Mineral inventory estimation in vein type gold deposits: case study on the Eastmain deposit

Clayton Deutsch, Computer Services, Placer Dome Inc.

ABSTRACT

Estimating the mineral inventory and the mineable reserves in underground gold deposits is a difficult problem. This paper will consider a number of estimation techniques and recommend a method based on the geostatistical technique of indicator kriging.

A general discussion on the modelling of vein deposits is followed by a more detailed presentation of the geostatistical estimation method. For comparison, the mineral inventory for one vein of the Eastmain deposit in northern Quebec has been calculated using a number of methods. The results obtained from polygonal and sectional methods are compared to the recommended geostatistical procedure. It is shown that this geostatistical method works very well when constrained by the available geological information. The advantages are an unbiased grade estimate without cutting any data and an estimate that accounts for the specific grade and structural continuity found in the vein.

INTRODUCTION

There is no cookbook or automated approach for estimating mineral inventories: however, there is a general framework that can be used to study certain types of deposits in a logical and consistent manner. This paper will examine some of the procedures relevant to the evaluation of vein type underground deposits.

Underground deposits can be divided into two categories. There are deposits that must be modelled with a three-dimensional model and there are deposits that can be reduced to a two-dimensional lode zone of varying thickness. If the mineralization is contained within a sequence of veins with complex geometry that cannot be followed with selective mining, or if the mineralization is disseminated within a large three-dimensional mass, it will be necessary to create a three-dimensional model. However, many underground precious metal deposits can be reduced to a two-dimensional vein. Although the vein may be warped or curved and the thickness may undulate, the geometry of the mineralization can essentially be described in two dimensions with varying thickness in the third dimension.

The scope of this paper will be restricted to deposits that can be modelled with a two-dimensional plane of varying thickness. Hereafter, the deposit will be referred to as a vein (some may prefer "lode zone" or "reef"). A deposit will usually have more than one vein and each vein must be evaluated separately.

The sequence of topics discussed in this paper is the same as the sequence of steps used to evaluate a vein type deposit. The sequence included:

1. vein description and mapping;
2. modelling the geological controls of the mineralization and selecting an algorithm to interpolate the grades and thickness; and
3. checking for errors and reporting the mineral inventory/ore reserve.

Following the detailed discussion of the geostatistical estimation algorithm proposed, the results from other estimation procedures will be compared for a vein in the Eastmain deposit.

Vein Description: Maps and Plotting

A vein can be seen as a tabular zone of mineralization dipping at some angle from the horizontal. The trace of the vein on a horizontal section is typically aligned along a constant azimuth (the strike direction). The strike and dip may not be constant but in many cases they are nearly constant in which case the orientation of a vein can be described by its strike and dip. Occasionally, a vein may be curved down dip and possibly along strike (i.e. an arcuate vein zone).

In most cases the drillhole intersections through the vein have to be plotted (projected) on a plan view, cross section, and longitudinal section to show the geometry of the vein. It is difficult to visualize the vein unless the vein is aligned with one of the principal planes (i.e. horizontal, north-south, or east-west section). To make the vein easier to visualize it is convenient to consider the vein in a new set of coordinates so that the vein can be viewed in the plane-of-the-vein (Fig. 1):

1. the distance along strike (denoted x_n);
2. the distance down the average dip (denoted y_n);
3. the deviation from the average dip plane (denoted z_n).

In this new coordinate system it is possible to map the lateral extent of the vein by plotting the x_n and the y_n location of all the intersections. Sections down dip and along strike are easily obtained by plotting the original elevation vs the x_n or y_n coordinate. Figure 1 shows an example of an appropriate coordinate system for vein deposits. The mineral inventory will be evaluated in this new set of coordinates which is customized for each deposit. Of course,

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Clayton Deutsch received a B.Sc. degree (with distinction) in mining engineering from the University of Alberta in 1985, and an M.Sc. in applied earth sciences (geostatistics) from Stanford University in 1987.

Since 1987, Clayton Deutsch has been employed by Placer Dome Inc., where he initially worked extensively on Sun workstations in all aspects of the position. He wrote an interactive computer package for data analysis, spatial statistics, and geostatistical estimation in Fortran, C, and GKS. As geostatistician/mining engineer, he is responsible for the accurate estimation of ore reserves for feasibility studies. He has constructed geostatistical orebody models and established grade control procedures at a number of gold mining operations.

