Using Geostatistics to Assist in Optimising Grade Control Estimation at KCGM's Fimiston Open Pit

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ABSTRACT

The Golden Mile, which has been mined continuously for the past 100 years by both underground and more recently open pit methods, occupies an area of 1.2km by 4km adjacent to the city of Kalgoorlie Boulder in Western Australia (Figure 1).

Large-scale open pit mining at the Kalgoorlie Consolidated Gold Mines (KCGM) Fimiston operations is currently extracting 7.8 million tonnes of oxide and sulphide ore for a total production of 522 000 oz per annum.

The effectiveness of grade estimation techniques at KCGM has been examined with reference to existing 10 m bench sample data from all operating areas within the Eastern Lode System of the Main and North pits. The aim of the study was to recommend practical parameters for grade control estimation.

The review included comprehensive variography and comparison of nonparametric estimation methods (Journel, 1983) such as indicator kriging and probability kriging with ordinary kriging, leading to the development of improved grade control parameters and procedures for both daily quality control and short term mine planning.

This paper reviews the geological, statistical, geostatistical, mining and modelling features studied in order to present KCGM's Mining Department with recommendations for improving grade control.

GEOLOGY

Regional geology

The Golden Mile is located in the Kalgoorlie Goldfields within the Norseman-Wiluna greenstone belt, a component of the Archaean Yilgarn Block of Western Australia.

The Kalgoorlie sequence consists of a basal ultramafic unit, the Hannans Lake Serpentinite, overlain successively by the Devon Consols Basalt, Kapai Slate, Paringa Basalt and Black Flag Beds. Mafic to ultramafic sills have intruded the stratigraphy with the most economically important being the Golden Mile Dolerite.

Mine geology

The Golden Mile is a mineralised system of anastomosing shear zones which has produced in excess of 1200 tonnes of gold and has been mined to a depth of about 1200 metres below surface.

The deposit has been divided into an Eastern and Western Lode system by a complex unit of sheared porphyries and shales known as the Black Flag Beds. The shear zones and lodes of the Eastern Lode System are developed extensively throughout the Golden Mile Dolerite and to a lesser extent the underlying Paringa Basalt, while those in the Western Lode System are restricted to Golden Mile Dolerite.

The term 'lode' is used to describe the areas of auriferous and pyritic hydryothermal alteration developed within parts of, or adjacent to, these shear zones.

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Individual lodes may vary from 30m to 1800m along strike, 0.01m to 8m across strike and 30m to 1160m in vertical extent. Elevated gold values are confined to the lodes but gold tenor within the lodes is highly variable. The ores are mineralogically complex and refractory, and contain a significant proportion of gold and silver bearing telluride minerals. Pervasive carbonate and potassium metasomatism accompanies the gold mineralisation (Clout, Cleghorn and Eaton, 1990).

All lodes are offset by a series of late easterly dipping faults striking oblique to the lode orientations in a northeasterly direction. These faults complicate the geometry of the ore in both strike and dip.

The lodes are classified according to their dominant geometry, as shown in Table 1 and Figure 2, and are characterised by various alteration assemblages. However, the ore/waste boundary is ultimately chosen by assay value not alteration.

Caunter lodes

The Caunter lodes typically have a strike orientation of 335° and an average dip of 70° to the west. They are essentially tabular structures with strike and dip continuity in the order of hundreds of metres.

Caunter lodes typically have a siliceous ± ankerite, pyritic often brecciated high grade (>10g/t) core with a width ranging from 0.5 to 5.0 metres. Surrounding the core is an alteration halo up to 80 metres wide which typically is dominated by ankerite alteration with varying amounts of pyrite (one to seven per cent) and silica. These halos provide ore within the 0.5g/t to 5.0g/t range. Caunter lodes account for approximately 60 per cent of all ore mined.

Cross lodes

The Cross lodes have strike orientations ranging from 270° to 300° and a dip ranging from 60° to 80° to the south.

Mineralogically the Cross lodes are similar to the Caunter lodes with a typical ore assemblage of silica, ankerite and pyrite. Ore widths in the Cross lodes range from 15 metres to 60 metres.

Main lodes

Main lode structures have a strike orientation ranging from 355° to 010° and an average dip of 70° to the west. Similar to Caunter lodes, the Main lodes are tabular structures with strike and dip extents in the order of hundreds of metres.

The Main lodes also have a high grade (>10g/t) siliceous, pyritic core ranging from 0.5 metres to 5.0 metres in width. The alteration halos associated with the Main lodes are typically very restricted (<10 metres) and characterised by a chlorite, calcite ± pyrite alteration assemblage. Main lodes often show a weak foliation fabric with mineralisation frequently restricted to narrow (<0.5m) stringers parallel to the foliation.

Table 1 represents 91 per cent of all known lode orientations. The remainder are either dip or dip azimuth variants.

