, is resistant to the influence of outliers, and is based on the knowledge that different parts of a mineralisation can have different spatial characteristics. High grade mineralisation may be limited in spatial extent, and in strongly skewed distributions, the contained metal can contribute a significant proportion of the ore reserves (Journel and Arik, 1988), although not all high grade occurrences may have been sampled. Alternatively, low grade mineralisation may be pervasive, and spatially extensive. It was therefore a suitable procedure for gold grade estimation in the Mount Morgan Deposit.

Data analysis

Underground mining at Mount Morgan was primarily by square set stoping, and large open stopes or chambers. A face sample was taken for each square set and assayed for gold, copper and in select areas silica, the assays being recorded on level plans. The square sets, were approximately 5 feet by 6 feet square by 7 feet 9 inches high (Patterson and Thomas, 1910). The assays for each square set from every fourth level were digitised as a point representing the centre of the square set location. The square set stope data was the basis of this study.

Moving window statistics

Moving Window Statistics were calculated for the study area as well as the rest of the Main Pipe mineralisation. They were used as a tool for examination of the data in a spatial context, and as a tool for determining if high grade zones could be separated from the remainder of the deposit for modelling purposes.

The contoured plans of the moving window statistics (Figure 1) and visual observations of the digitised data indicate that the high grade shoot had gradational boundaries. It was therefore not split into a domain separate to the main data.

Statistical summary of data distribution

The histogram of the Au data (Figure 2) shows a distribution that is positively skewed, the histogram of the logarithm of Au is roughly symmetrical, and the log-probability plot is relatively smooth and roughly straight with a high grade population of data above around 80g/t Au.

Preparation of indicator variables for Au

The principle of indicator kriging involves the transformation of the original random variable into indicator data instead of using the variable itself.

The thresholds are chosen from the histogram of the data such as z_1, z_2, z_3, z_4 and z_5, respectively the 10^{th}, 30^{th}, 50^{th}, 70^{th} and the 90^{th} percentiles (Isaaks and Srivastava, 1989). Isaaks and Srivastava (1989) also comment that it is important to include more thresholds where the information is required, for instance in a precious metal deposit there might be more thresholds in the higher grades.

In the first Indicator Kriging study, the indicators I1, I2, I3, ..., I9 had thresholds of the 10th, 20th, 30th, ..., 90th, percentiles.

