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# A geostatistical study of the Cinola gold deposit Queen Charlotte Islands, British Columbia

**ABSTRACT.** Cinola gold deposit, owned by Consolidated Cinola Mines Ltd, is a large low grade deposit that has been explored extensively by diamond drilling. The deposit has been the subject of a feasibility evaluation. Drill holes are mostly vertical and over much of the deposit are spaced at about 30m. Half core lengths of 2m were assayed for most of the drilling to provide an extensive data base. An exploration adit also provided essential assay and geological information.

Two geological features are important in developing a semi-variogram model for the ore: (1) presence or absence of extensive argillic alteration; (2) a preferred orientation to gold-bearing quartz veins and veinlets, viz. vertical dip with an average strike of 028 degrees. A three-dimensional semi-variogram model for the deposit consists of a nugget effect, a short range spherical isotropic model plus a long range spherical anisotropic model.

Two-dimensional and three-dimensional kriging results are compared and potential applications or problems with each approach are discussed. One of the most striking results of the study has been the documentation of the relative uniformity of grade distribution at Cinola compared with much more erratic grade distribution in other large, low grade gold deposits.

**INTRODUCTION.** Ore reserve estimation of gold deposits is probably one of the most difficult problems faced by geologists and mining engineers. The apparently erratic distribution of gold in many ore bodies is the main reason for a common lack of confidence in making estimations of mean grades for selection units (mining blocks). This paper documents a rigorous geostatistical approach to grade estimation at the Cinola gold deposit, based on a relatively uniform and dense distribution of sampled diamond drill holes. The mathematical concepts used in this analysis have been described in numerous publications, such as Journel and Huijbregts (1978), and Clark (1980).

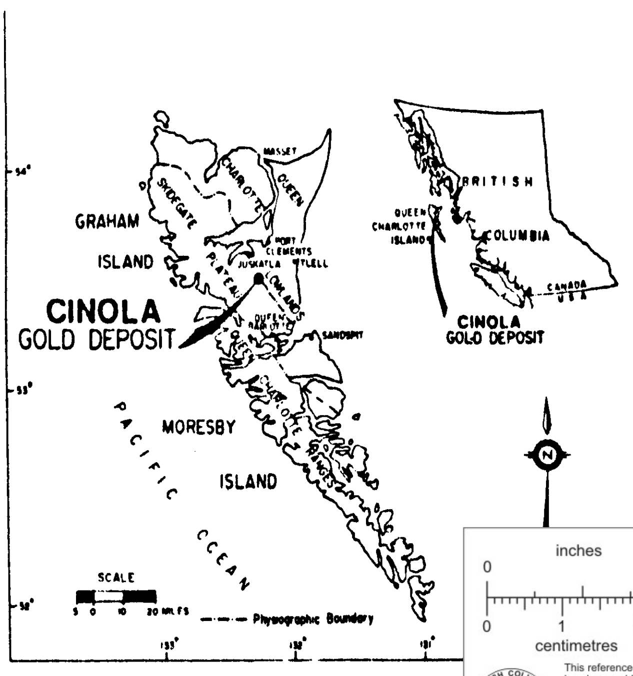
Cinola is a large-tonnage low-grade gold deposit in central Graham Island, Queen Charlotte Islands, BC (Figure 1). About 50-million tons of low grade material were inferred on the basis of limited drill information early in the exploration history of the property (Richards et al 1976). It was not until 1980 that the present operator, Consolidated Cinola Mines Ltd, proved by diamond drilling 45.4-million tons at an average grade of 0.054 oz Au/st (short ton), using a cutoff of 0.025 oz Au/st and using a modified polygonal method of grade estimation.

The gold deposit is contained in a coarse-grained, clastic, sedimentary sequence of Middle Miocene age which is cut by a rhyolite-porphyry as shown in Figure 2 (Champigny and Sinclair, 1981). The sequence is composed of interbedded conglomerate and sandstone units dipping gently (15 degrees) to the east. Upper Cretaceous shales are in fault contact with the rhyolite intrusion on the west and constitute the footwall of the deposit. These three units are cut by several generations of quartz veins that locally contain high grade values (higher than 0.20 oz Au/st). Gold is also disseminated through the silicified coarse-grained sediments, to a lesser extent in the rhyolite-porphyry, and rarely in the shales. Pyrite and marcasite are the most abundant sulphides, and gold particles are mainly of submicroscopic size. A steeply dipping envelope of intensive argillic alteration abruptly truncates the economic mineralization on the east and north.

The ultimate goal of this study was to develop a geostatistical model for the Cinola deposit and to develop a procedure for estimating mean grades and errors for blocks measuring 30x30x10m, where 10m is the bench height proposed for open-pit mining. An important product of the geostatistical approach includes testing whether the drill hole spacing, commonly about 30 to 40m at Cinola, is close enough to provide reasonable estimates for 30x30x10m blocks. To answer these questions, we proceeded in four stages as follows: (1) data evaluation, (2) generation of experimental semi-variograms, (3) development of semi-variogram models, and (4) kriging.

More than 20,000m of assayed drill core provide the data base for this study. Calculations involving this quantity of data must be done with a computer. In addition, extensive care must be taken in editing data so that errors are not built into subsequent expensive computer runs.