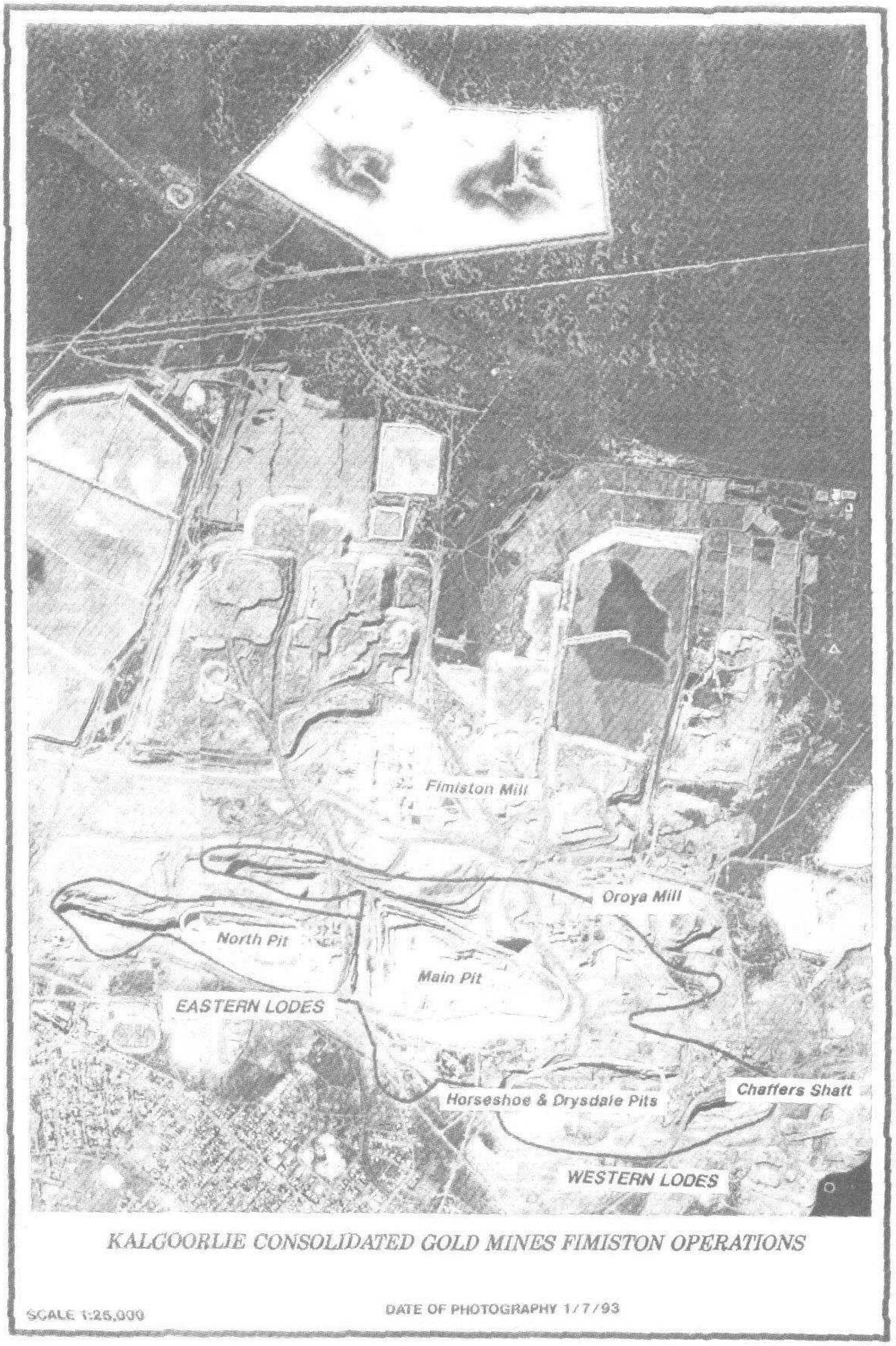

FIG 1 Plan of Kalgoorlie Consolidated Gold Mines Fimiston operations. Scale 1:25 000.