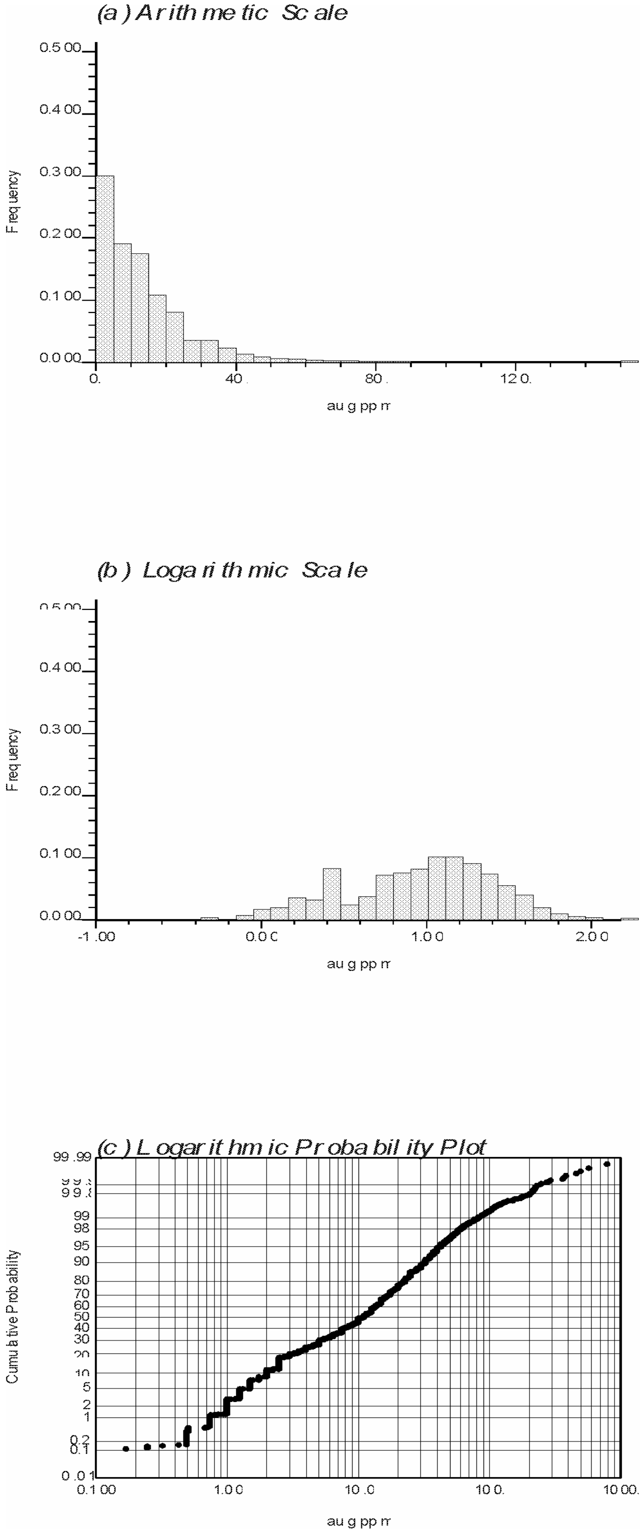

Figure 2, the de-clustered histogram (top), log-histogram (centre) and log-probability plot (bottom) of the Au data.

Calculation of the contained metal represented by samples above the threshold grade was by spread sheet. The samples, all being the same length, were multiplied by their de-clustered weight and grade in order to get the weighted value for the histogram from the de-clustered data. The samples were then sorted by grade, and the cumulative totals of the weight*grade determined. The cumulative total at each of the sample grades is then a relative representation of the contained metal below that grade within the study area when compared to the cumulative total for the highest grade. The contained metal represented by samples above that grade are then the cumulative total for the highest grade minus the cumulative total at the threshold grade.

In the second Indicator Kriging study, the thresholds were modified to balance the contained metal in the high threshold classes. More than 80 percent of the contained metal was represented by the data above the 50 percentile (10.73 g/t Au), and more than 50 percent of the data was above the 80 percentile (22.48 g/t Au). 35 percent of the contained metal was represented in the top decile of the data. The disproportionate amount of metal occurring in the top classes was unsatisfactory with decile thresholds (not enough thresholds to define the distribution and control the amount of contained metal), and in the second Indicator Kriging study, the data threshold approach was modified using the quantity of contained metal.

The criteria for selection of the indicator thresholds in the second Indicator Kriging study was as follows:

- Thresholds below the median grade (as defined by the de-clustered data) were selected on every tenth percentile (the decile values).

- Thresholds above the median grade were selected on the basis of the cumulative metal content above the median grade. The classes were divided up so that each class represented approximately 10% of the contained metal in the study, as represented by the samples.

There were 13 thresholds in the secondary indicator kriging study, including 8 above the median.

Indicator variograms for the Au variable

Indicator variograms of the Au variable were prepared in this study for grade threshold values based on the Au variable grade thresholds. Full directional variography studies were prepared by firstly determining any axes of anisotropy of the spatial continuity for the indicator variables at each threshold, calculating experimental indicator variograms for each of the axes of anisotropy determined for the indicator variables at each threshold, and finally preparing a mathematical model for each of the variograms.

Determination of the principal axes of anisotropy by planimetric variogram maps. Experimental indicator variograms were not calculated for threshold grades below the 20 percentile (3.17 g/t Au) or above the 82 percentile (23.72 g/t Au) as there is not enough data in the class above or below to prepare stable and valid variograms suitable for interpretation. Variograms applied to lower or higher thresholds were those of the nearest threshold with an experimental variogram.

In relation to the mineralisation, the determined orientation of the major axis of the mineralisation is approximately that of the core of the Main Pipe mineralisation.
Variogram models were prepared for directional variograms for each grade threshold and the model parameters recorded for grade estimation. Apparent zonal anisotropy between the directions 1 and 2, and direction 3 (as for lower grade thresholds) is caused by a mixture of similarity in grades in the direction of principal anisotropy, and the influence of hole effects across the mineralisation in directions 2 and 3.

The directions of the $Z_c = q_{0.50}$ or median variogram are very similar to those of the pair-wise relative variograms for the Au variable that were interpreted separately. The median indicator experimental variograms are presented in figure 3 with fitted models.