Clayton Deutsch is the recipient of several awards including the Harold E. Lake Memorial Award (top student in mining engineering) and is the author of numerous publications.

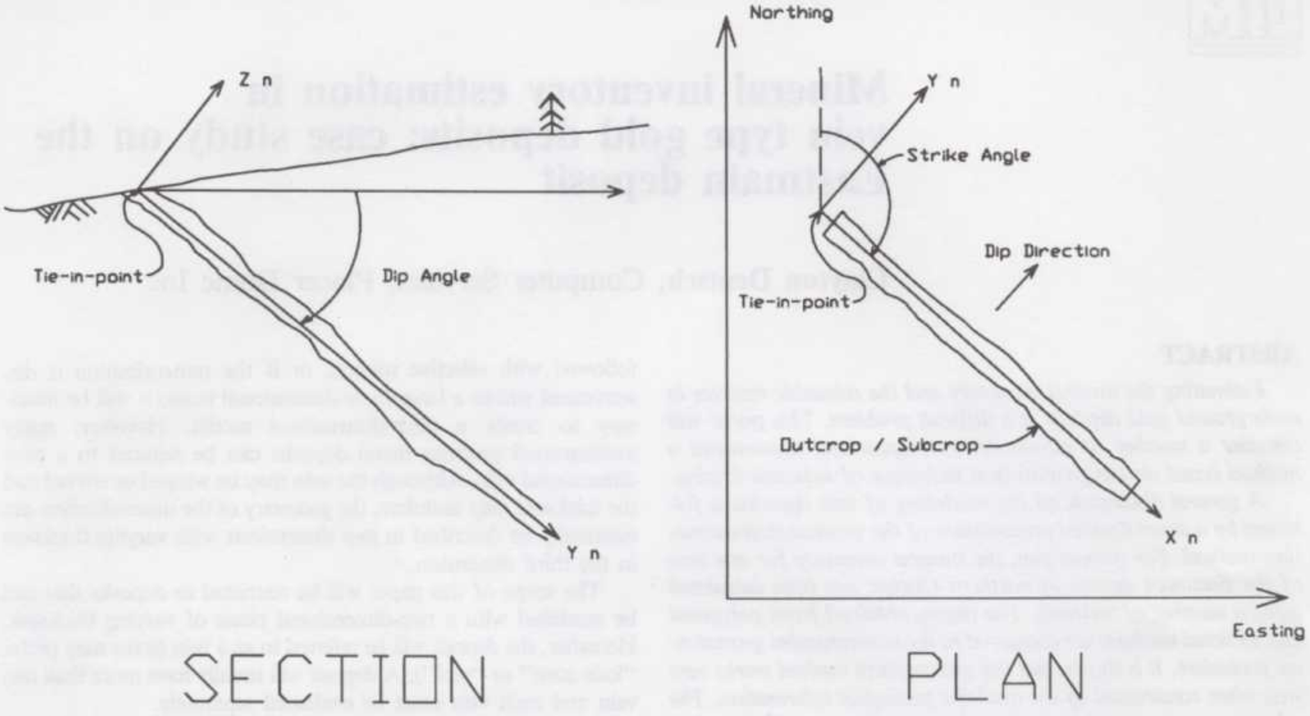


FIGURE 1. Appropriate coordinate system for vein deposits.

for mine layout it will be convenient to plot projections onto level plans and vertical sections so that the slopes and angles are correctly calculated from the horizontal and vertical.

A vein that has a pronounced curvature or a special structure (e.g. a sinusoidal undulation) can be modelled with coordinates that essentially flatten out the vein. The goal of the coordinate conversion is to obtain a coordinate system in which the vein appears continuous in two directions and all of the thickness variation is in the third direction. Unless the deposit is unusually complex, a three-dimensional rotation and translation of the original north, east, and elevation coordinates is usually enough.

After determining the appropriate coordinate conversion parameters (tie-in-point, average dip, and average strike) all of the spatial information can be recorded in both systems of coordinates. The type of information that may be involved is:

- drillhole intersections;
- underground exploration data, such as the location of chip samples, muck grab samples, and exploration drifts;
- the topographic surface and the overburden limits.

