# Multi-metal Recoverable Estimation and its Impact on the Cove Ultimate Pit Design


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## Abstract

Open pit optimization and mine design depend upon a realistic estimate of the grade-tonnage distribution. The estimate should reflect what can be reasonably recovered and processed. The McCoy/Cove operation in central Nevada, USA, is a gold and silver mine. Recoverable reserve estimations of gold and silver were made using indicator kriging and the indirect lognormal variance correction to construct the grade-tonnage distribution. Optimal pits were generated using this distribution, and the results were compared with the pits generated by ordinary kriging and indicator kriging block mean methods. The results indicate that the proposed method for multi-metal recoverable reserve estimation shows an improvement in terms of predicting recoverable tons and grade. The optimal pits generated from the recoverable resource model are larger than those generated by the ordinary kriging and indicator kriging block mean methods. This model maximizes the overall recovery of the mineral resource.


## Introduction

In reserve estimation of a precious metal deposit with high grade variation, it is essential to have a reasonably accurate estimate of contained metal; however, it is more important to have the best possible estimate of the grade-tonnage relationship. This will result in a correct optimal open pit and an effective mine design and selection of ore processing capacity. Recoverable reserves are the estimated tonnage and grade that can be recovered at a given economic cutoff. The recoverable reserve grade-tonnage curve estimate of a deposit is a distribution that reflects what possibly will be mined and processed with respect to tons and grade. In order to optimize the mine, mill and leach production, it is very important to have the best possible estimate of the grade-tonnage relationship.

The recoverable reserve grade-tonnage distribution is not unique since it depends on the size and shape of the selective mining units (SMU). All mineral deposits are made up of mixtures of ore and waste rock. If a deposit could be mined by sampling each bucket load of an excavator, this would result in fewer ore tons being mined at a higher grade with low production rates and high mining cost. In this case the SMU would be as small as the size of the bucket. However, realistically, in an operating open pit mine, ore and waste are mined according to two-dimensional digging polygons determined from blast assays, using either a traditional or geostatistical interpolation method. This results in less selectivity between ore and waste, with the lower mining costs and higher productivity being offset by a lower grade, i.e. higher dilution.

The size of the SMU for a particular deposit generally depends upon, 1) the variability of the mineralization and geology, 2) the spacing and burden of the blast holes, 3) the interpolation method used to locate a digging polygon, 4) the minimum size of the digging polygon, and 5) the bench height and size of loading equipment.

In the 1970s and 1980s, several geostatistical methods were developed to provide a means of estimating in-situ recoverable reserves, particularly for precious metal deposits with extreme geologic complexity and grade variation. The methods include indicator kriging (Journel, 1982; Sullivan 1985), probability kriging (Journel, 1983; Sullivan, 1985), disjunctive kriging (Matheron, 1976), multigaussian kriging (Verly, 1985), and conditional simulation (Parker & Switzer, 1975).

An effective estimation technique should provide the flexibility of modeling the grade-tonnage distribution with a wide range of cutoff grades for different sizes of SMU. This paper discusses the use of indicator kriging (IK) to estimate the spatial grade distribution of sample size units (SSU), i.e. drill hole composites, and an indirect lognormal variance reduction technique to modify the distribution to the size of the SMU.

The major advantage of IK is that it can model the spatial grade distribution at different cutoff levels. Linear interpolation techniques, such as ordinary kriging, should not be considered as tools for recoverable reserve estimation since they will only estimate a grade distribution for a particular size of block. For example, consider a gold deposit modeled with block dimensions of 50x50x20 feet, containing approximately 4000 tons of material. A non-recoverable reserve estimation would usually overestimate tons and underestimate grade. This can lead to an incorrect optimal open pit, mine plans and the selection of an ore processing capacity higher than necessary.

## Estimation of multi-metal recoverable resources

In 1995, the McCoy/Cove mine was the largest silver producer in North America and the third largest in the world. The mine is a hydrothermal disseminated and stockwork veined gold and silver deposit with complex geology. Both gold and silver grades are highly variable with very high coefficients of variation. Both metals have significant impact when determining the economic cutoffs. The reserves need to be estimated separately for both gold and silver.

This paper presents case studies of recoverable reserve estimation for gold and silver as applied to a multi-metal deposit. The grade-tonnage distribution of recoverable reserves was constructed and compared with the distributions defined by blast holes and ordinary kriging. Stockpiles with different cutoffs at different recoveries were used to optimize ore processing operation in pit optimization. Optimal pits were created from the recoverable resource model and compared with the optimal pits generated from the ordinary kriging block model.

## Mineralization correlation of gold and silver

The oxide portion of the Cove deposit exists in limestone and clastic rocks. The sulfide portion of the deposit exists entirely in clastic rocks and contains most of the reserves. The mineralization occurs as stockwork veins or along the bedding of sedimentary rocks that dip to the south at 18 degrees.

Both gold and silver occur in the same rock units. The correlation coefficients between gold and silver range from 0.60 to 0.85. This indicates that, at the same location, a sample with a higher grade of gold will have a higher grade of silver, and vice versa. Figure 1 illustrates this correlation for a particular bench.