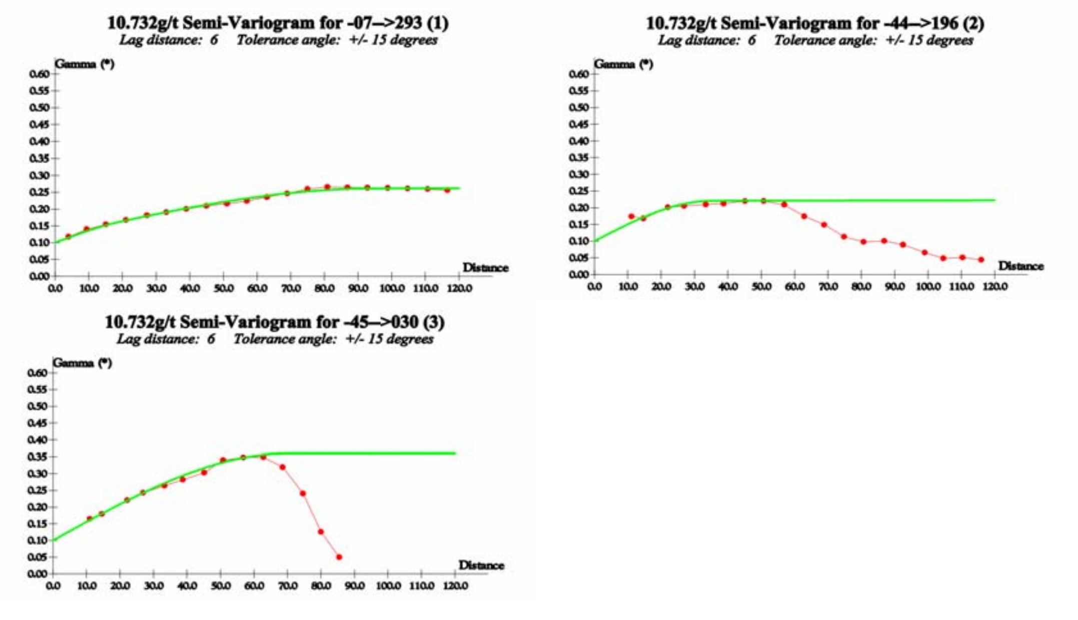

Figure 3 Experimental indicator variograms for $Z_c = q_{0.50}$ The variogram for the principal axis of anisotropy is variogram (1), the variogram for the semi-major axis is variogram (2) and the variogram for the minor axis is variogram (3).

Grade estimation of Au by indicator kriging

The Au variable in this study has a distribution that is positively skewed and characterised by mixed sample populations in the data. Indicator kriging has been used for estimating the grade distribution in this study.

As discussed already, two estimates by indicator kriging were prepared. The first indicator kriged estimate (IK1) used the nine decile thresholds, a power function to estimate the distribution in the lower class and a hyperbolic function for the top class. The second indicator kriged estimate (IK2) used threshold values determined using the decile values for the first five grade thresholds (up to the median), the balance of metal to determine the higher thresholds (8 classes representing 10% contained metal in each class), a power function to estimate the distribution in the lower class and a hyperbolic function for the top class.

The required result from the indicator kriging was an expected average value of each block (an E-type estimate). The E-type estimate for the block is first determined using the probabilities and the mean grade of each class for each cell.

Estimation of the lower tail distribution

The lower class (the class below the lowest threshold of the indicators) was estimated using a power model (Deutsch and Journel, 1992).

The power model was used for the lowest class estimate because, even though the class is the lowest class, the grades are still of economic interest. The calculated model was plotted against the de-clustered data on a scatter plot (percentile versus value) to ensure the fit of the power model to the de-clustered data. A p value of 2.1 was determined to provide a relatively good fit to the data. The power model was the same for both the IK1 and IK2 indicator kriged estimates, as there was no change to the lowest class threshold between these estimates.

Estimation of the upper tail distribution

The top class (above the highest grade threshold of the indicators) was estimated using a hyperbolic model (Deutsch and Journel, 1992).

The hyperbolic models for the top class in the IK1 and IK2 estimates were determined using an excel spreadsheet. The calculated hyperbolic models were plotted against the de-clustered data to ensure the models matched the data.

Order relations corrections

Order relation corrections were calculated as an average of the upper and lower values.

There was a relatively small number of order relation corrections in the lower classes is because the variograms and their orientations are roughly consistent between neighbouring thresholds. The largest number of order relation corrections is in the grade thresholds near the middle of the distribution, but the average correction was in the order of 1%.

Correction for the volume-variance relationship.