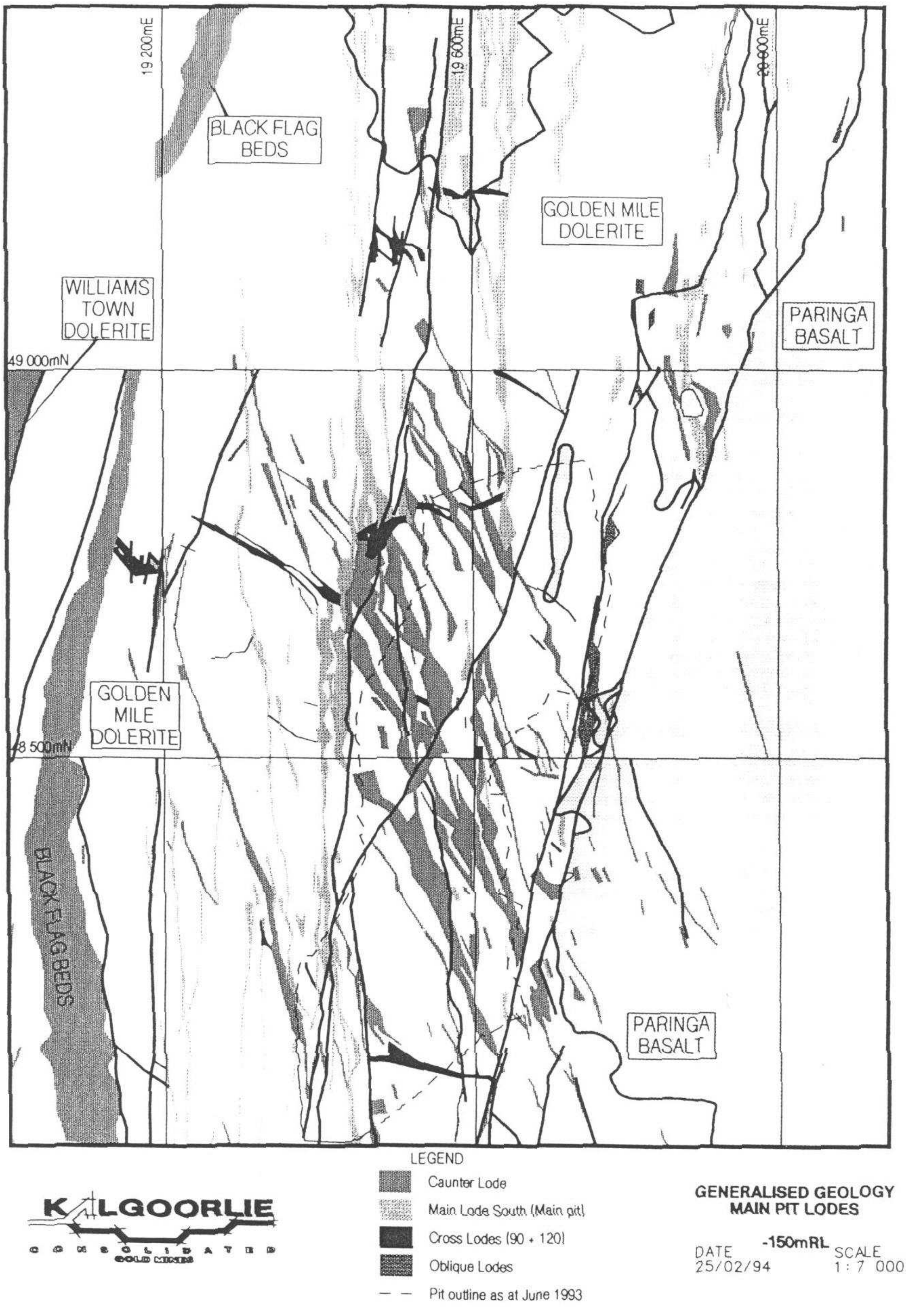

FIG 2 - Illustration of lode geometry in Main Pit

TABLE 1
Lode type orientation and classification.

Name and Code	Strike	Dip	Dip Azimuth	Number of Lodes Occurring within Deposit
Caunter Lodes	335	65	245	359
Cross 120 Lodes	120	70	210	39
Cross 90 Lodes	90	80	180	32
Main Lodes North (North Pit)	010	55	280	106
Main Lodes South (Main Pit)	355	70	265	243
Oblique Lodes	010	70	280	21

SAMPLING

Blasthole samples are taken from cones of drill cuttings deposited on the bench after drilling. A wedge is cut to the floor and scraped out to expose the central core of the cone which is then sampled in upward cuts to obtain a 10kg sample. The maximum particle size is 95 per cent passing 14mm and, less commonly, 95 per cent passing 6mm. No riffle splitting of the full interval of drill cuttings has been possible to-date, due to the proximity of large open stopes.

In the laboratory the 10kg sample is crushed to 90 per cent passing 1mm. 500g of this is pulverised to 90 per cent passing 75 microns, from which a 30g charge is fire assayed.

This sampling method was adopted when the bench height was changed from 7.5m to 10m. Fundamental sampling error was calculated for various collection sizes and crushing scenarios (Chapman and Stevens, 1992). Each blasthole (6m spacing) has a support of 3000 tonnes. A new sampling system is being considered in order to reduce sample collection error. An automated splitter would be likely to reduce uncertainty caused by splitting the 10kg sample from the rest of the cone. However as the full 10kg sample is subsequently crushed to 90 per cent passing 100 microns before taking the next split down to 500g, the laboratory split should be representative of the 10kg sample.

PRODUCTION BLOCK DELINEATION

Run of mine ore is delineated above a block cut-off of 1.5g/t based on grades kriged within a nominal 0.3g/t assay cut-off boundary which delineates waste from anomalous material for each shot. Block grades are kriged using parameters defined for a particular lode type.

The minimum selective mining unit is 4 m x 10 m x 10 m. As-mined tonnages are calculated by direct truck tallies from each mining block and these are assigned the average kriged grade for that block.

The ore is dug from west to east (hangingwall to footwall). This allows the waste to rill down dip and enhances the ability of the operator, with the help of the geologist, to mine the hangingwall of each (west dipping) lode selectively.

STATISTICS

Assays are close to lognormally distributed within the nominal 0.3g/t assay lode type boundaries, which successfully reduce mixing of waste and mineralised populations although most zones show evidence of a remnant separate high grade population. Internal low grade assays are encompassed within the boundary and isolated high grades may be either included or excluded according to the prevailing structure. Table 2 summarises the statistics for each lode type. Figure 3 illustrates the log histograms and log probability plot for Caunter lodes within the assay perimeters.

TOP CUTS

The minimum top cut for ordinary kriging without a search constraint would be the 97.5 percentile grade. This is based on lognormal statistics and is the top cut which removes the bias from the arithmetic mean, making it equivalent to the log estimate of the mean. When populations are mixed it is not possible to have a single optimal top cut but at least some degree of bias is potentially incurred if no cut is used for skewed

TABLE 2
Summary statistics for coded blastholes 10m bench samples (no upper cut applied).

Lode	Number	Max	Mean	Variance	Log Variance	Median	Coefficient Variation
Caunter Lodes	11692	120	1.79	14.72	2.07	0.90	2.14
Cross 120	393	60.3	3.03	50.35	2.32	0.85	2.34
Cross 90	115	31.3	2.77	18.75	2.79	1.5	1.56
Main Lodes North (North Pit)	2936	95.3	1.69	14.87	2.44	0.90	2.28
Main Lodes South (Main Pit)	3806	148	2.54	38.33	2.67	0.90	2.44
Oblique Lodes	669	23.3	1.88	9.53	2.44	0.75	1.64

TABLE 3
Composite statistics (below 97.5 percentile).

Field	Caunter Lodes	Cross 120 Lodes	Cross 90 Lodes	Main Lodes North	Main Lodes South	Oblique Lodes
Min Au	0.001	0.001	0.001	0.001	0.001	0.001
Max Au	9.5	25	12.5	9	18	13
Number	11.450	391	111	2874	3730	658
Mean	1.40	2.10	2.14	1.32	1.88	1.6
Abs Var	2.56	12.27	6.14	2.47	7.52	4.86
Rel Var	1.30	2.77	1.34	1.41	2.12	1.91
Log Var	1.90	2.03	2.55	2.27	2.43	2.30

distributions. The original KCGM kriging method employs top cuts and restricted search distances in an attempt to compensate for the skewness. The method derived is empirical and has been adopted on the basis of extensive validation. Unless indicator kriging is used, grades must be cut and/or searches restricted to avoid over-estimation. The effect of eliminating the top 2.5 per cent of the data on the distribution statistics, particularly the absolute variance, is shown in Table 3.