Before proceeding with plotting and data analysis, it is necessary to have all the thickness measurements defined in the same coordinate system. For example, it is unacceptable to use the apparent or measured thickness of the vein because the dip and azimuth of each drillhole will likely be different. Furthermore, the apparent thickness is always greater than the true thickness which implies that the mineral inventory calculated with the uncorrected thickness may overstate the tonnage. The thickness should be converted to the thickness perpendicular to the average dip plane. Figure 2 shows an example of the correction required.

At this point we can have a good picture of the geometry of the vein. A map of thickness using the y_n and x_n coordinates of the drillholes (and underground samples) indicates the variability of the vein thickness. A map of the z_n location of the intersections indicates the undulations in the vein and possible fault discontinuities.

Modelling the Mineralization

The general steps required to calculate the mineral inventory of a vein are the same whether a "manual" or a geostatistical procedure is used:

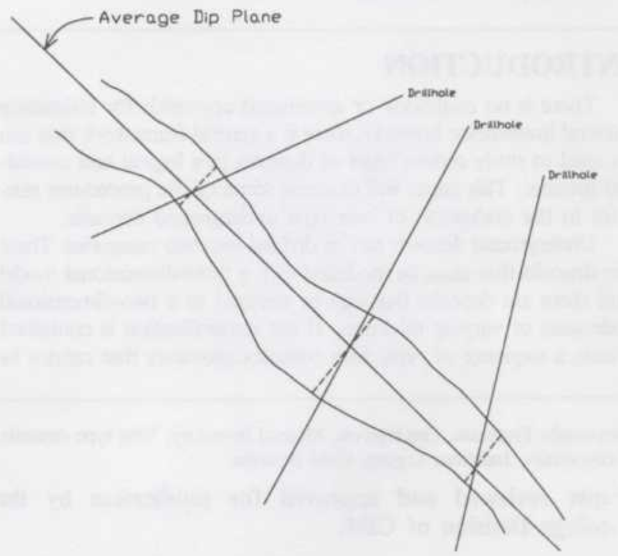


FIGURE 2. Measuring thickness perpendicular to average dip plane.

1. The first step is to determine the lateral extent of the vein. This is determined as either the geological/structural bounds of the mineralization or a limit such that the ore grade material is not being extrapolated too far from the available intersections.
2. The thickness of the vein within the lateral extent must be estimated. This can be done with a weighted average procedure (e.g. kriging), polygonal areas of influence, or the thickness can be evaluated on sections and projected between sections (i.e. a sectional method).
3. The metal assays must also be estimated within the lateral limits of the vein. This can be done with a weighted average procedure, polygons of influence, or a sectional procedure.

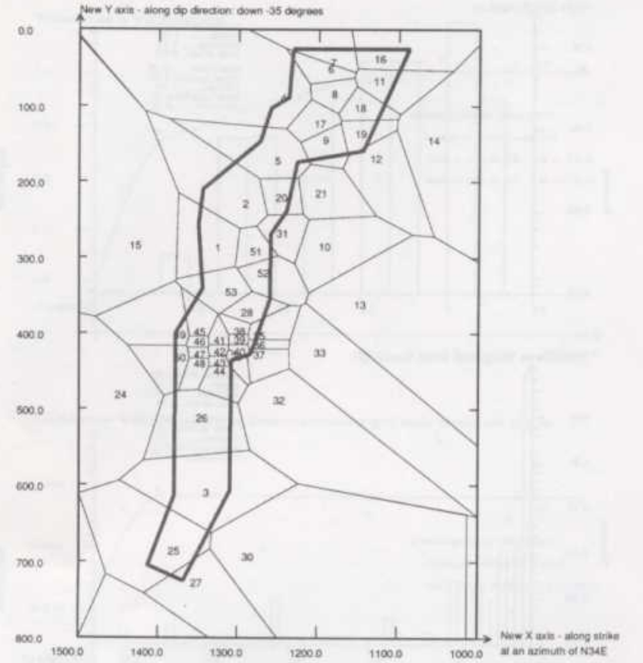


FIGURE 3. Polygonal areas of influence in the plane-of-the-vein for Eastmain.