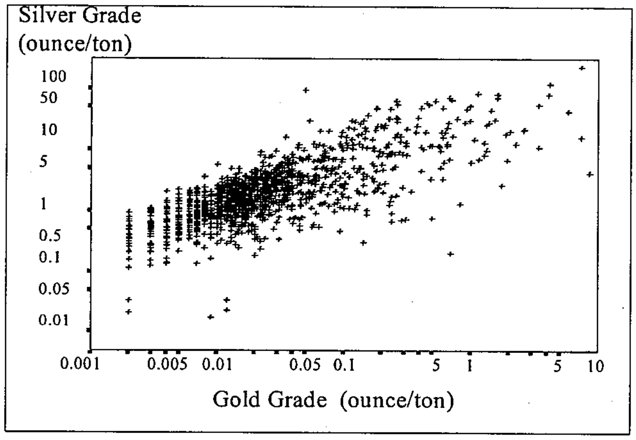


**Figure 1:** Gold and Silver Mineralization for Bench 4185, Total 1383 Samples, Correlation Coefficient is 0.74

## Rock lithologies and geologic structures

Eleven different rock lithologies exist at the Cove deposit. They represent oxide, sulfide and carbonaceous rock units. The deposit is cut by a series of pre-, syn-, and post-mineralization normal faults. The reserve estimation honors eleven rock lithologies and six structural zones. Blast hole assays were used to generate indicator variograms for gold and silver values.

## Ore control practices

Blast hole spacing varies from 13 to 20 feet depending on rock type, blast hole diameter, bench height etc. An averaging method is used to locate an ore control digging polygon. Due to geologic complexity of the deposit, loading units recognize partial depth ore zones to minimize mixing.

## Indicator kriging

Indicator kriging utilizes a number of cutoffs to estimate a block grade distribution using the samples inside or near the block. The estimate represents the local distribution of sample size units (SSU).

The following is a brief summary of indicator kriging. A complete explanation of indicator kriging is given in other references (Journel, 1982; Sullivan, 1985).

For a given cutoff $zc_k$, if a sample grade $z_i(x)$ is greater than the cutoff $zc_k$, then the indicator variable $ik(z_i(x), zc_k) = 1$, otherwise $ik(z_i(x), zc_k) = 0$. Indicator variograms will be created for the given cutoff $zc_k$ using $ik(z_i(x), zc_k)$. Ordinary kriging is performed with indicator variography parameters by using the indicator value $ik(z_i(x), zc_k)$ transformed from the sample grade. If s samples are chosen to estimate a block and their corresponding kriging weights are $\lambda_i$ (i=1,2,3...s), then the proportion of the block above the cutoff $zc_k$ is given by:

$$P(zc_k) = \sum_{i=1}^{s} \lambda_i \, ik(z_i(x), zc_k)$$

and:

$$ik(z_i(x), zc_k) = 1, \text{ if } z_i(x) \geq zc_k$$
$$ik(z_i(x), zc_k) = 0, \text{ if } z_i(x) < zc_k$$

Where:

| | |
|---|---|
| $zc_k$ | Given cutoff |
| $z_i(x)$ | Sample value |
| $\lambda_i$ | Ordinary kriging weights |
| s | Number of samples used in ordinary kriging |
| $P(zc_k)$ | Proportion of the block above cutoff $zc_k$ |

The flexibility of the IK approach is obtained at the cost of order relation problems. The corrected grade distribution of a block is calculated by averaging the probabilities of the forward and downward corrections (Deutsch & Journel, 1992).

If n cutoffs are used, n+1 classes are defined to cover the sample grade from zero to infinity, using $zc_0$ to denote grade cutoff = 0, defining $P(zc_0) = 1$, and using $zc_{n+1}$ to denote infinite grade, and defining $P(zc_{n+1}) = 0$.

The proportion between two consecutive cutoffs of $zc_k$ and $zc_{k+1}$ is calculated as:

$$p_k = P(zc_k) - P(zc_{k+1}) \quad k = 0,1,2...n$$

If $m_k$ represents the class mean between $zc_k$ and $zc_{k+1}$, then the block mean is expressed as:

$$m = \sum_{k=0}^{n} p_k m_k$$

The block variance $\sigma^2$ of the SSU is calculated as:

$$\sigma^2 = \sum_{k=0}^{n} p_k m_k^2 - m^2$$

The proportion of the block tonnage above a given cutoff $zc_k$ for the SSU is given as:

$$P(zc_k) = \sum_{i=k}^{n} p_i$$

The mean grade above the cutoff $zc_k$ for the SSU is:

$$g_k = \sum_{i=k}^{n} p_i m_i / P(zc_k)$$

A large number of sample grade cutoffs provide a better definition of grade distribution, but require much more computing time. For most precious metal deposits, a small number of samples is responsible for most of the metal content. The five lowest cutoffs were determined based on an equal number of samples in each class, while the last five cutoffs were chosen based on an equal quantity of metal content in each class. Six intervening cutoffs were used to fill the rest of the grade range in order to select specific cutoff levels (such as the economic cutoffs for different processes and the grade change due to multi-phase mineralization). Therefore, sixteen cutoffs were used to delineate a block grade distribution. The class mean was calculated as the total metal content between two consecutive cutoffs divided by the number of samples within the class.

Exploration holes are typically not drilled in a regular pattern. The spacing of the Cove exploration holes ranges from 50 to 200 feet. The average spacing is approximately 70 feet. Drill holes are closely spaced in the high grade area of the deposit and widely spaced in a low grade or non-mineralized area. Therefore, exploration sample data must be declustered before determining cutoffs and calculating means for each class.