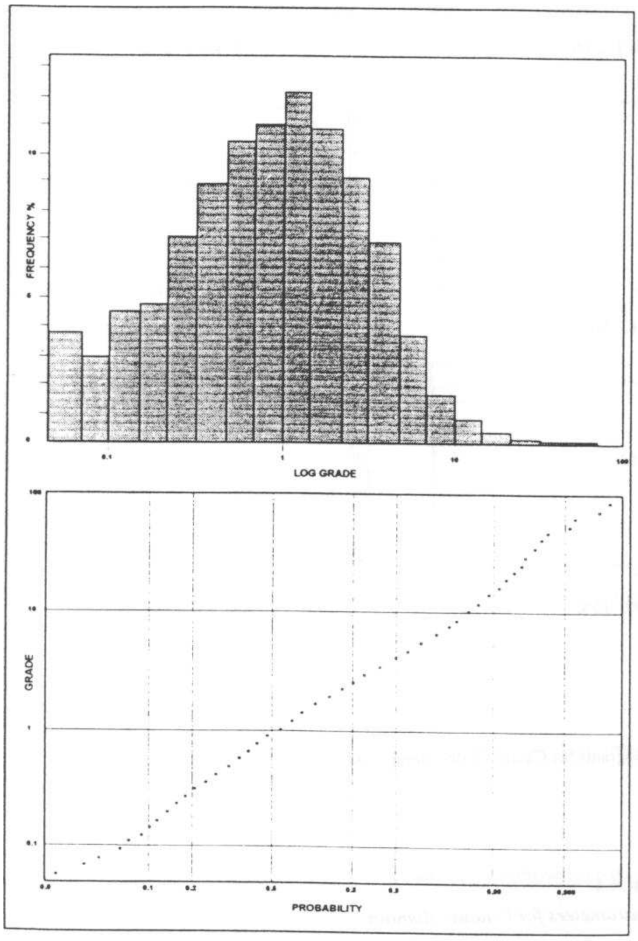

Fig 3 – Histograms and log probability plot - Caunter

SEMIVARIOGRAMS

Semivariograms were run on 10m bench composites for each geological zone using all the assay data within the zone, and separately for each lode type using only assays within the defined perimeters. Absolute and logarithmic semivariograms were run after cutting data to the 97.5 percentile to avoid the disturbance to absolute semivariograms caused by erratic high grades. In addition, indicator semivariograms were calculated for each of the 10 decile cut-offs, that is the cut-offs separated by each 10 percentile of data. Fans of median indicator semivariograms were run for each lode to establish the horizontal anisotropy within each province and to establish the dip and potential plunge orientations of the mineralisation. Semivariograms for the main structural directions were run on the rank transformed data and rank+indicator variables.

The number of 10m benches available on which to determine dip continuity is limited. Blastholes on 7.5m benches were added to the database to assist in this direction. The total variability using the mixed data was, however, understandably not representative of the 10m benches. Down dip continuity is still likely to be data limited and could be found to be underestimated in some cases.

Absolute, logarithmic and indicator semivariograms

Most semivariograms are well-defined and display nested short and long range structures. Figures 4, 5 and 6 display the modelled semivariograms for each indicator along strike, down dip and across strike within Caunter lode perimeters.

The comparative semivariogram results for each of the methods applied to Caunter, Main South and Main North lode types are summarised in Tables 4 to 6. The nugget and sill components are expressed as a percentage of the total variance and ranges are in metres.

Nuggets effects are generally around 50 per cent of the total population variance for each lode and increase towards about 70 per cent at higher decile cut-offs. Caunter and Main Lode North lode types have nested structures between which the spatial variances are equally distributed (Sill 1 and Sill 2). Main Lode South tends to have a higher variance associated with the small range structure (Sill 1) except for higher decile cut-offs where more variance is explained by the long range structure (Sill 2).

There were insufficient data to estimate down dip continuity on Main Lode North and the strike semivariogram ranges were subsequently used for the dip direction for this lode type.

Rank transform and rank + indicator semivariograms

Probability kriging requires co-kriging of the indicator transformed grade together with the rank transformed grade. In addition to indicator semivariograms, the semivariograms on the grade transformed to a rank of between 0 and 1 and the semivariograms on the sum of the indicator plus rank variable are required. The rank is derived by sorting the data in order of increasing grade then dividing the record number by the total number of records.

Figure 7 displays rank order directional semivariograms for Caunter lode and Figures 8 to 10 show the semivariograms based on the rank plus indicators from the 10^{th} to the 90^{th} percentile. These semivariograms display a similar pattern of spatial continuity to that of the indicator semivariograms in Figures 4 to 6 and are well formed for all cut-offs.

The probability kriging parameters for indicators plus rank and for the rank order variable itself are used in conjunction with the indicator semivariograms to allow interpolation by probability kriging. Tables 7 and 8 summarises the probability kriging parameters for Caunter and Main Lode South. Main Lode North lodes were not tested.

Discussions

The semivariograms for the Fimiston Lodes are characterised mainly by geometric anisotropy but some zonal effects were noticed in the indicator semivariograms for both Caunter and Main Lode North.

Caunter lode semivariograms have a high nugget effect compared with the first and second sills which are both similar in value. In Main South the nugget effect increases and the first sill