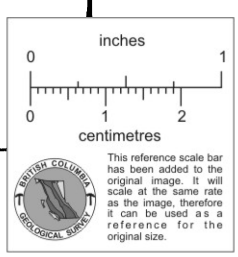
*Figure 1. Location map of Cinola Gold Deposit*




**DATA EVALUATION.**
Borehole gold assays obtained during all exploration phases of the deposit since discovery to the time of this study were made available to the authors by Consolidated Cinola Mines Ltd. These data represent about 75 percent of total data available at the time of writing. Several information types make up the data set as listed in Table 1. Nearly all holes are vertical, and the core was analyzed in continuous sample lengths of 1.5, 2, or 3m. Limited interlaboratory check analyses were available to us. Those we investigated indicated the presence of an expectable random error but were insufficient to determine the existence of bias. For purposes of our study we assume gold assay data used by us to be representative of the Cinola deposit.

Our data base was developed using the GEOLOG computer-based coding system (Godwin et al 1982) and included the coding of a number of geological variables. For example the three principal host rock categories are: (1) conglomerate-sandstone, (2) rhyolite-porphyry, and (3) shale. Early in the study it appeared that all rock types could not be taken into account because of the small proportion of both rhyolite-porphyry and shale. All assays of shale are below the 0.025 oz Au/st cutoff, and are excluded from the study.

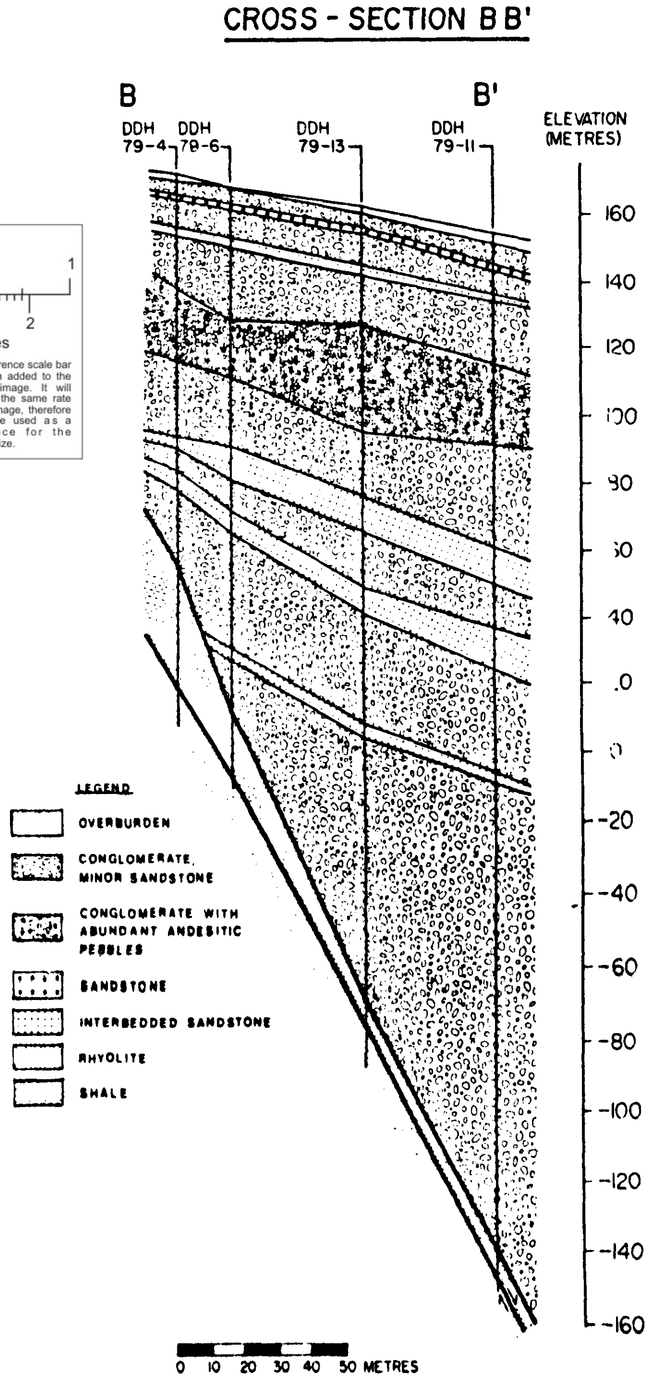
Probability graphs were constructed for assays for each of three



different core lengths, 1.5, 2 and 3m. An example, for sample length of 2m, is shown on Figure 3. Two lognormal populations are apparent in each case, and a threshold separating them was selected using the partitioning procedure described by Sinclair (1976). The thresholds represent optimum separation of a high-grade population from a low-grade population. An approximately linear relationship was found between the threshold values and the core sample length. Longer and therefore bigger core samples are less variable in their gold values than are shorter samples, and thresholds separating the two populations are lower for shorter sample lengths.