## Variance reduction

Variance reduction must be carried out to transform the grade distribution of an SSU, determined by IK estimation, into the distribution of an SMU. There are several mathematical procedures for adjusting an estimated distribution to account for change of support. They are the affine correction, the indirect lognormal correction, and the Gaussian transformation (Journel & Huijbregts, 1978; Isaaks & Srivastava, 1989). All these methods only reduce the variance without changing the mean of the distribution of a block.

The gold and silver grades of the Cove deposit are lognormally distributed. The indirect lognormal correction was used for variance reduction. The transformation is described as follows:

For a given cutoff $zc_k$ (k = 0,1,2...n), there is a proportion, $P(zc_k)$, above the cutoff. There are n+1 class means of $m_k$ and n+1 probabilities of $p_k$ which represent the proportion of a block between two consecutive cutoffs of $zc_k$ and $zc_{k+1}$. Therefore, the block mean, m, is:

$$m = \sum_{k=0}^{n} p_k . m_k$$

The transformation of class means of $m_k$ is carried out using the following equations (Isaaks & Srivastava, 1989):

$$m_{k'} = a.(m_k)^b$$

Where:

$$a = \frac{m}{\sqrt{f.CV^2 + 1}} \left(\frac{\sqrt{CV^2 + 1}}{m}\right)^b$$

$$b = \sqrt{\frac{\ln(f.CV^2 + 1)}{\ln(CV^2 + 1)}}$$

and:

f = Affine correction factor
m = Mean of the distribution
CV = Coefficient of Variation

After the transform, the block mean can be recalculated as:

$$m' = \sum_{k=0}^{n} p_k . m_{k'}$$

Since m' may not be the same as the original mean of m, an additional step is required to correct any discrepancies. The new class means after the indirect lognormal correction will be corrected as:

$$m_{k''} = \frac{m}{m'} m_{k'}$$

The new transformed cutoffs of $zc'_k$ for different blocks will not be the same as the original cutoffs since the grade distributions of different blocks may not be the same. They can be recalculated according to the transformed new means $m''_k$:

$$zc_{k'} = \exp\left[\frac{\ln(m_{k''}) + \ln(m_{k''-1})}{2}\right]$$

The proportion of the block tonnage above the new transformed cutoff $zc'_k$ of the SMU is given as:

$$P(zc_{k'}) = \sum_{i=k}^{n} p_i$$

and:

$$P(zc_{k'}) = P(zc_k)$$

The mean grade above the cutoff $zc'_k$ of the SMU can be derived as:

$$g_{k'} = \frac{\sum_{i=k}^{n} p_i \cdot m_{i''}}{P(zc_{k'})}$$

This transformation assumes that the log grades are linear. However, the Cove data indicate that the distribution is not a perfect log-linear relationship. Additional errors from the transformed class means and cutoffs can be introduced into the estimation when transforming the distribution of an SSU to one for an SMU. It is assumed that the errors from this process will have a minimum impact on the estimated values. Therefore, the use of this method can be justified because of its relative simplicity.

A numerical example is given in Table 1 to demonstrate the IK data manipulation and the procedures of the indirect lognormal variance correction.

| **Original Cutoff** | **$zc_k$** | **0** | **0.006** | **0.034** | **0.500** |
|---|---|---|---|---|---|
| Proportion of the block above original cutoff | $P(zc_k)$ | 100% | 100% | 40% | 10% |
| Proportion between original cutoffs | $p_k$ | 0% | 60% | 30% | 10% |
| **Class mean between original cutoffs** | **$m_k$** | **0.002** | **0.015** | **0.130** | **0.700** |
| Block mean, m =Σ $p_k$*$m_k$ = 0.1180 | | | | | |
| Variance of block mean = Σ $p_k$*$(m_k)^2$ - $(0.1180)^2$ =0.0403 | | | | | |
| Indirect Lognormal Correction: $m'_k$ = a * $(m_k)^b$ f=0.0907; CV=2.7 | | | | | |
| ILC corrected class means | $m'_k$ | 0.0210 | 0.0561 | 0.161 | 0.367 |
| Block mean after the ILC correction: m' =Σ $p_k$*$m'_k$ = 0.1187 | | | | | |
| Corrected block mean, m' = 0.1187, is not equal to the original block mean of 0.1180. This requires to adjust the class means to make the block mean equal to 0.1180 | | | | | |
| **Adjusted class mean =$m'_k$*(m/m')** | **$m''_k$** | **0.0209** | **0.0558** | **0.160** | **0.365** |
| Variance of New Distribution = Σ $p_k$*$(m''_k)^2$ - $(0.1180)^2$=0.00894 | | | | | |
| **New Cutoff, $zc'_k$= exp{[ln($m''_k$)+ln($m''_{k-1}$)]/2}** | | **0** | **0.0341** | **0.0946** | **0.242** |
| Proportion of the block above new cutoff remain the same | | 100% | 100% | 40% | 10% |

**Table 1:** Numerical Example of the IK Data Manipulation and the Indirect Lognormal Correction.

Figure 2 illustrates the probability distributions before and after the indirect lognormal correction of a selected block. The figure shows that the corrected cutoffs and class means are closer to the block mean as the result of the variance reduction.

If only exploration sample data are available, the following procedures are used to determine the amount of variance reduction. First, two grade distribution curves are created. One represents the proportion of a block above a cutoff for an SSU, the other is the block mean distribution, i.e., 100% of a block will be classified either as ore or as waste. This implies that the size of an SMU is the size of the model block. Both distributions are plotted on the same logarithmic paper. Although, a correction factor can be objectively calculated from the variogram for a particular size of an SMU (Isaaks & Srivastava, 1989), trial and error was still used to find the indirect lognormal correction factor due to the varied ore control practices used at the mine. The factor is from 0 to 1. This creates a transformed IK distribution that is between the two bounding curves of the IK distribution for the SSU and the block mean distribution. The size of the SMU for the transformed IK model will be greater than the size of the SSU and is less than the block size of the block model.