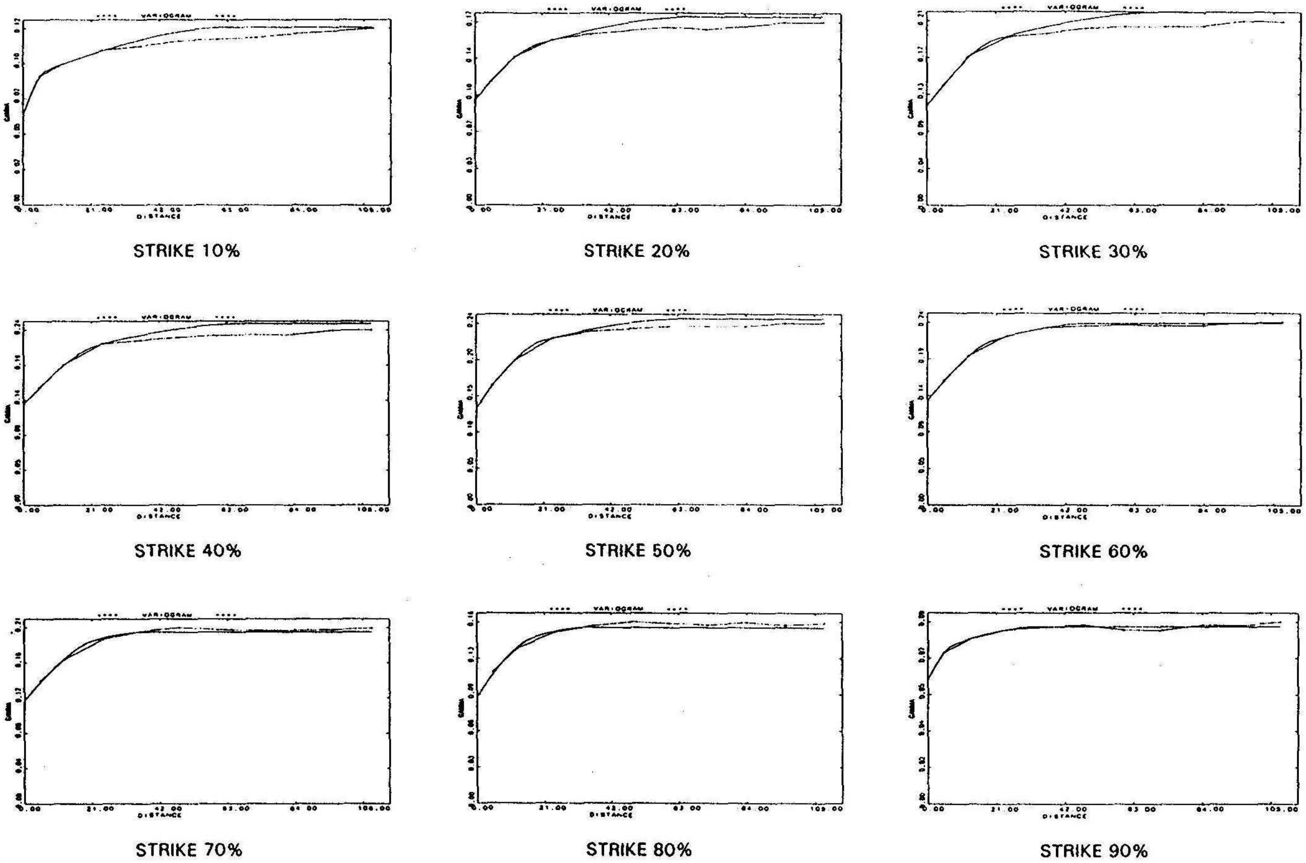

FIG 4 – Directional indicator semivariograms for Caunter lodes along strike

TABLE 4
Comparative semivariogram parameters for Caunter domain.

Semivariogram Type	Log	Absolute	Indicator								
			10%	20%	30%	40%	50%	60%	70%	80%	90%
Cut-off (g/t)	-	-	0.15	0.30	0.46	0.65	0.90	1.30	1.80	2.60	4.00
Nugget (%)	42	57	50	56	52	55	52	57	60	60	70
Sill 1 (%)	29	21	21	19	24	23	24	21	20	20	15
Sill 2 (%)	29	22	29	25	24	22	24	22	20	20	15
Total Sill (%)	100	100	93	97	100	100	100	100	100	100	100
Range (m)											
STK1	23	22	7	20	22	24	21	21	22	17	8
DD1	31	16	31	27	25	24	21	18	19	17	8
XSTK1	5	6	8	6	7	8	9	9	9	8	6
STK2	108	72	65	70	74	70	65	50	38	34	34
DD2	165	30	160	155	130	110	85	50	23	34	34
XSTK2	25	15	13	12	16	19	16	14	12	10	10