The two populations can be interpreted as follows: (1) a "high-grade" population which totals 3.5 percent of the data and is assumed to be distributed randomly throughout the deposit, and (2) a "low-grade" population which comprises the bulk of the data and whose distribution is more continuous. The values above threshold, that is, the "high-grade" population, were deleted for

*Figure 2. East-west cross-section demonstrating drill hole spacing and general geological character of the Cinola Gold Deposit. Heavy line at base of rhyolite unit is the Footwall fault below which negligible gold mineralization occurs*





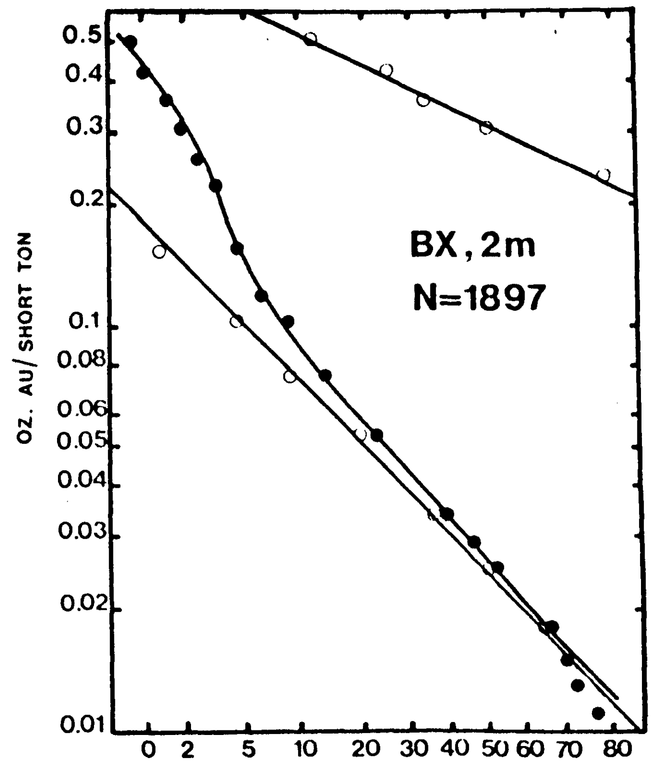




*Figure 3. Probability graph of gold assay values for the 2m samples, B drill core, Cinola Gold Deposit*

**Table 1. Data types**

| Drill type | Core size | Sample length (m) | % of total metres drilled |
|---|---|---|---|
| Percussion | | 3.0 | 1.4 |
| Diamond | AX | 1.5 | 0.3 |
| | BX | 1.5 | 6.0 |
| | BX | 2.0 | 40.5 |
| | BX | 3.0 | 2.5 |
| | NX | 3.0 | 49.3 |

mathematical modelling of the "low-grade" population. Justification for this procedure is simply that different autocorrelation functions are to be expected for each of the two populations because the two have different modes of occurrence. The low grade population is essentially micron gold whereas the high grade population is coarser-grained free gold in quartz and native gold associated with chalcopyrite and sphalerite.

## EXPERIMENTAL SEMI-VARIOGRAMS

The semi-variogram, γ (h), is a measure of the difference between the grades of samples separated by a distance h. An experimental semi-variogram is calculated using the equation:

$$\gamma(h) = \frac{1}{2n} \Sigma [g(x) - g(x+h)]^2$$

where g is the grade, x indicates the location of one sample in the pair, and x + h indicates the location of the other. The total number of pairs for each spacing, h, is given by n. γ (h) has units of grade squared if calculated as above, that is, $(\text{oz Au/st})^2$ in our case, and is determined for a maximum number of different values of h. Relative semi-variograms are obtained by dividing various γ (h) values by the squared mean grade of all samples used in their respective calculation. All the semi-variograms reproduced here are relative semi-variograms.

**Down-hole semi-variograms** were generated by computer separately for each drill hole, and average semi-variograms were produced for each data support (Table 1). The purpose of generating these is to compare the variability of gold values from the different categories of data. Such a comparison may lead to: (1) grouping certain data types with similar variability, and (2) recognizing data supports that have distinctly different levels of variability. Experimental semi-variograms from very limited data sets for AX and percussion drill holes are markedly different from those for other data types, and these two data types were excluded from the study because of the likelihood of the small available sample sets not being representative.

All the semi-variograms for BX drill holes are very similar regardless of the sample lengths (Figure 4). Similar curves based on NX drill holes are divided into two groups: one group has semi-variograms comparable to those for BX core samples, whereas a second set of NX data has a much higher nugget effect. This second group of semi-variograms was calculated from drill holes located in zones of extensive argillic alteration, whereas those with a lower level of variability, as well as all the semi-variograms based on BX core, derive from the main mineralized part of the Cinola deposit (Figure 4). Consequently, the following two geological groups are defined for geostatistical purposes, (1) "mineralized" samples with negligible argillic alteration, including all BX and some NX drill holes and (2) "argillically altered" samples comprising only part of the NX drill holes and consisting of extensively altered rock.

From the foregoing we conclude that type of alteration, as opposed to small variations in core size, dictates the behaviour of experimental down-hole semi-variograms at Cinola. Fortunately the data can be divided into two spatially distinct groups, an argillically altered zone fringing the main mineralized zone on the east and north (Figure 5). Argillically altered rocks have grades less than .025 oz Au/st and are of no economic interest at the present time. The remainder of our study is confined to a geostatistical evaluation of data representing the main mineralized zone at Cinola.

**Horizontal Semi-variograms.** Drill core assays from the mineralized drill holes were combined into 10m bench composites, 10m being the proposed bench height at Cinola. For each level, horizontal semi-variograms were generated for four directions with azimuths 028 degrees, 073 degrees, 118 degrees and 163 degrees. The 028 degrees direction is the average strike of vertically dipping quartz veins in the deposit. In addition, an average isotropic semi-variogram for each level and a weighted average isotropic semi-variogram for all levels were produced. Experimental semi-variograms for the four directions were similar for a given level and were also similar to the grand average semi-variograms for all levels, as reproduced in Figure 6. A substantial anisotropy is evident in the two semi-variograms of Figure 6, representative of the cross-vein direction (118 degrees azimuth) and the parallel vein direction (028 degrees azimuth).