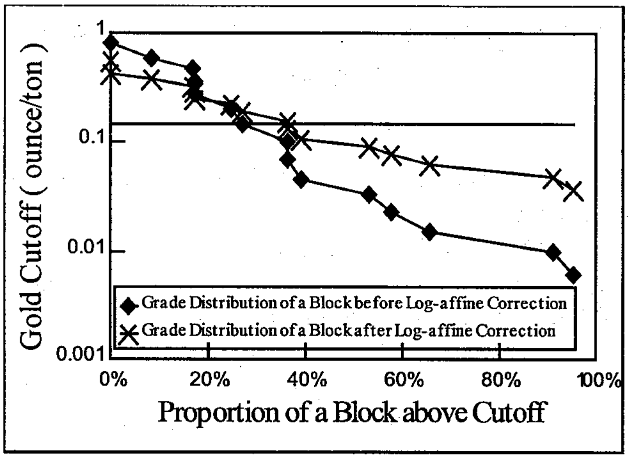


**Figure 2:** Probability Distributions of a Selected Block before and after Indirect Lognormal Correction. The Correction is 0.0907 with CV=2.7.

At the McCoy/Cove mine, part of the Cove ore body has already been mined out. A grade-tonnage curve was generated from a block model estimated from the blast hole assays. This distribution represents the actual SMU's grade-tonnage relationship that was realized from the blast hole assays. Trail and error resulted in a correction factor of 0.907 for the the IK distribution transformation which matched the blast hole grade-tonnage curve quite well, as shown in Figure 3. The log-affine variance reduction technique, a similar method used by Newmont Gold Company (Hoerger, 1992), was also used and compared with the indirect lognormal correction. It was determined that, when the coefficient of variation is equal to 2.7, the log-affine correction with a factor of 0.24 creates the same transformation as that of the indirect lognormal correction with a factor of 0.0907.

### Combination of the SMU's distributions

Gold and silver generate 70% and 30% of the Cove revenue respectively, an economic cutoff is determined using gold equivalent grade. This requires the combination of the transformed gold and silver distributions, in order to interpolate a proportion of a block above the economic cutoff and the corresponding mean grades of gold and silver.

Gold equivalent cutoff grade for silver can be calculated as silver grade divided by a gold equivalent ratio. The equivalent ratio is determined as:

$$\frac{\text{Gold Price} * \text{Gold Recovery}}{\text{Silver Price} * \text{Silver Recovery}}$$

The mineralization correlation between gold and silver indicates that they are positively correlated. The combination of the transformed SMU's distributions were conducted as follows:

1. Construct a gold equivalent grade distribution of a block by adding gold and silver transformed cutoffs at the same proportion level, i.e. a higher transformed gold cutoff is added to a higher transformed silver cutoff at the same proportion value.
2. Interpolate a proportion of the block above a given economic cutoff from the gold equivalent grade distribution of the block.
3. Use the interpolated proportion to calculate mean grades of gold and silver of the block from their corresponding transformed distributions.

The following is a numerical example to demonstrate the procedures of the combination of gold and silver transformed distributions and the interpolation of the proportion of a block above a given gold equivalent economic cutoff and the corresponding mean grade above this cutoff.

Table 2 summarizes gold and silver distributions before and after the indirect lognormal correction.

The combination of the transformed gold and silver distribution is performed at proportions of 100%, 40%, 30% and 10%

At proportion of 100%:

Gold cutoff = 0.0341 opt
Silver cutoff = 1.780 opt
If gold equivalent ratio for silver is 100, then,
gold equivalent cutoff = 0.0341 + 1.780/100
= 0.0519 opt

At proportion of 40%:

Gold cutoff = 0.0946 opt
Silver cutoff can be interpolated as:
exp{ ln(4.463)-[ln(4.463)-ln(1.780)]*(40%-30%)/(100%- 30%) } = 3.83 opt
Gold equivalent cutoff = 0.0946 + 3.83/100
= 0.136 opt

At proportion of 30%:

Silver cutoff = 4.463 opt
Gold cutoff can be interpolated as:
exp{ ln(0.242)-[ln(0.242)-ln(0.0946) ]*(30%-10%)/(40%-10%) } = 0.129 opt
Gold equivalent cutoff = 0.129 + 4.463/100
= 0.174 opt

At proportion of 10%:

Gold cutoff = 0.242 opt
Silver cutoff = 8.806 opt
Gold equivalent cutoff = 0.242 + 8.806/100
= 0.330 opt

| Gold Grade Distributions ( CV=2.7, f=0.0907, m = 0.118) | | | | | |
|---|---|---|---|---|---|
| Original cutoff | $zc_k$ | 0 | 0.006 | 0.034 | 0.500 |
| New cutoff after ILC | $zc'_k$ | 0 | 0.0341 | 0.0946 | 0.242 |
| Proportion of the block above cutoff | $P(zc_k)$ | 100% | 100% | 40% | 10% |
| Original class mean | $m_k$ | 0.002 | 0.015 | 0.130 | 0.700 |
| Corrected class mean | $m''_k$ | 0.0209 | 0.0558 | 0.160 | 0.365 |
| **Silver Grade Distributions ( CV=1.7, f=0.1335, m = 4.504 )** | | | | | |
| Original cutoff | $zc_k$ | 0 | 0.35 | 5.0 | 12.50 |
| New cutoff after ILC | $zc'_k$ | 0 | 1.780 | 4.463 | 8.806 |
| Proportion of the block above cutoff | $P(zc'_k)$ | 100% | 100% | 30% | 10% |
| Original class mean | $m_k$ | 0.20 | 1.32 | 7.90 | 20.00 |
| Corrected class mean | $m''_k$ | 1.110 | 2.853 | 6.981 | 11.11 |