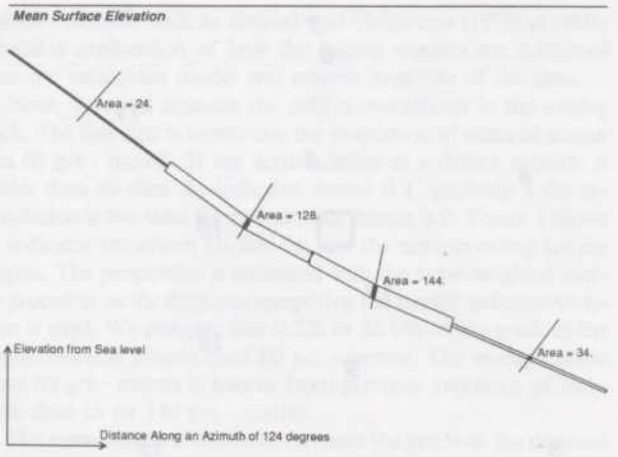


FIGURE 4. Example of a section used for a sectional reserve.

4. The tonnage (area·thickness·specific gravity) and the grade can be summed up within the lateral extent of the vein to report the geological mineral inventory.
5. Finally, the model of the vein can be used for mine design and to report mineable reserves.

Histograms, probability plots, and scatterplots of the assays are helpful to detect errors in the data. The basic statistical analysis will also identify any potential problems in the future thickness and grade estimation (e.g. identify anomalously high or low values).

The grade accumulation must be interpolated rather than the grade because each drillhole intersection may have been assayed over a different length. For example, there may be one small stringer within the vein that has a very high assay while the remainder of the vein is essentially barren. If the thickness is picked as the small stringer thickness the grade is recorded as very high; however, if the total vein thickness is picked then a much lower grade is recorded because the barren portion of the vein dilutes the small high-grade portion. For this reason, it is necessary to interpolate the grade accumulation (defined as the grade multiplied by the thickness) which is the metal content per square unit. The grade accumulation is independent of how the thickness was picked. The grade estimate can be obtained by dividing the estimated accumulation by the estimated thickness. A general comment is that the lateral estimation limits should be defined by geological bounds rather than grade bounds. All assays from the same mineralized population should be used to interpolate the grades. If grade boundaries are chosen the exclusion of lower grade data can cause the grade to be overstated.

The following discussion on estimation procedures will consider the separate estimation of the thickness and the grade accumulation. The erratic nature of gold grades requires more attention than the relatively smooth nature of vein thickness.

Polygonal Procedure

One method of interpolating a variable such as vein thickness or gold grade is to assign to each unsampled location the value of the closest drillhole intersection. That is, each drillhole will have a polygonal area of influence within which the thickness or grade is constant. The polygon of influence around a drillhole is determined by constructing the perpendicular bisectors of the lines joining the location of the drillhole to the locations of all nearby drillholes. All points within the polygon of influence are closer to the central drillhole than any other drillhole.

Figure 3 shows a plane-of-the-vein view, i.e. a map of the intersections using the x_n and y_n coordinates of vein A at Eastmain. The vein strikes at N34E and dips 35 degrees to the south; therefore, the x_n axis on Figure 3 is along N34E and the y_n axis is down the average dip of 35 degrees. The polygonal areas of influence for the intersections are shown with the outside polygons truncated by a geological limit to the mineralization. This limit is based on both geophysical anomaly data and interpretation on how far the influence of the drillholes should be spread.

This procedure yields a model where the variable is constant over each polygon with sharp discontinuities mid-way between the data.

Sectional Procedure

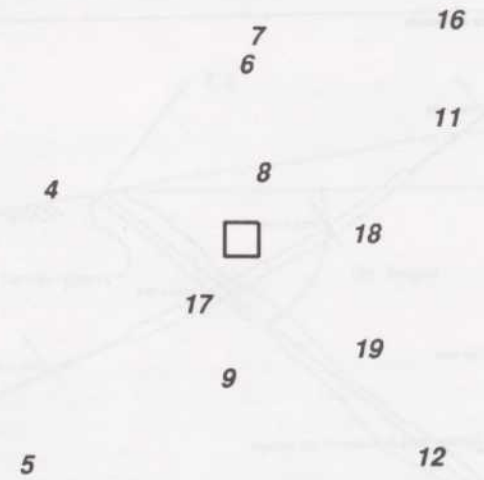
Typically, drillholes are aligned along section lines. In this case, rectangular blocks of equal thickness can be drawn around each drillhole on a section and projected half way to the adjacent sections. This estimation method is referred to as a sectional method. This method is similar to the polygonal method with the differences being the plane in which the polygons are determined (plane-of-the-vein or section view) and the rectangular shape of the sectional blocks when viewed in the plane-of-the-vein. The variable is interpolated as constant for rectangular blocks with discontinuities mid-way between section lines and the drillholes on a section.