Experimental semi-variograms were calculated independently for horizontal channel samples and vertical channel samples (Figure 6) along a segment of a horizontal adit cutting "moderate" to "high" grade material. Horizontal channel samples (about 2m long) on the two sides of this adit gave comparable but slightly different experimental semi-variograms, as did two corresponding sets of vertical channel samples. The average experimental semi-variograms (relative) for both horizontal and vertical channel samples are almost identical as are the standard deviations (Figure 6) indicating that the variabilities of the two types of samples are comparable.

This conclusion is of the utmost importance because exploration drilling to date has been mostly vertical, having been completed prior to the driving of the exploration adit and the recognition of a preferred orientation to quartz veins (028 degrees strike, vertical dip). Because of this preferred orientation of veins some concern was felt about the reliability of vertical core samples on which ore reserve estimates were to be based. It appears that the two types of samples (horizontal chip and vertical chip) are comparable in their representation of the deposit. By extension, we expect that vertical drill core samples having roughly the same support and less obvious chance of bias are equally acceptable as being representative of the Cinola deposit.

## SEMI-VARIOGRAM MODELS

Experimental semi-variograms shown in Figures 4 and 6 are saw-tooth curves that can be approximated by smooth mathematical models. The most common model that applies to experimental semi-variograms is the spherical model defined as follows:

$$\gamma(h) = C_0 + C_1 [(3h/2a) - (1/2)(h/a)^3] \quad \text{for } h < a$$

$$\gamma(h) = C_0 \bullet C_1 \quad \text{for } h \geq a$$

where $C_0$ is the nugget effect, $C_1$ is the sill of the spherical model, "a" is the range, and "h" is any sample separation. The range of influence of a sample, a, is the distance at which samples become independent. The sill, $C_1$, represents the structured part of the regionalization, whereas the nugget effect is a random component and indicates the presence of one or more smaller scale structural components (ie. smaller than the minimum sample spacing of about 30m), each with its own sill and range.

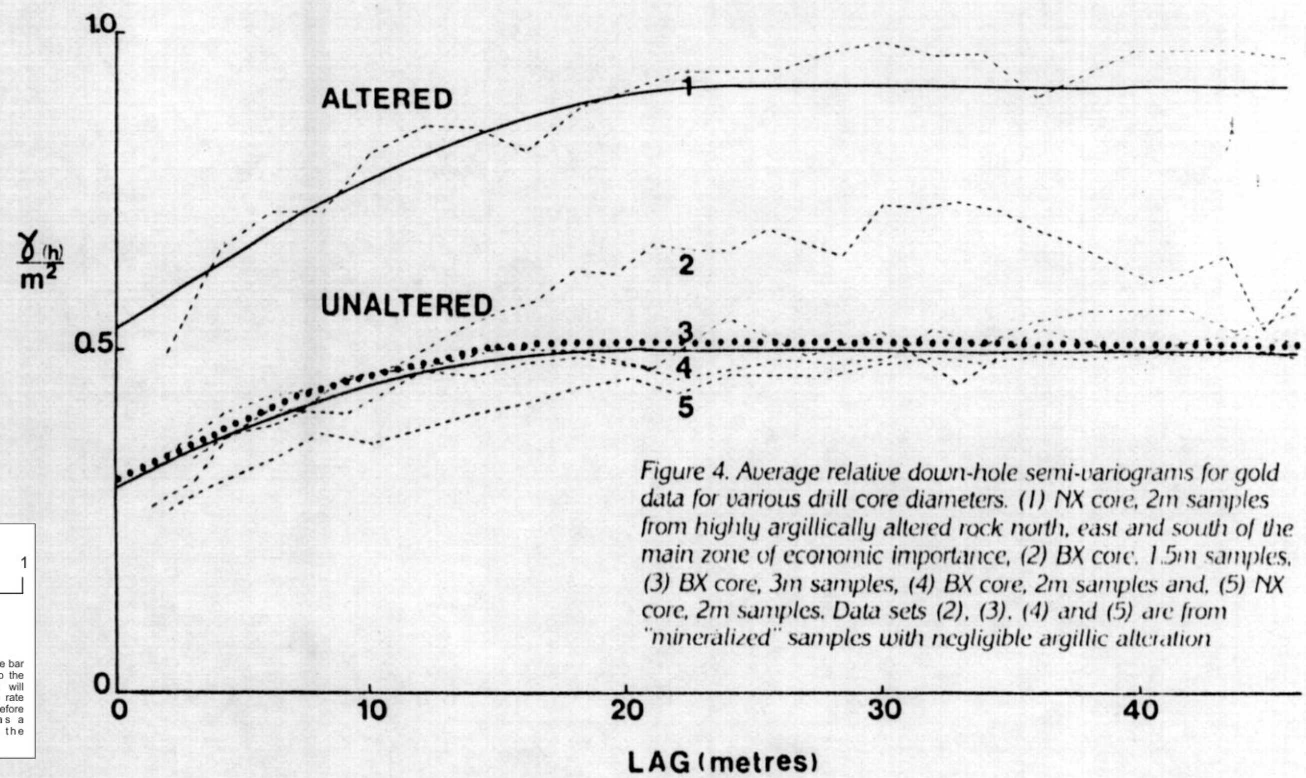
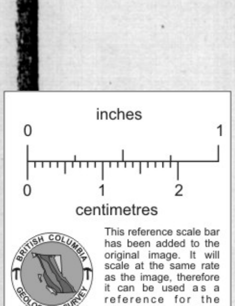