**Table 2:** Gold and Silver Grade Distributions before and after Indirect Lognormal Correction (ILC)

If the gold equivalent economic cutoff is 0.1 opt. A proportion of the block, $P_{above\ cutoff}$, above the cutoff can be interpolated from the combined gold equivalent cutoffs of 0.0519 and 0.136 at proportions of 100% and 40% respectively.

$P_{above\ cutoff}$ = 40%+(100%-40%)*[ln(0.136)-ln(0.1)] / [ln(0.136)-ln(0.0519)]
= *58.35%*

Gold cutoff at the proportion of 58.35% is calculated as:

exp{ln(0.0946)-[ln(0.0946)-ln(0.0341)]*(58.3%-40%)/(100%-40%) } = *0.0692 opt*

Silver cutoff at the proportion of 58.35% is calculated as:

exp{ ln(4.463)-[ln(4.463)-ln(1.780)]*(58.35%-30%)/(100%-30%) } = *3.08 opt*

or: (0.1-0.0692)*equivalent ratio = *3.08 opt*

The gold class mean between cutoffs of 0.0692 and 0.0946 needs to be interpolated in order to calculate mean grade above the cutoff of 0.0692.

Class mean between cutoffs of 0.0341 and 0.0692

= exp{ [ln(0.0341)+ln(0.0692)]/2 }= *0.0486 opt*

Class mean between cutoffs of 0.0692 and 0.0946

= exp{ [ln(0.0692)+ln(0.0946)]/2 } = *0.0809 opt*

From these class means of 0.0486 and 0.0809, the new class mean between cutoffs of 0.039 and 0.100 is calculated as:

$$\frac{0.0486*(100\%-58.35\%) + 0.0809*(58.35\%-40\%)}{(100\%-40\%)}$$

= *0.0585 opt*

This new class mean of 0.0585 is not the same as the transformed mean of 0.0558, therefore, the class means of 0.0486 (between cutoffs of 0.0341 and 0.0692) and 0.0809 (between cutoffs of 0.0692 and 0.0946) must be adjusted to ensure the class mean of 0.0558 between cutoffs of 0.0341 and 0.0946 remains the same. The adjusted class mean between cutoffs of 0.0692 and 0.0946 is calculated as:

0.0809 * 0.0558 / 0.0585 = *0.0772 opt*

Gold mean grade of the block above the gold equivalent cutoff of 0.1 opt is then calculated as:

$$\frac{0.0772*(58.35\%-40\%)+0.160*(40\%-10\%)+0.365*10\%}{58.35\%}$$

= *0.169 opt*

With the same method, silver mean grade above the gold equivalent economic cutoff of 0.1 opt is interpolated as 6.072 opt.

## Block model reconciliation

In order to construct a grade-tonnage curve, five block models were created from blast hole assays. Three models with block sizes of 12.5x12.5, 15x15 and 20x20 were estimated using the nearest blast assay to assign a block. Two models with block sizes of 25x25 and 50x50 feet were created by averaging all blast assays within a block. All blast hole models reproduced virtually the same tons and ounces as the production results. It was decided that the grade-tonnage curve generated from the 25x25 block model was used to evaluate the rest of the models generated from the exploration drill holes.

Bench composites were used in reserve estimation. This makes a composite have a similar volume to that of a blast hole assay.

Four block models were created from the exploration composites with the same block size of 50x50 feet. Their grade-tonnage and grade-ounce curves were generated to demonstrate the reserve changes due to different grade estimation methods (Figures 3, 4 and 5). Tons and grades above the mill cutoff are listed in Table 3 for these four models.

Indicator kriging block mean model. This model uses the mean of the block to report reserves. Maximum of seventeen composites and maximum of two composites from one hole were used in the estimation. An entire block is classified either as ore or as waste.

Ordinary kriging model. This model uses the same number of composites and searching strategy as the indicator kriging block mean model. The estimated gold and silver grades of a block are used to report reserves.

Uncorrected indicator kriging model. This model uses the proportion of a block above a cutoff to report the reserves. No volume variance reduction was carried out. The grade-tonnage and grade-ounce curves of this model represent the distributions of sample size units (SSU).

Corrected indicator kriging model. This model uses indicator kriging and the indirect lognormal correction technique for grade estimation. The proportion of a block above a cutoff was utilized to report reserves.

| Block Models | Tons x1,000 | Gold Grade oz/ton | Silver Grade oz/ton | Gold Ounces x1,000 | Silver Ounces x1,000 |
|---|---|---|---|---|---|
| Blast Holes Defined | 7,525 | 0.090 | 3.733 | 678 | 28,091 |
| Ordinary Kriging | 9,025 | 0.075 | 3.152 | 676 | 28,449 |
| IK Block Mean | 9,105 | 0.074 | 3.124 | 677 | 28,446 |
| Uncorrected IK | 6,401 | 0.106 | 4.487 | 681 | 28,723 |
| Corrected IK | 7,527 | 0.089 | 3.760 | 668 | 28,302 |

**Table 3:** Tons, Grade and Ounces Above the Mill Cutoff.

The following observations can be made from Table 3 and Figures 3, 4 and 5.