One advantage of the sectional method is that it allows a close examination of the vein continuity on both section and in the plane-of-the-vein. The disadvantage relative to the polygonal procedure is that in the plane-of-the-vein, the rectangular blocks are not true polygons of influence.

Figure 4 shows an example of one section through the example deposit and the sectional areas of influence that have been drawn. The geometric importance of correcting the thickness can be appreciated from this figure. If the thickness is not corrected the tonnage may be overestimated by as much as 20 per cent.

Geostatistical Procedure

Geostatistical methods like krirging were not used extensively in eastern Canadian underground gold deposits because they did not account for typically strong geological and geometric continu-



Drillhole	Thickness (m)	Thickness weight	Au grade (g/t)	Indicator	Indicator weight	"low" grade weight
4	0.30	0.023	3.08	0	0.078	0.066
5	1.77	0.014	4.11	0	0.078	0.051
6	1.47	0.051	13.94	0	0.074	0.200
7	1.77	-.018	8.75	0	0.074	0.052
8	1.17	0.625	63.43	1	0.150	0.000
9	3.53	0.003	13.71	0	0.078	0.021
11	3.29	-.018	7.27	0	0.078	0.038
12	1.46	0.012	0.15	0	0.078	0.047
16	2.99	0.017	35.13	1	0.078	0.000
17	3.16	0.145	18.15	0	0.078	0.225
18	2.40	0.136	5.86	0	0.078	0.281
19	2.39	0.010	14.73	0	0.078	0.019

Thickness Estimate = 1.63 m

Grade Accumulation Estimate = 0.228 · 130.0 + 0.772 · 24.82 = 48.80 g/t · m

Grade Estimate = 48.80 / 1.63 = 29.94 g/t

FIGURE 5. Example of indicator kriging (IK).

ity. When such strong geological controls are ignored any estimate will be poor. The advantage of a manual interpretation is the incorporation of these geological and structural controls. The advantage of geostatistical procedures is that the uncertainty and grade variability is quantified and better interpolation algorithms are used. The geostatistical method proposed here is constrained by the available geological information. In this manner, the advantages of both a geostatistical and a manual interpretation are combined.

The goal of the modelling step is to develop a model of the spatial distribution of the mineralization that can be used for mine planning and that provides a realistic estimate of the grade that can be achieved at the time of mining. The model must account for the nature of the mineralization and unavoidable internal dilution. The problem with polygonal and sectional methods is the imposed high level of continuity on the mineralization; the actual grade does not remain constant for large areas mid-way between drillholes or between sections. In traditional reserve estimation by either a polygonal or a sectional procedure the erratic nature and lack of continuity is accounted for by cutting the high grades. Cutting schemes are dangerous unless production experience is used to confirm the cutting level. One danger is that the metal content of the deposit will be under-estimated and the correct economic decision will not be made. Another danger is that the cutting level will be too high causing the deposit to be overvalued.

Geostatistical estimators have been developed to handle the varying levels of spatial continuity found in different mineralizations and in different grade classes of the same mineralization. The indicator kriging (IK) procedure has been developed to avoid cutting or trimming. The idea is to separate the data into two or more classes; for example, a high-grade class which contains the "extreme" or problematic high-grade assays and a class containing the rest of the data. This method breaks the problem of grade estimation down into three more manageable problems:

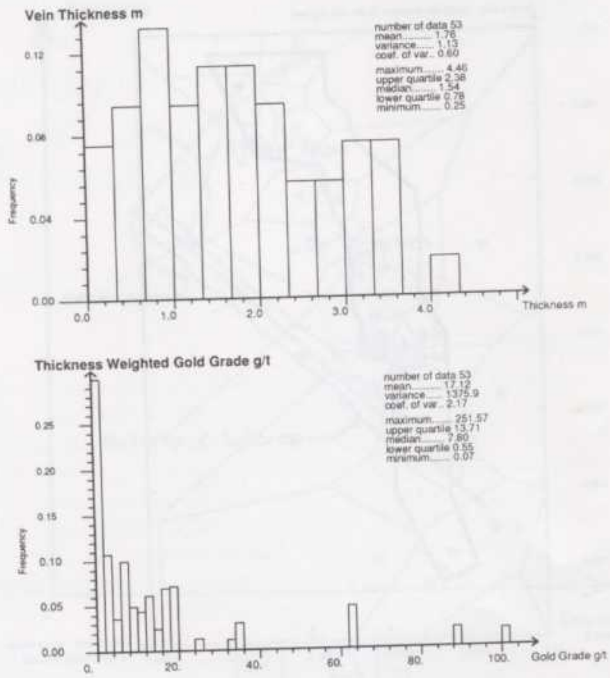


FIGURE 6. Histograms of vein thickness and gold grades (thickness weighted).

1. What is the proportion of material in the high-grade class?
2. What is the grade of the "high grade" material?
3. What is the grade of the "low grade" material?

When an intersection has a grade or accumulation greater than the high-grade cutoff the corresponding indicator value is set to "1". Similarly, when an intersection is below cutoff the corresponding indicator vaue is set to "0". This data set of 1s and 0s can be used through ordinary kriging (OK) to estimate the probability that a given unsampled location is high grade. An indicator variogram must be determined from the data set of 1s and 0s prior to the indicator kriging. The author's experience has shown that indicator variograms are easy to estimate and model.

The grade of the high class category cannot be estimated locally because there are very few "high grade" data. A good estimate of the grade data corresponding to an indicator of 1 is the arithmetic average of all the values above the high-grade cutoff. If the project geologist or mining engineer is not comfortable with a specific high-grade assay it can be cut in addition to using the IK procedure. Although it should not be necessary to cut when separating the high grades by an indicator kriging; however, one may want to allow a certain amount of conservatism at the risk of under-valuing the deposit.

The grades of the lower class are less of a problem because there are many corresponding low-grade data; thus the ordinary kriging (OK) procedure can be applied without difficulty to obtain the grade of the low-grade material. A second variogram computed from samples below the high-grade cutoff must be used in this second kriging. Finally, an estimate of the accumulation is constructed with the following relationship:

$$acc^* = (1-p)\cdot acc_l^* + p\cdot acc_h^* \quad (1)$$

where:

acc^* = estimated accumulation

p = fraction of high accumulation

acc_l^* = accumulation of the low accumulation material

acc_h^* = accumulation of the high accumulation material

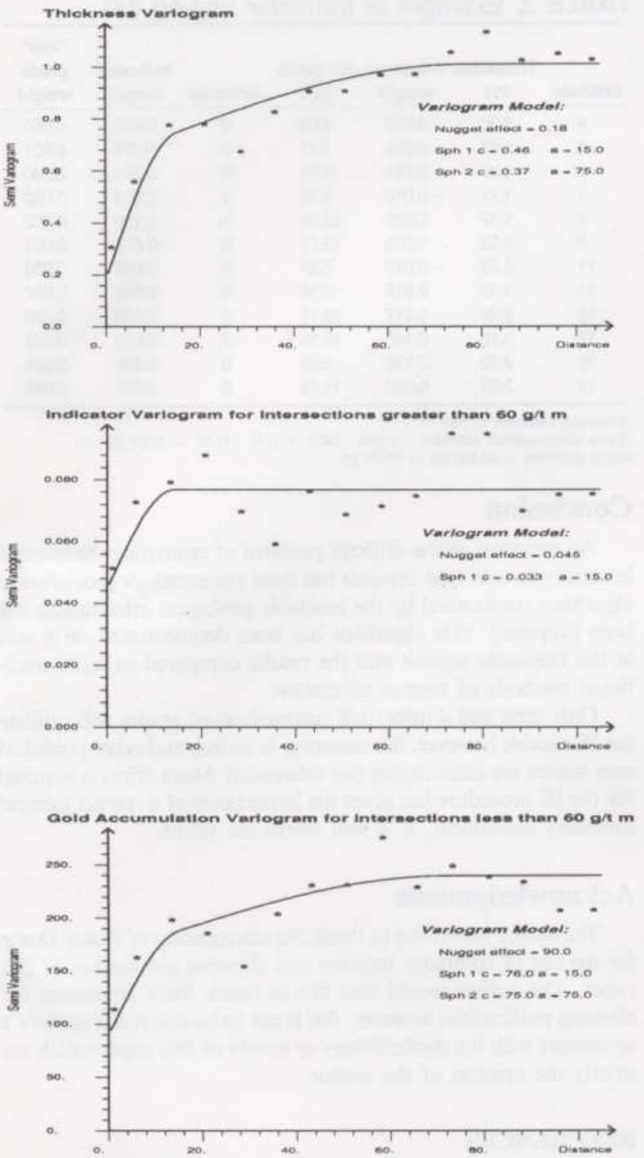


FIGURE 7. Variograms for thickness, high grade indicator, and gold grades.

The procedure is neither complicated nor difficult and the method is effective in providing a grade estimate that is resistant to extreme high grades. The method can be viewed as an alternative to cutting. This is a desirable feature because cutting can be very subjective unless production experience from the mine can back up the decision.

Figure 5 presents an example of indicator kriging (IK) taken from the Eastmain deposit. A mining block is being estimated with the nearest 12 intersections. In this case the cutoff separating the high grade and more common grade populations is 60 *g/t·m*.

The thickness estimate is constructed as a weighted average of the thickness at the nearby data points. The thickness and weight values shown in Figure 5 can be put into the following equation to calculate the estimate of 1.63:

$$Th^* = \sum_{i=1}^{n} w_i \cdot th_i \qquad (2)$$

where:

Th^* = the thickness estimate
w_i = the kriging weight assigned to datum i
th_i = the thickness of datum i

A good reference such as Journel and Huijbregts (1978) provides a detailed explanation of how the kriging weights are calculated from the variogram model and relative locations of the data.

Now, we must estimate the gold accumulation in the mining block. The first step is to estimate the proportion of material greater than 60 g/t · metres. If the accumulation at a datum location is greater than 60 then the indicator datum is 1, similarly if the accumulation is less than 60 the indicator datum is 0. Figure 5 shows the indicator transform (1s and 0s) and the corresponding kriging weights. The proportion is estimated with the same weighted average procedure as the thickness except that the specific indicator variogram is used. We estimate that 0.228 or 22.8% of the grade in the mining block is greater than 60 g/t · metres. The average grade above 60 g/t · metres is known from previous averaging of high-grade data to be 130 g/t · metres.

The remaining problem is to estimate the grade of the material less than 60 g/t · metres. This is done by another kriging using only the values less than 60 g/t · metres. Figure 5 shows the grade, thickness, and the kriging weights. The estimate of the accumulation below the 60 g/t · metres cutoff is 24.82 g/t · metres.

The final estimate of the accumulation is shown below (equation 1):

$$\text{Grade Accumulation} = 0.228 \cdot 130.0 + (1.0 - 0.228) \cdot 24.82 = 48.80$$

Finally, to obtain the grade estimate we must divide the grade accumulation by the estimated thickness:

$$\text{Grade} = \frac{48.80}{1.63} = 29.94 \text{ g/t}$$

The procedure described above is not a complete indicator kriging procedure as described in the literature. A single indicator cutoff has been used to separate the problematic high grades into a separate class, and a classical ordinary kriging procedure has been retained for the grades that are less of a problem. A full indicator kriging study would consider many grade classes (up to 10) and as many indicator variograms.

Case Study of a Vein in the Eastmain Deposit

The following example is an evaluation of a vein in the Eastmain deposit located 310 km northeast of Chibougamau in northern Quebec. The gold is contained in sulphides within lenses of chert. The chert lenses are tabular, striking approximately northwest-southeast, and dip at 35 degrees to the south. Details of the geological setting and the exploration program can be found in Boldy, *et al.* 1986. The vein being considered here is the smaller "A" vein to the northwest of another economically attractive zone.

The drillhole intersections, polygons of influence, and the geological limits of this vein are shown in Figure 3. There is an exploration adit through the upper part of the vein. Channel samples were taken with each 3 m to 4 m advance of the adit and have been used to compute the variogram and grade above the high-grade cutoff, but have not been used in the mineral inventory presented below. This is not because of sample quality; the channel samples are unbiased because the hard ore-bearing chert does not lend itself to preferential sampling. The channel samples were not used so that this presentation of the mineral inventory would be more straightforward. A histogram of the vein thickness and a thickness weighted histogram of the gold grades are shown in Figure 6.