Figure 4. Average relative down-hole semi-variograms for gold data for various drill core diameters. (1) NX core, 2m samples from highly argillically altered rock north, east and south of the main zone of economic importance, (2) BX core, 1.5m samples, (3) BX core, 3m samples, (4) BX core, 2m samples and, (5) NX core, 2m samples. Data sets (2), (3), (4) and (5) are from "mineralized" samples with negligible argillic alteration



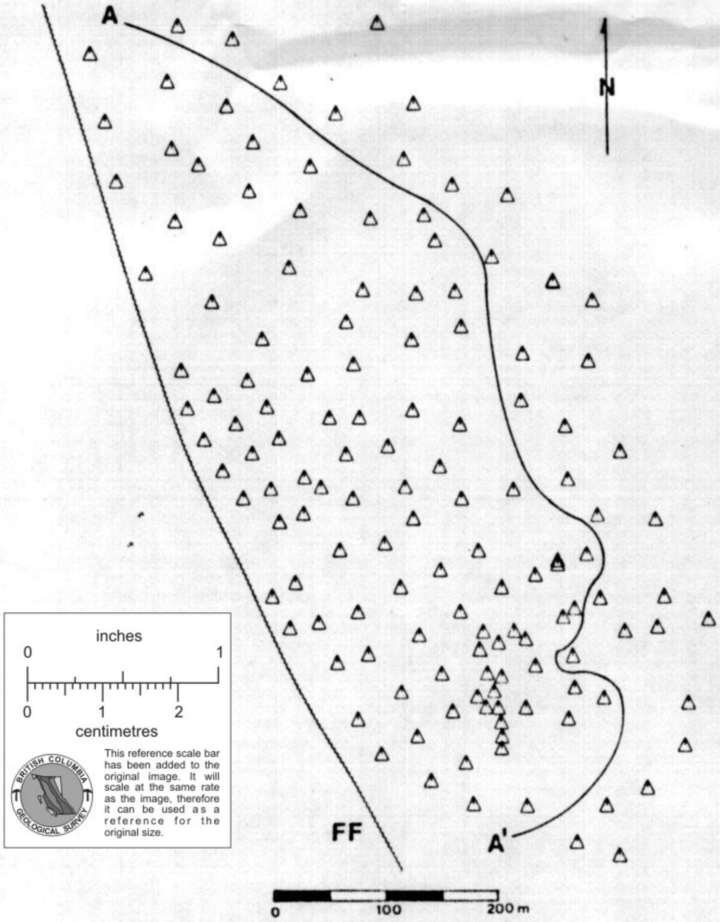



*Figure 5. Collar locations of drill holes with assay data used in this study. FF is the surface trace of the Footwall fault which dips moderately to the east and forms the western and lower boundary to the main zone of gold concentration. The sinuous line, AA' separates the main zone of gold mineralization from an easterly zone of intense argillic alteration*

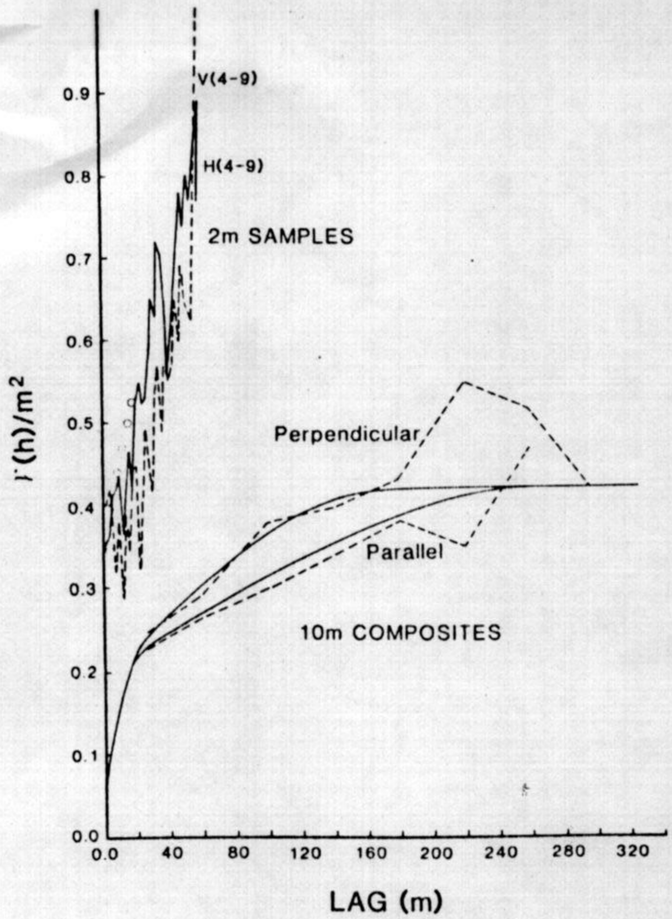



*Figure 6. Horizontal semi-variograms, Cinola Gold Deposit. Two lower experimental curves, for directions parallel and perpendicular to the mean quartz vein orientation (strike 028 degrees, dip vertical) are fitted by smooth nested spherical models with a common sill and represent a model for 10m composites. The two upper jagged experimental curves are based on vertical and horizontal chip samples (over 2m) from an underground exploration adit and are fitted by a 2m model (open circles) consistent with the accompanying 10m model*