- All models estimate similar gold and silver ounces above the mill cutoff, as indicated in Table 3.
- Both grade-tonnage and grade-ounce distributions of the corrected IK model are extremely close to the distributions defined by the blast holes, especially in the range above the mill cutoff. Therefore, the IK, with the indirect lognormal variance correction, is suitable for the recoverable resource estimation of the Cove deposit.
- Using the same sample searching strategy as the corrected IK method, both ordinary kriging and IK block mean models overestimate tonnage at the mill cutoff by 20%. If one of these models were used for the Cove mine and mill design, this would have led to selecting a much larger mill capacity than necessary. It would be very difficult to feed the mill using the current mine design. Therefore, both estimation methods cannot be considered as suitable recoverable resource estimation methods due to the incorrect estimate of the grade-tonnage relationship.
- The distribution characteristics of ordinary kriging and IK block mean models are quite similar. If the number of cutoffs for IK is large enough, the IK block mean model will produce an identical estimation to ordinary kriging. With a defined number of cutoffs, the IK block mean has a slightly higher smoothing effect. Usually, ordinary kriging can replace the IK block mean because it is a much simpler method as compared with the IK block mean.
- The uncorrected IK block model produces fewer tons with a higher grade due to a high degree of ore and waste separation. This makes the ounces above the mill cutoff slightly higher than those of any of the other block models. The model yields a bounding curve of grade-tonnage distribution that is

used to find a proper amount of variance reduction for recoverable reserve estimation.

The indicator kriging method with the volume variance correction has the flexibility to match the grade-tonnage relationship to one for a particular size of an SMU. However, it is much more complicated in data manipulation than that of ordinary kriging, especially in the case of multi-metal deposit like the Cove, and it is not easy to use an IK model in reporting reserves and pit optimization. This makes ordinary kriging more attractive in practice because of its simplicity.

By trial and error, the ordinary kriging model using a maximum of four composites and one composite from one drill hole estimated grade-tonnage and grade-ounce curves which were quite close to those of the corrected IK model. This exercise indicates that, 1) ordinary kriging is capable of estimating a recoverable resource model but it must be used properly, 2) an OK model using a large number of composites does not necessarily predict an accurate grade-tonnage and grade-ounce relationship, it will estimate more tons at a low grade, and 3) if ordinary kriging is considered for the estimation of a precious metal deposit similar to the Cove, with extremely high grade variation, it is suggested that a defined number of samples should be used for the estimation. This will honor the local variability and the smoothing effect can be reduced.

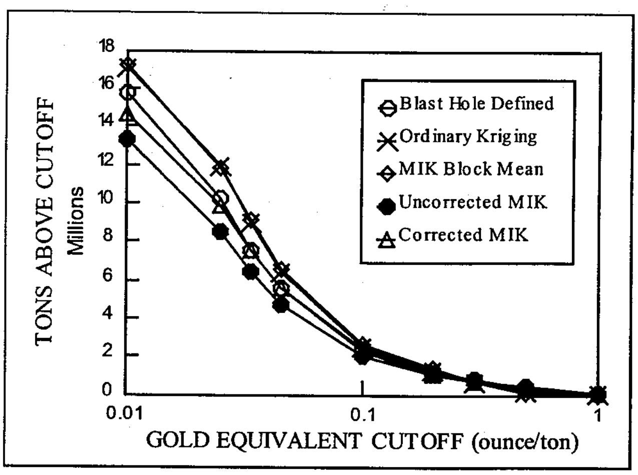


**Figure 3:** Grade-Tonnage Distribution of the Reconciled Area.

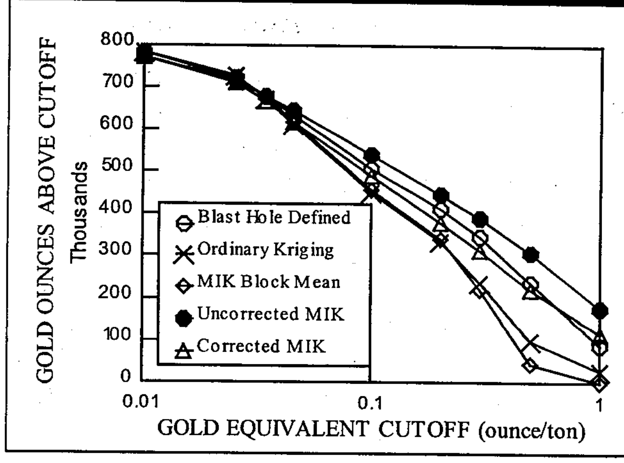


**Figure 4:** Gold Ounce Distribution of the Reconciled Area.

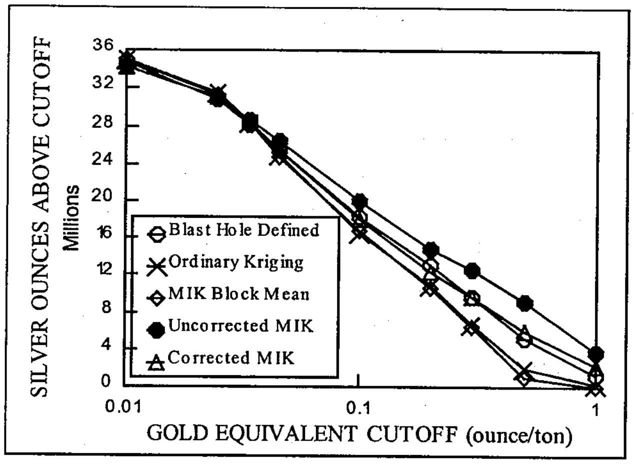


**Figure 5:** Silver Ounce Distribution of Reconciled Area.

## Pit optimization and recoverable reserves

The following definitions are used for recoverable of mineral resources/reserves

Recoverable resource model: A block model that can predict a grade-tonnage distribution. The distribution approximates to a curve that reflects what should be recovered by a particular mining method.