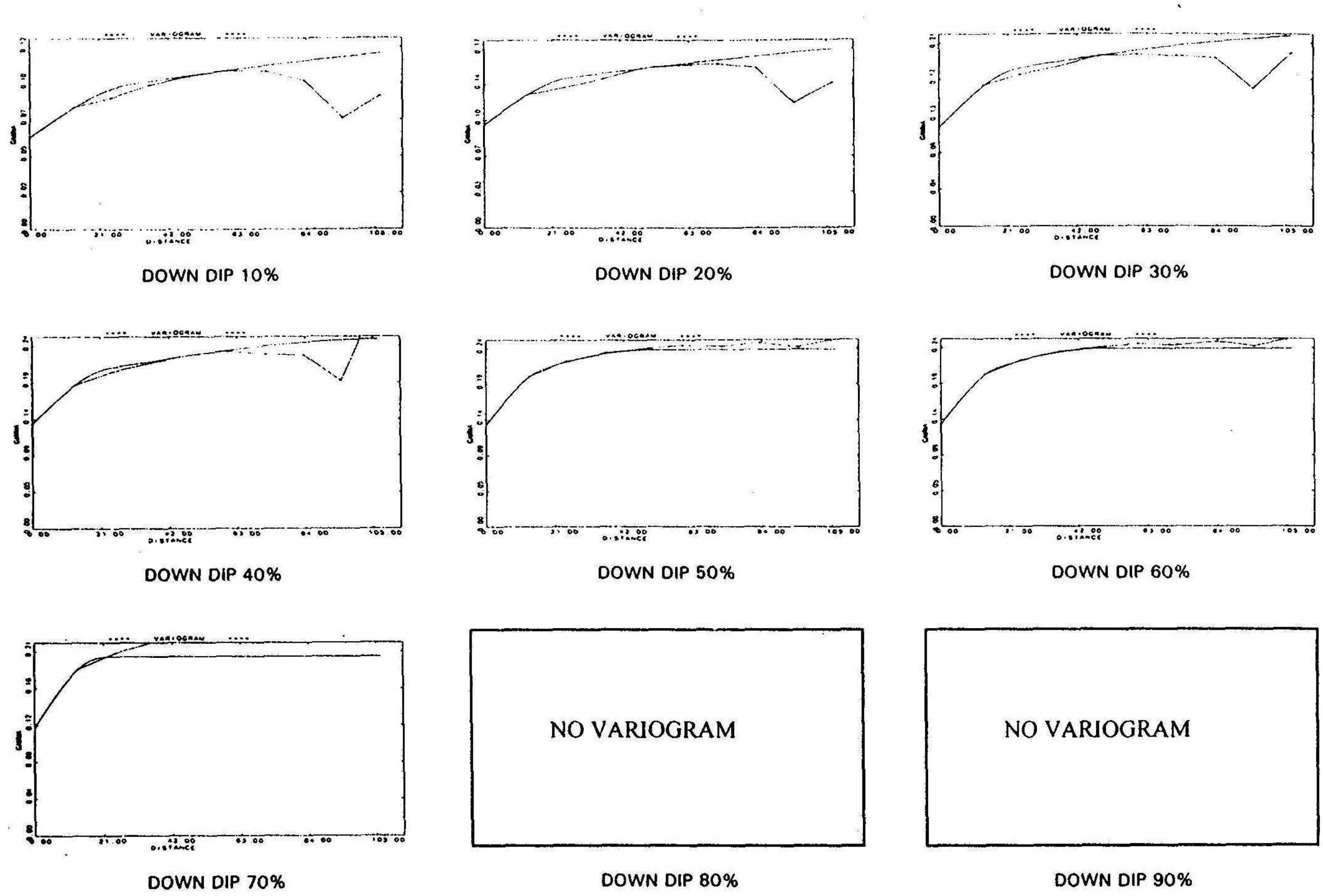

FIG 5 – Directional indicator semivariograms for Caunter lodes down dip

TABLE 5
Comparative semivariogram parameters for Main South domain.

Semivariogram Type	Log	Absolute	Indicator								
			10%	20%	30%	40%	50%	60%	70%	80%	90%
Cut-off (g/t)	-	-	0.13	0.28	0.40	0.60	0.90	1.50	2.00	3.40	6.00
Nugget (%)	45	53	46	46	45	66	72	74	67	67	79
Sill 1 (%)	33	23	42	41	37	11	12	10	16	13	9
Sill 2 (%)	22	24	12	13	18	23	16	16	17	20	12
Total Sill (%)	100	100	100	100	100	100	100	100	100	100	100
Range (m)											
STK1	24	16	22	22	21	22	23	32	23	23	23
DD1	-	28	33	22	19	24	24	29	27	32	32
XSTK1	7	4	7	6	5	7	9	9	6	3	3
STK2	83	30	96	80	57	60	72	49	38	30	27
DD2	-	28	100	90	52	31	24	29	35	47	60
XSTK2	16	6	19	10	9	12	15	15	12	6	6