The experimental down-hole semi-variograms for "mineralized" and "argillically altered" sample data are very different (Figure 4). Both data groups have relatively short ranges (22 and 18m), and the semi-variogram for argillically altered data has a sill 1.8 times higher than the sill for the main mineralized zone. These results clearly demonstrate the dramatic influence that geological character exerts on the semi-variogram. It is apparent that a single model for all data would have been inappropriate and would have resulted in a semi-variogram biased on the high side for all ore estimation which is confined entirely to the "mineralized" category.

**The foregoing spherical models** were used merely to illustrate the differences between "altered" and "mineralized" parts of the Cinola deposit. A three-dimensional model is required for estimation purposes and must fit horizontal experimental semi-variograms as well as down-hole semi-variograms.

The procedure we used to determine a three-dimensional semi-variogram model was as follows: two nested spherical models were fitted to the experimental horizontal semi-variogram for the 118 degrees direction (perpendicular to quartz veins). The nugget effect was estimated from semi-variograms for the 2m chip samples from the adit (Figure 6). A nested model with comparable sills, nugget effect and short range structure, but different long range structure was then fitted to the experimental horizontal semi-variogram for the 028 degrees direction (parallel to quartz veining). Regularized models are shown fitted to the two experimental curves in Figure 6. The parallel-to-vein model clearly fits the mean vertical (down-hole) experimental semi-variogram as shown in Figure 4.

The validity of the model is further emphasized because the comparison is made for a 2m regularized model rather than the

**Table 2. Relative point semi-variogram models for Au, Cinola gold deposit**

| | ISOTROPIC | ANISOTROPIC parallel | ANISOTROPIC perpendicular |
|---|---|---|---|
| $C_o$* | 0.06 | 0.06 | 0.06 |
| $C_1$ | 0.20 | 0.19 | 0.19 |
| $a_1$ | 20m | 18m | 18m |
| $C_2$ | — | 0.228 | 0.228 |
| $a_2$ | — | 180m | 280m |

*Assuming 10m composites.

10m composites from which the model was derived originally. A comparable verification of the general model is shown by the close fit of the perpendicular-to-vein, 2m regularized model to the mean 2m experimental semi-variogram for chip samples from the exploration adit (Figure 6).

The three-dimensional nested spherical model is thus consistent with all available data; point parameters are listed in Table 2. This model can be expressed as a short range isotropic structure (range 18m) and a long range anisotropic structure (perpendicular-to-vein range of 180m; parallel-to-vein range of 280m). The short range structure probably represents "clustering of veins" and their lack of uniformity of orientation. The geological significance of the longer range structure is far from certain and, of course, the ranges are not well defined; nevertheless, the scale of these long range structures would suggest the possibility of control by large scale features such as variations in host rock characteristics. This latter speculation remains to be demonstrated.

## KRIGING

Kriging is a weighted average procedure for estimating local mean grade, and is optimal in the sense that the estimation variance is minimized. Procedures are summarized by various authors (eg. Journel and Huijbregts 1978), and will not be outlined here. The low sill level and ranges of the Cinola nested semi-variogram model relative to the 30m dimensions of the blocks to be evaluated suggest that reasonable block estimates might be obtained by two-dimensional kriging using 10m bench composites. Because values in the kriging procedure will be based on a sample spacing of about 30m or more, a simple, point isotropic model fitted directly to the experimental horizontal semi-variograms for 10m composites might be adequate for kriging.

One such model given in Table 2 was deduced from an early subset of total drill data (Champigny 1981) assuming isotropy. We will examine the application of this model to grade estimation because it represents an early stage in our geostatistical knowledge of this deposit. The isotropic model was developed prior to recognition of the pronounced preferred vein orientation in underground workings. The orientation of these veins (028 degrees strike) is substantially different than any of the four horizontal directions for which semi-variograms were first determined (0 degree, 045 degrees, 090 degrees, 135 degrees), and this, combined with the procedure for determining semi-variograms for randomly distributed data in a two-dimensional field, masked the existence of an anisotropy. Once the preferred orientation of veins was clearly defined the more representative anisotropic three-dimensional semi-variogram model of Table 2 was developed. This latter model can also be considered a two-dimensional anisotropic model if only two-dimensional data assays are used in block estimation.

To compare the effects of these two two-dimensional models we have kriged 30x30x10m$^3$ blocks for the 110m level in three ways; that is, using each of the models in Table 2. A visual comparison of results can be made by plotting estimated grade by a two-dimensional model versus estimated grade by the three-dimension model (Figure 7). The relative quality of two- and three-dimensional models is demonstrated by an XY plot of block errors obtained for the two kriging approaches (Figure 8). Examination of these two graphs shows that large block estimates are not sensitive to detailed difference in two-dimensional semi-variogram models.

The three-dimensional approach, must, by definition give better estimates on average than the two-dimensional approach. The level of block error is clearly less for three-dimensional than for two-dimensional estimates. All models appear to provide unbiased estimates of block means.