Recoverable resources: Amount of tons or metal estimated by a recoverable resource model.

Recoverable reserves: The proportion of the recoverable resources that can be mined or recovered economically.

This reserve classification requires an additional step to estimate a block model, with categories of proven, probable and possible blocks (or resources). Then, the recoverable reserves are further classified as proven, probable and possible reserves.

Therefore, pit optimization is needed to define an ultimate pit limit to calculate the reserves.

Only proven and probable reserves are used for this pit optimization.

A non-recoverable resource model will often overestimate tons at a lower grade compared with reality. This means that a higher processing expense is incurred to recover a similar amount of contained metal. The ultimate pit created from this model will be conservative. This could result in the mining of a smaller pit with a decrease in the overall recovery of a mineral resource.

Typically, processing recovery depends on ore grade. Ore with a lower grade will yield a lower recovery. If a model estimates more tons at a lower grade, this implies that less gold and silver ounces will be recovered. This will also lead to a conservative ultimate pit design.

Whittle 4D pit optimization software was used to generate three optimal pits. The first one is from the corrected IK model. The second one is from the IK block mean model. The third one is from the ordinary kriging that uses the same number of composites as the IK models. Leach material was not used in pit optimization to simplify the calculations. The recoveries are listed in Table 4.

| Gold Equivalent Grade Range in oz/ton | Gold Recovery in Percent | Silver Recovery in Percent | Equivalent Ratio If Gold and Silver Price Ratio=83.33 |
|---|---|---|---|
| 0.000 -- 0.025 | 50% | 30% | 138.89 |
| 0.025 -- 0.034 | 60% | 40% | 125.00 |
| 0.034 -- 0.100 | 70% | 50% | 116.67 |
| 0.100 -- 0.200 | 80% | 60% | 111.11 |
| More than 0.200 | 90% | 75% | 100.00 |

**Table 4:** Carbon In Pulp (CIP) Recovery Assumptions for Gold and Silver at Different Ranges of Gold Equivalent Grade

The grade-tonnage curve from the corrected IK model was divided into five categories (or parcels). This means that an individual block can be reported into five different categories in terms of both tons and metals. Silver grade was divided by its corresponding gold equivalent ratio and then added to the gold grade within the same class. Each parcel contains tons (units) and gold equivalent ounces (metals). The original topography was used in the pit optimization. It is assumed that all waste material will be sent to the outside pit dumps.

Since the actual costs are confidential, the capital costs were not considered and the following generalized operating costs were used: mining cost = $1.00/ton; processing cost = $8.00/ton. This results in the simple relationship:

Net Income = Revenue - Operating Costs

The following observations can be made from Tables 5 and 6, and Figure 6.

☞ At a gold price of $375 per ounce, the pit generated from the IK block mean model is 9% (or 22 million tons) smaller than the pit created from the corrected IK model. The corresponding contained ounces and net income are approximately 10% (or 0.26 million ounces) and 15% (or $52.73 millions) lower respectively compared with the corrected IK model.

☞ If the pit created by the corrected IK model at a gold price of $375/oz is used for comparison, the IK block mean model produces 15% (or 3.34 million tons) more mill ore than that of the corrected IK model inside the same pit. Total contained ounces of the two models are virtually the same. The IK block mean model projects 10% (or $35.28 millions) less in net income due to processing more mill tons to recover a similar number of ounces.

| Pit Size, Reserves and NI at Gold Price $375/Ounce | Pit Created by the Corrected IK Model | Pit Created by the IK Block Mean Model | Reserves of IK Block Mean Model inside Corrected IK Pit |
|---|---|---|---|
| Size of Pit (million tons) | 257.79 | 235.70 | 257.79 |
| Mill Tons (million) | 22.40 | 21.58 | 25.74 |
| Gold Equivalent Ounces (million) | 2.62 | 2.36 | 2.58 |
| NI(million) | $360.32 | $307.59 | $325.04 |

**Table 5:** Comparisons of Pit Sizes, Reserves and Net Income between Indirect Lognormal Corrected IK Model and IK Block Mean Model at Gold Price $375 per Ounce.

| Pit Size, Reserves and NI at Gold Price $400/Ounce | Pit of the Corrected IK Model | Pit of IK Block Mean Model |
|---|---|---|
| Size of Pit (million tons) | 471.06 | 241.96 |
| Mill Tons (million) | 38.42 | 22.75 |
| Gold Equivalent Ounces (million) | 3.79 | 2.42 |
| NPV (million) | $427.51 | $355.92 |

**Table 6:** Comparisons of Pit Sizes, Reserves and Net Income between Indirect Lognormal Corrected

IK Model and IK Block Mean Model at Gold Price $400 per Ounce.