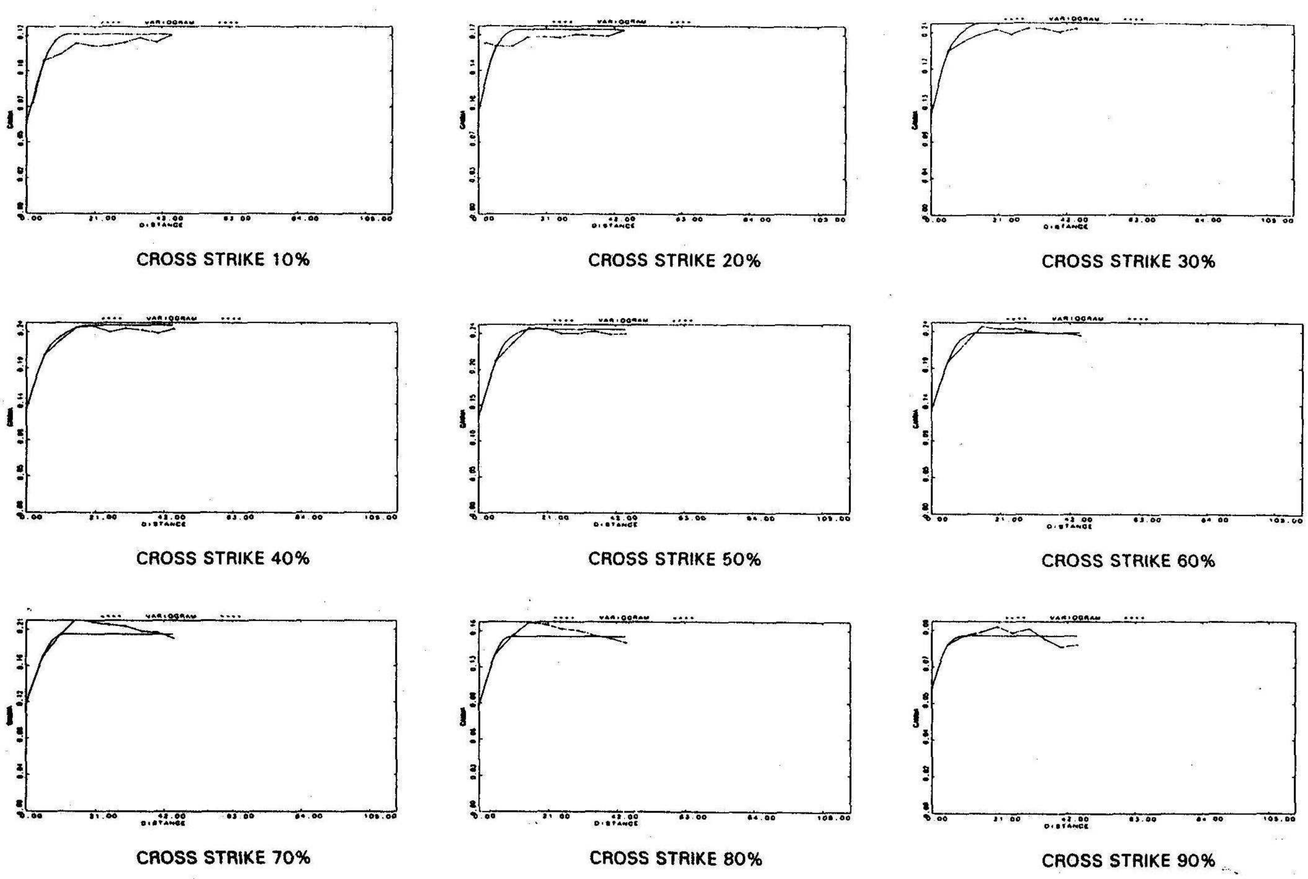

FIG 6 – Directional indicator semivariograms for Caunter lodes across strike.

TABLE 5
Comparative semivariogram parameters for Main North domain.

Semivariogram Type	Log	Absolute	Indicator								
			10%	20%	30%	40%	50%	60%	70%	80%	90%
Cut-off (g/t)	-	-	0.13	0.26	0.40	0.60	0.90	1.30	1.80	2.54	4.00
Nugget (%)	40	71	58	43	41	37	36	39	60	74	-
Sill 1 (%)	18	11	20	26	27	28	33	35	25	20	-
Sill 2 (%)	42	17	22	31	32	35	31	26	15	6	-
Total Sill (%)	100	99	86	91	91	100	100	100	100	100	100
Range (m)											
STK1	24	19	11	14	18	15	16	17	20	23	-
DD1	-	-	-	-	-	-	-	-	-	-	-
XSTK1	13	-	-	7	7	8	8	10	20	-	-
STK2	126	92	83	85	87	150	120	97	58	42	-
DD2	-	-	-	-	-	-	-	-	-	-	-
XSTK2	52	-	-	15	13	15	17	21	23	-	-

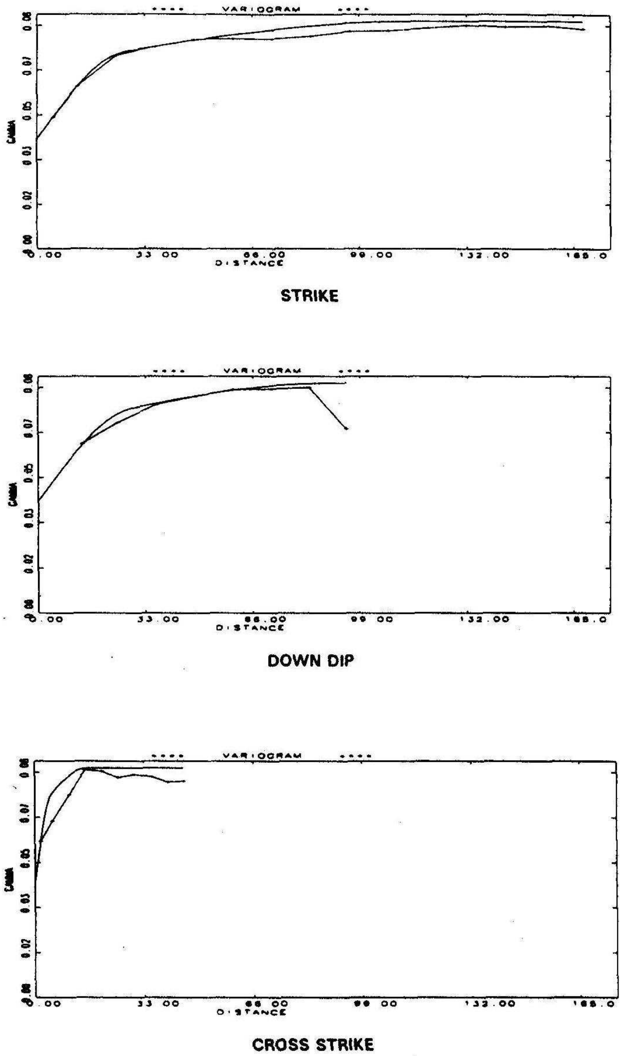

FIG 7 - Directional rank order semivariograms for Caunter lodes.

decreases as the cut-off increases and the second sill remains constant. In Main Lode North the nugget drops towards the median indicator then rises again and the sills are sympathetic in reverse. Each lode is characterised by a different relationship between the parameters and the indicator cut-off. This reinforces a separate geological/grade identify for each domain.

The nugget effect will generally tend to increase as the indicator is raised. This is a natural consequence of the inherently more spotty nature of higher grades and their lower sampling reproducibility. The indicator semivariograms presently recommend a large amount of smoothing of Main Lode South data because of the high nugget effects above a cut-off of 0.6g/t. Field splits should be checked for reproducibility of assays in higher grade material above 0.6g/t. Any improvement would result in lowering of the nugget effect and would allow better ore/waste delineation and more successful selective mining in these areas.

Model development

The smallest mining unit is 4m x 5m x 10m. Planning based on the resource model uses blocks of 4m x 10m x 10m in ore. The standard mining unit blocked out in the pit is 8m x 20m x 10m.

A subset of blasthole data for Caunter mineralisation was used to illustrate the relationship between blocks and variance within and between blocks.

Figure 11 shows how the variability within a block increases as the block size increases and the variability between blocks (the dispersion variance) decreases, both rapidly at first and then more gradually with increasing block size.

The position of the standard 8 m x 20 m x 10 m mining unit (160 sqm area) on the flat parts of the curves suggests that there is a large degree of variability within blocks compared with the variability between blocks. The variance of blastholes within blocks is 1.3 compared with a between block variability of 0.45. The ability to be selective increases as the variance between blocks increases, that is as blocks become smaller.