Drill hole spacing is sufficient for estimates of the type demonstrated here and the three-dimensional semi-variogram model is applicable to global estimates by the method of conditional probability. However, estimation of grades of blocks corresponding to reasonable selection units during mining (say 10x10x10m$^3$) for purposes of pit design cannot be done to an entirely acceptable quality with the present drill hole spacing.

The general procedure we have used in obtaining all the kriging results referred to here is as follows for a specified block size:

For the 110m level we attempted kriging of blocks (30x30x10m$^3$) arranged in a rectangular array measuring 22 blocks by 16 blocks. Individual blocks were kriged only if: (1) four or more assays (bench height composites) are found within the search radius of 80m from the centre of the block to be kriged, (2) one or more bench composites occur within the block to be kriged, and (3) the block centre lies between the footwall fault and the eastern zone of intense argillic alteration. These restrictions lead to estimates for a maximum of only one aureole of blocks beyond the limit of available drill data. Estimated grades for the 110m level are summarized on Figure 9. Final block estimated grades consist of two components combined in a manner

*Figure 7. Comparison of block grades kriged by two different semi-variogram models for 30m blocks, 110m level, Cinola Gold Deposit. The two models are a two-dimensional isotropic model and a three-dimensional anisotropic model*

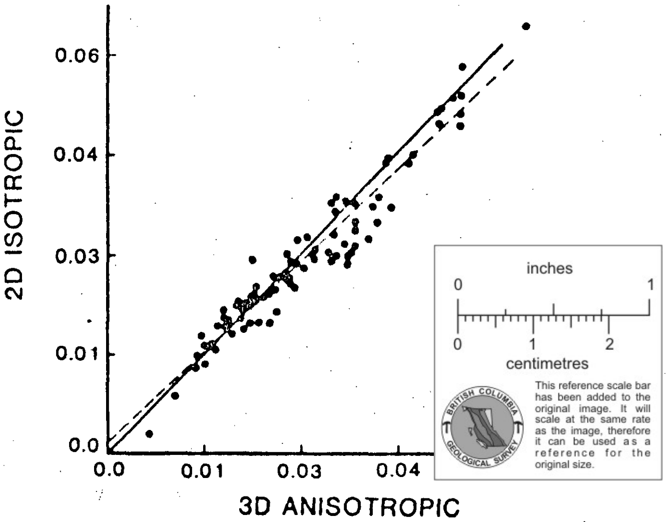
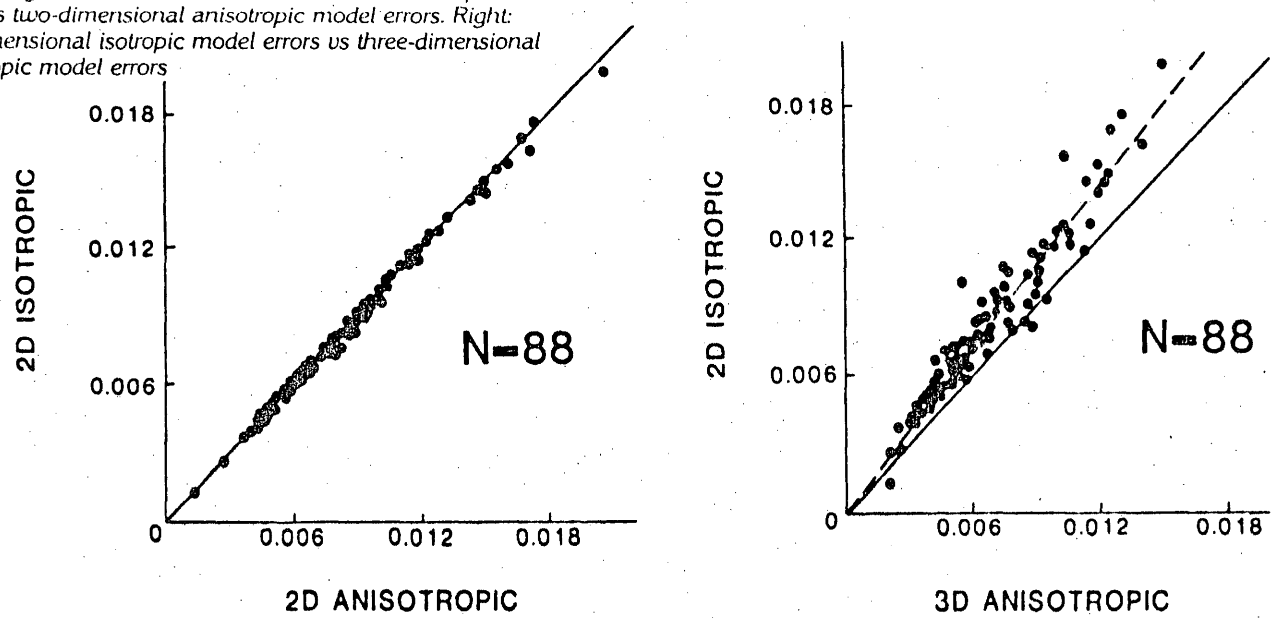



*Figure 8. Plot of 30m block kriging errors using two different semi variograms models. Left: two-dimensional isotropic model errors vs two-dimensional anisotropic model errors. Right: two-dimensional isotropic model errors vs three-dimensional anisotropic model errors*



suggested by Giroux and Sinclair (personal communications 1981) for the Equity Silver deposit. Each block estimate consists of a kriged component and a purely random component. The two components are present in the proportion of 96.5 and 3.5 percent for the low grade and high grade populations respectively. For each block the estimated grade (m) is determined as follows:

$$m = (1-p)\,m_k + p\,m_h$$

$$m = 0.965\,m_k + 0.035\,m_h$$

where $m_k$ is the kriged block grade and $m_h$ is the average of the high grade component. The high grade random component has a mean value of 0.235 oz Au/st, or an average contribution of 0.008 oz Au/st for each block.