In order to get block estimates for recoverable reserves from indicator kriging, a volume-variance correction is often used as indicator kriging produces point estimates. Individual recoverable reserves in blocks were not required for this study, and so no volume-variance correction was applied.

Validation of indicator kriged estimates

After checking the order relation corrections, the indicator kriged estimates were checked by examination of the mean against the declustered data mean, visual examination of the estimates in relation to the data, and examination of scatter plots of moving window statistics for raw data against the average of all the block estimates in the same window.

The simplest validation is to look at the statistics of the data, and compare the de-clustered mean of the raw data to the mean of the estimates. Table 1 shows that the estimates have a lower mean value than the de-clustered raw data, and that the IK1 estimate had a relatively low maximum value.

Table 1 Comparison of statistics of gold for de-clustered data with indicator kriged estimates.

	De-clustered data Au g/t	Indicator kriged IK1 estimate g/t	Indicator kriged IK2 estimate g/t
mean value	12.41	10.98	11.40
Median	10.73	8.51	8.59
Range	787	86.31	125.17

A factor in the lower mean grade is the inability of the estimates to reproduce the extreme values. Removal of the four top high grade values from the de-clustered data reduced the mean of the de-clustered data by approximately 0.2 g/t.

Another factor in the lower estimate is the zone around the upper, lower and northern limits of the workings which were a part of the block model, and which were not sampled. This part of the deposit is the low grade boundary where the orebody graded into the weakly mineralised host rock (uneconomic for mining at the time of underground mining). Inclusion of the blocks in these peripheral parts of the deposit in the calculation of the statistics give a lower mean grade for the estimates than for the de-clustered data, as the de-clustered data does not include the low-grade halo. By restricting the blocks to those closer to the raw data (removing some of the more peripheral blocks in an arbitrary manner), the mean of the indicator kriged Au estimates was 12.12 g/t (using the decile thresholds) and 12.39 g/t (using the modified thresholds), as opposed to the declustered mean for the Au data (12.41 g/t).

Visual inspection was also an important part in the validation of these estimates. The estimations were checked in cross-sectional and plan views against the raw data. The large amount of raw data made this difficult, and summaries using coloured grade ranges were used to compare the two data sets.

Further examination of the estimates was made using a comparison between the log-probability plots of the de-clustered raw data and the estimates. The most obvious features of this comparison are the minimum low grade estimate, and that the higher grade estimates are lower than those of the raw data. There is an apparent artificial maximum estimate in the indicator kriged estimate using the decile grade thresholds, but this is not a feature of the estimate using the modified thresholds. The higher grade estimates using modified thresholds appear to represent the de-clustered histogram better than the indicator kriged estimate using the decile thresholds.

Examination of the basic Au statistics, the visual inspections of the indicator kriged estimates with the raw data and the comparison of the log-probability plot of the de-clustered Au data and the indicator kriged Au estimates indicate the indicator kriged estimates using the decile thresholds did not reproduce the high grade end of the distribution well. The low grade estimates were also not well reproduced with a lack of definition of the distribution at the low end, and an artificial minimum.

An attempt to review some of the estimates on a local basis was made by preparing moving window statistics of the Au and comparing the average value (if more than 30 data points) with the average of the indicator kriged estimates from within the same window in the model. Comparison between the average estimate in the block, and the average of the sample data in the block was not entirely valid as the estimates used data outside of the block as well to estimate the grade in the block model, and the average of the data was no more than a simple average (a polygonal estimate). Outliers were a problem in each of the comparisons. Although a point on the scatter plot indicated that the estimates were much lower than the mean of the data, the mean data value was controlled by an extreme value / outlier, and the estimates did not reproduce this extreme value. A small spread of points around the 45 degree line on the scatter plot is a result of a lack of precision in local estimates. This is because the estimates are conditioned by the class the data belongs to, not the actual data value.

The indicator kriged Au estimates using the modified thresholds are more consistent with the raw data, and from the review of the estimates and the data, there is no reason to assume this model is not valid.

Grade-tonnage results

In a global sense, the grade tonnage figures for the various estimates are compared. The high grade blocks are crucial with a large proportion of the metal in the deposit being represented by only a small amount of high value data and consequently only a few blocks in the model. An important feature of these global numbers is the relatively low amount of contained metal in the indicator kriged estimate using decile thresholds for the 50 g/t cut-off.