☞ The sensitivity analysis shows that, if the gold price increases to $400 per ounce, the pit from the corrected IK model will increase 83% (or 213 million tons) in size, as shown in Figure 6, 72% (16 million tons) in mill ore and 45% (or 1.2 million) in gold equivalent ounces. However, the net income only increases 19% (or $67.2 million dollars). This is because the ore within the increment is low grade. The increment is very sensitive to operating costs, recoveries and gold price. Since the IK block mean model overestimates mill tonnage, this results in a higher processing cost compared with reality, the model makes the increment uneconomic. This will lead to designing a pit that is about 50% of its optimal size, and recovering approximately 64% of ounces estimated by the corrected IK model. Therefore, the corrected IK model will result in leaving less gold in the ground and maximize the recovery of the mineral resource.

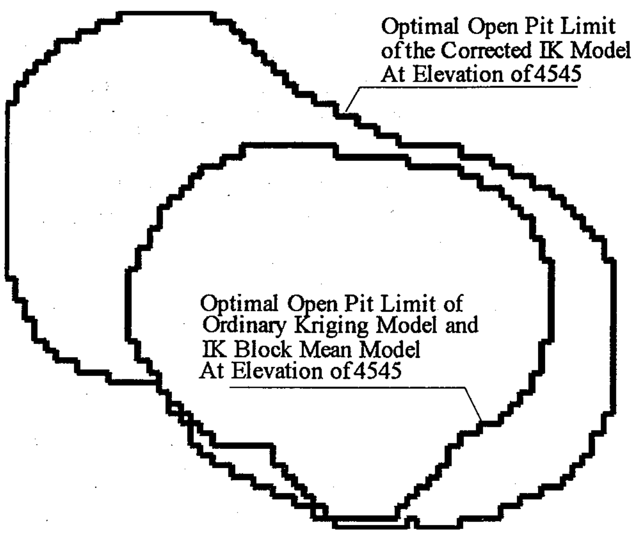


**Figure 6:** Optimal Open Pit Limits of the Corrected Model and the IK Block Mean/Ordinary Kriging Models at Gold Price of $400 Per Ounce.

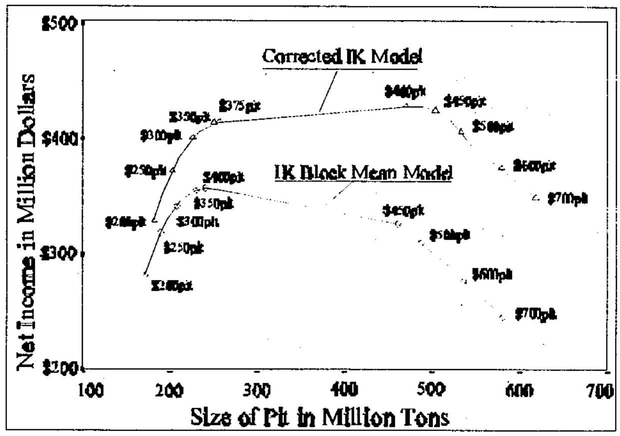


**Figure 7:** Relationships between Net Income at Gold Price of $400 Per Ounce and Size of Pit at Different Gold Price.

Figure 7 illustrates the relationships between net income at a gold price of $400/ounce and sizes of pit at different gold price for both the corrected IK and the IK block mean models. For example, the $375 pit for the corrected model means that the pit shell was determined at a gold price of $375/ounce. The total excavation of the pit was 258 million tons. However, the net income was calculated using a gold price of $400/ounce.

At the gold price of $400/ounce, Figure 7 indicates that the optimal $400 pit of the corrected IK model only generates $15 million (or 4%) more in net income compared to the $375 pit with $413 million of net income for the same model. However, the excavation increases 83% from 258 to 471 million tons. Since the size of the pit is very sensitive to the gold price (or operating costs), a high risk would be involved in mining the increment between the $375 pit and $400 pit shells. In reality, the Cove is designed to mine out the $375 pit first. This will allow the waste from the increment to be backfilled inside the $375 pit shell, which dramatically decreases the mining cost. This mining sequence makes the increment much more economic.

It is important to note that, due to the incorrect grade-tonnage relationship from the IK block mean model, the pit optimization does not realize this increment from this model until the gold price increases up to $450/ounce, as shown in Figure 7.

## Conclusions

In reserve estimation of a precious metal deposit with high grade variation, it is essential to ensure that there is no significant overestimation or underestimation in total contained metal. From a mine and process optimization point of view, it is extremely important to have the best possible estimate of the grade-tonnage relationship for a selected mining method. If a deposit has a large portion of the ore body in a low grade category, the ultimate open pit limit is very sensitive to the grade-tonnage curve. The correct grade-tonnage relationship will result in an economically and technically correct ultimate open pit, mine design, and selection of ore processing capacity.

A non-recoverable resource model often overestimates tonnage. This can lead to selecting a much bigger mill capacity than necessary. It could be very difficult to find the tons to feed the mill with a mine design generated from this incorrect estimate of the grade-tonnage relationship.

The results indicate that indicator kriging with indirect lognormal variance reduction is suitable for the recoverable reserve estimation of the Cove deposit. The block model reconciliation shows that the estimated grade-tonnage curve from this method is quite close to the curve defined by blast holes. The recoverable reserve estimation can also maximize the global recovery of a mineral resource.

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The operating costs and recoveries do not reflect the conditions at the McCoy/Cove mine. The reserves, size of pit and net income presented in this paper are not the same as the actuals due to the simplified case study.

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