## DISCUSSION

This study demonstrates the importance of a clear understanding of geological factors that relate to mineralization in attempting to define an appropriate semi-variogram model. For example, experimental semi-variograms for an extensive argillic altered zone surrounding the main mineralized zone on the north and east are dramatically different than for the main mineralized zone. Had these two environments not been recognized and if both sets of data had been merged for semi-variogram modelling purposes, unnecessary complexities and uncertainties would have been introduced.

In addition, sill level and nugget effect would have been substantially higher than found for the main mineralized zone with the result that different block grades would have been estimated with larger apparent errors. A second geological feature of importance to semi-variogram modelling is the preferred orientation of gold-bearing quartz veins, a feature not apparent in the early part of our study but observed and verified during driving and mapping of a lengthy exploration adit. The four directions chosen to establish experimental semi-variograms unfortunately happened to be as far removed as possible from the preferred orientation. Thus, in early work an anisotropy escaped detection and an isotropic horizontal semi-variogram model was assumed (Champigny 1981). Subsequently, of course, we were able to refine this model to a nested anisotropic model using as a guide the detailed geological information from the exploration adit.

Present drill spacing is adequate to define kriged grades of large blocks ($30x30x10m^3$) and provide a generalized view of grade distribution. Errors for these blocks are generally from 15 to 50 percent of the kriged value with larger errors mostly at the fringes of the main mineralized zone where drill spacing is widest. Errors for smaller blocks that might represent a reasonable selection for mining units (say $10x10x10m^3$) are much larger except for the small number of such blocks that are intersected by a drill hole.

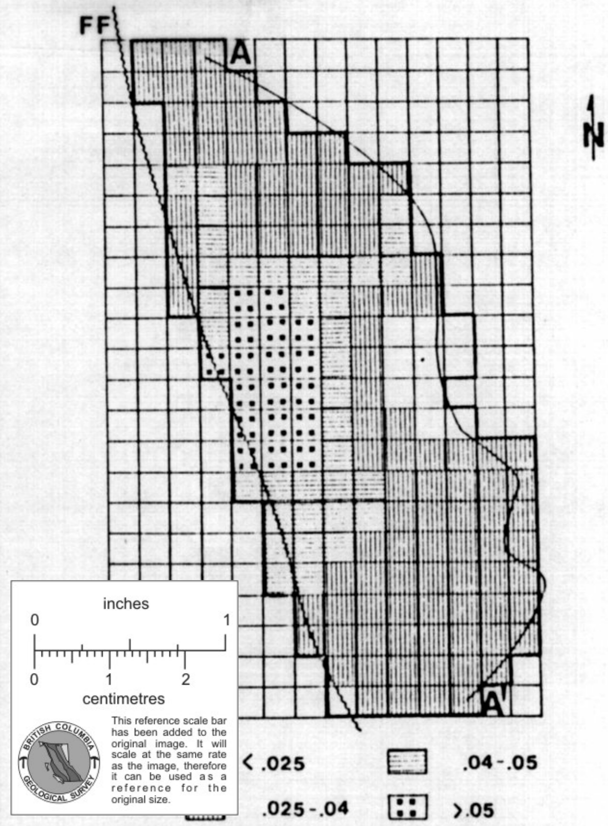
The kriging procedure adopted here takes into account the presence of two distinct grade populations, referred to here as high and low grade populations. The high grade population is assumed to be distributed randomly throughout the deposit; the low grade and abundant population is the one we have kriged. Consequently, our kriging estimates for all blocks must have an additional random component added to them as described in an earlier section. This procedure is not appropriate if the high grade population has a pronounced preferred location within the deposit. In such a case, an alternative procedure such as multi-gaussian kriging using the entire data set might be a more appropriate approach to block estimation.

**CONCLUSIONS.** This study has provided a systematic procedure for geostatistical ore reserve estimation of a large tonnage, low grade gold deposit. The procedure includes:

1. Careful editing of the data.
2. Construction of probability plots to partitioned "high" grade and "low" grade populations.
3. Generation of experimental down-hole and horizontal relative semi-variograms and development of a three-dimensional point model.
4. Block kriging.

Specific results for the Cinola gold deposit are summarized as follows:

1. Core size (NX, BX) and core length from 1.5 to 3 m do not appreciably change the behaviour of experimental semi-variograms.




**110 LEVEL – Au (oz/s.t.)**

*Figure 9. Example of generalized grade distribution for 30m blocks, 110m level, Cinola Gold Deposit. Results based on kriging using the isotropic two-dimensional semi-variogram model*

2. Argillic alteration has a pronounced effect on the behaviour of experimental semi-variograms, by increasing the relative variability.
3. Geological anisotropy in the Cinola deposit is clearly reflected in the corresponding anisotropy exhibited in the semi-variograms.
4. Kriging using a three-dimensional anisotropic point, relative, semi-variogram model provides block estimates of substantially better quality than do two-dimensional models.

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