Table 2 Tonnes, grade and contained gold above cut-off gold grades by the IK1 and IK2 estimates.

Cut-off	2 g/t Au	5 g/t Au	10 g/t Au	25 g/t Au	50 g/t Au
IK1	3,526,800t 11.98 g/t Au 42,251 kg Au	2,640,480t 14.91 g/t Au 39,370 kg Au	1,702,200t 18.99 g/t Au 32,325 kg Au	339,240t 34.31 g/t Au 11,639 kg Au	11,040t 52.37 g/t Au 578 kg Au
IK2	3,526,920t 12.24 g/t Au 43,170 kg Au	2,649,360t 15.21 g/t Au 40,297 kg Au	1,726,920t 19.32 g/t Au 33,364 kg Au	339,480t 35.90 g/t Au 12,187 kg Au	29,760t 57.00 g/t Au 1,696 kg Au

The IK2 reports slightly higher tonnages and grade at the 25 g/t Au and 50 g/t Au cut-off reports. Examination of the amount of contained metal above each cut-off for the IK1 and IK2 estimates showed that for each of the cut-offs, there was more contained metal reported by the IK2 estimate than by the IK1 estimate. An interesting feature of the IK1 estimate is the low amount of contained metal above the 50 g/t Au cut-off. The IK2 estimates report 1,100 Kg of gold more than the IK1 estimates in the 50 g/t Au cut-off report. In this case, if a resource estimate was applied using the decile thresholds only (as was the IK1 estimate), it is probable that the resource will be under-stated by the estimates and the grade-tonnage figures.

Observations from visual comparison of the estimates

The indicator kriged estimates had good continuity of the high grade estimates. The indicator kriged estimates also had minor near vertical shoots of high grade estimates that were not as well defined as the main shoot. These high grade shoots were too small to have been separated from the remainder of the data by building them into separate geological domains during the data review phase.

The lowest estimates for the indicator kriged estimates were higher than the low end of the de-clustered data distribution. This is because the indicator kriged estimates are conditioned on the class the sample value belongs to, rather than the actual sample value as in the linear estimates.

An obvious overall trend was that in the indicator kriged estimates the effect of smearing of extreme values was restricted.

Discussion

In this study, the available data was sufficiently dense throughout the study area to allow a fairly detailed examination of how different techniques perform. It is not possible to examine them against reality because the exhaustive dataset is not known, and local production figures are not available. Global production figures are not suitable for comparison either as the deposit included several different geological domains including an oxidised zone, supergene enrichment zone (gold) and depletion zone (copper - Mundic Zone) and pyrrhotite rich ore-bodies near the western margins of the deposit.

Two indicator kriged estimates were prepared, one using decile thresholds (the IK1 estimate) and another using modified thresholds (the IK2 estimate). The IK1 estimate, which used grade thresholds based on the declustered sample deciles, was a poor estimator. It was particularly poor at preserving the contained gold in the grade-tonnage figures and in nearly all the grade-tonnage estimates (Table 2), the IK1 estimate reported nearly 1 tonne less of contained gold than the IK2 estimate. The IK1 estimate resulted in only 578 kg Au reported above 50 g/t Au , approximately 1,100 kg Au less than was reported for the IK2 estimate. The biggest problem with the IK1 estimate appears to have been the use of grade thresholds based on declustered sample decile values, and the consequent poor definition and use of the high grade values. This resulted in significant under estimation of the resource represented by the high grade values, and subsequent under estimation of the total resource. Clearly this degree of under estimation of a resource would be reason for concern in a feasibility study to determine the economics of mining a mineralisation with a skewed distribution.

The IK2 estimate, which used grade thresholds based on the balance of metal for thresholds above the median value, was much better than the IK1 estimate. The extreme values were better accounted for by the increased number of classes. This effectively controlled the influence of high grade values on surrounding blocks.
Indicator kriging dealt with the outliers in the most effective manner, but lacked the precision for local estimates. The indicator kriging did however provide the best global estimate because of the control on the high grade values.

This study supports the earlier reports that the orebody was concentrically zoned in respect to the gold grades. The peripheral parts of the Main Pipe were also shown to be gradational, but were not defined adequately by grade control samples and therefore not accurately defined by the modelling.

The high grade shoots, also defined by the model appeared more prolific than were previously thought, and appeared to be evenly distributed along the central axis of the deposit. It was further recognised that the high grade shoots had irregular and gradational boundaries, and were more irregular in shape than previous reports have suggested.

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