A polygonal mineral inventory has been computed with the polygons shown in Figure 3. A sectional mineral inventory has also been determined. One section is shown in Figure 4 as an example. To account for dilution and the high level of continuity assumed by both these methods, a 1.0 oz/ton (34.3 g/t) cutting scheme has been considered.

TABLE 1. Mineral inventory for different estimation procedures

Method	Cutting level (g/t)	Grade cutoff (g/t)	Tonnage (tonnes)	Thickness (m)	Grade (g/t)
Polygonal	no cutting	5.0	362 930	2.49	24.54
Polygonal	34.3	5.0	362 930	2.49	16.14
Sectional	no cutting	5.0	302 470	2.38	18.15
Sectional	34.3	5.0	302 470	2.38	10.67
Geostatistical	no cutting	5.0	385 220	2.36	14.06

After establishing a new coordinate system the geostatistical mineral inventory was determined in five steps:

1. The average thickness of 10 m by 10 m blocks in the plane-of-the-vein was estimated by ordinary kriging.
2. A high accumulation cutoff has been picked which separates the problematic high grades into a separate class. The average high accumulation value was then estimated by averaging all accumulation data above the cutoff. It is not necessary to consider the declustered high-grade data because we assume they have no spatial correlation.
3. The fraction of high accumulation in each block was estimated by indicator kriging using the indicator (1-0) data set.
4. The average accumulation of the lower accumulation fraction was estimated by ordinary kriging with the low accumulation data.
5. The high and low accumulation fractions were then combined and divided by the estimated thickness to obtain a grade estimate.

This IK procedure requires variograms for the thickness, high accumulation indicator, and the low accumulation values. The three variograms are shown in Figure 7. No anisotropy could be detected because of the relatively wide drillhole spacing and the orientation of the underground exploration drifts.

Table 1 gives the result obtained by each method.

All gold grade composites across the geological thickness that exceed the cutting level were trimmed back to the cutting level. The grade cutoff was applied to report only economic material in the mineral inventory. It is important to note that low-grade internal polygons or sectional blocks were added into the mineral inventory above the grade cutoff. This was done to approximate what might be mined rather than believe that certain low-grade blocks could be left. Another important note is that a minimum thickness of 1.5 m has been considered. The minimum mining width is a practical mining constraint that is usually accounted for when reporting mineral inventories of this type.

The mineral inventory estimates are considerably different for all of the three methods. The cut sectional grade is less than the cut polygonal grade because the cutting was performed on assays rather than on composites over the thickness of the vein. The following general observations can be made:

1. The geostatistical tonnage estimate is 6% higher than the polygonal estimate which is 20% higher than the sectional tonnage estimate. In this case, the sectional estimate was the most selective.
2. The grade estimates are reasonably close (polygonal is 13% higher than the geostatistical estimate which is 30% higher than the sectional estimate). The true grade is not known; therefore, it is difficult to make definitive statements about the correctness of the various estimates.

A cutting limit may exist that would provide a good polygonal or sectional estimate, but it is unknown until mine/mill comparisons are available. The strength of the IK procedure is that fewer subjective decisions are required while still honouring the geological and structural information available.

TABLE 2. Example of indicator kriging (IK)

Drillhole	Thickness (m)	Thickness weight	Au grade (g/t)	Indicator	Indicator weight	"low" grade weight
4	0.30	0.023	3.08	0	0.078	0.066
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18	2.40	0.136	5.86	0	0.078	0.281
19	2.39	0.010	14.73	0	0.078	0.019

Thickness estimate = 1.63 m
Grade accumulation estimate = 0.228 · 130.0 + 0.72 · 24.82 = 48.89 g/t · m
Grade estimate = 48.80/1.63 = 29.94 g/t

Conclusion

An overview of the difficult problem of estimating the mineral inventory in vein type deposits has been presented. A geostatistical algorithm constrained by the available geological information has been proposed. This algorithm has been demonstrated on a vein in the Eastmain deposit and the results compared to more traditional methods of reserve estimation.

Only time and a mine/mill comparison of grades will validate the IK model; however, the reasoning is sound, and other published case studies are encouraging (see references). More effort is required for the IK procedure but given the importance of a correct mineral inventory assessment, it is well worth the effort.

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