This has to be balanced against the estimation variance which, as shown in Figure 12, decreases rapidly as block size increases then more gradually towards the largest block size, even increasing again slightly as the block becomes bigger than the range of influence of the semivariogram (in this case the small scale structure affecting the kriging variance has a range of influence of 8 m x 20 m in the horizontal plane).

There is a close similarity between the behaviour of 4 m x 5 m blocks and 2 m x 10 m blocks (both 20 sqm area). They also both represent the same data storage requirement. The more compact 4m x 5m blocks would be more suitable for the angled and cross cutting lodes and would therefore be a better choice overall.

INTERPOLATION METHODS

A range of interpolation methods have been compared for Caunter and Main Lode South on bench –140 mRL and for Main Lode North on bench –100 mRL. The primary kriging runs were constrained to blocks coded within the 0.3 g/t envelope using only assays from within the envelope.

Ordinary kriging derives a weighted block grade estimate from the grades within a defined search ellipse using the semivariogram to calculate the weights for the best linear unbiased estimate. It is a parametric estimate in that is assumes a normal distribution for the input grades. As such it is not ideal for skewed data and necessarily requires some moderation of the high grades to avoid overestimation. This usually takes the form of high grade cuts and/or restriction of the influence of high grades.

Indicator kriging is a non-parametric estimation method suitable for any type of input distribution (Journel, 1983). It involves ordinary kriging of the indicator transformed data for a range of indicator cut-offs. Grades are transformed to 1 above cut-off, 0 below cut-off. The kriged estimate is the proportion of the block above cut-off. Once a series of cut-offs have been estimated, the average grade of the block is calculated by weighting average composite bin grades (between cut-offs) by the proportion of the block within the same cut-offs. Indicator kriging uses indicator semivariograms run on the 1's and 0's to set kriging weights for calculating each kriged proportion.

Probability kriging is an advance on indicator kriging (Kim *et al* 1987) in that the indicator as above is co-kriged with the rank of the grade. This means that the estimate relies on the identity of the input grades above and below cut-off as well as the relative rank of the input grades. It relies on the indicator semivariograms as well as the semivariogram on the rank transformed data and, in addition, the semivariograms on the sum of the rank plus individual indicators. Co-kriging is usually recommended when

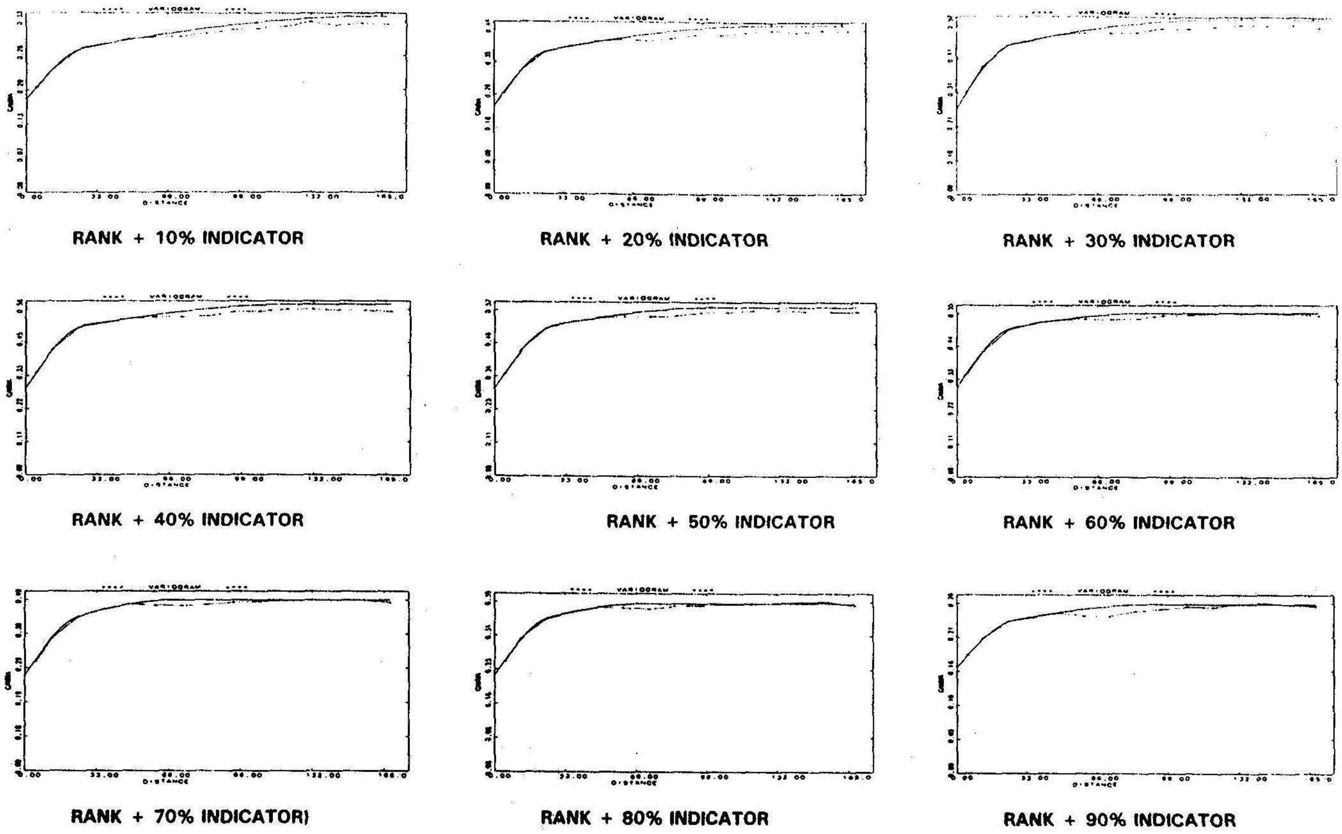

FIG 8 - Directional (rank + indicator) semivariograms for Caunter lodes along strike.

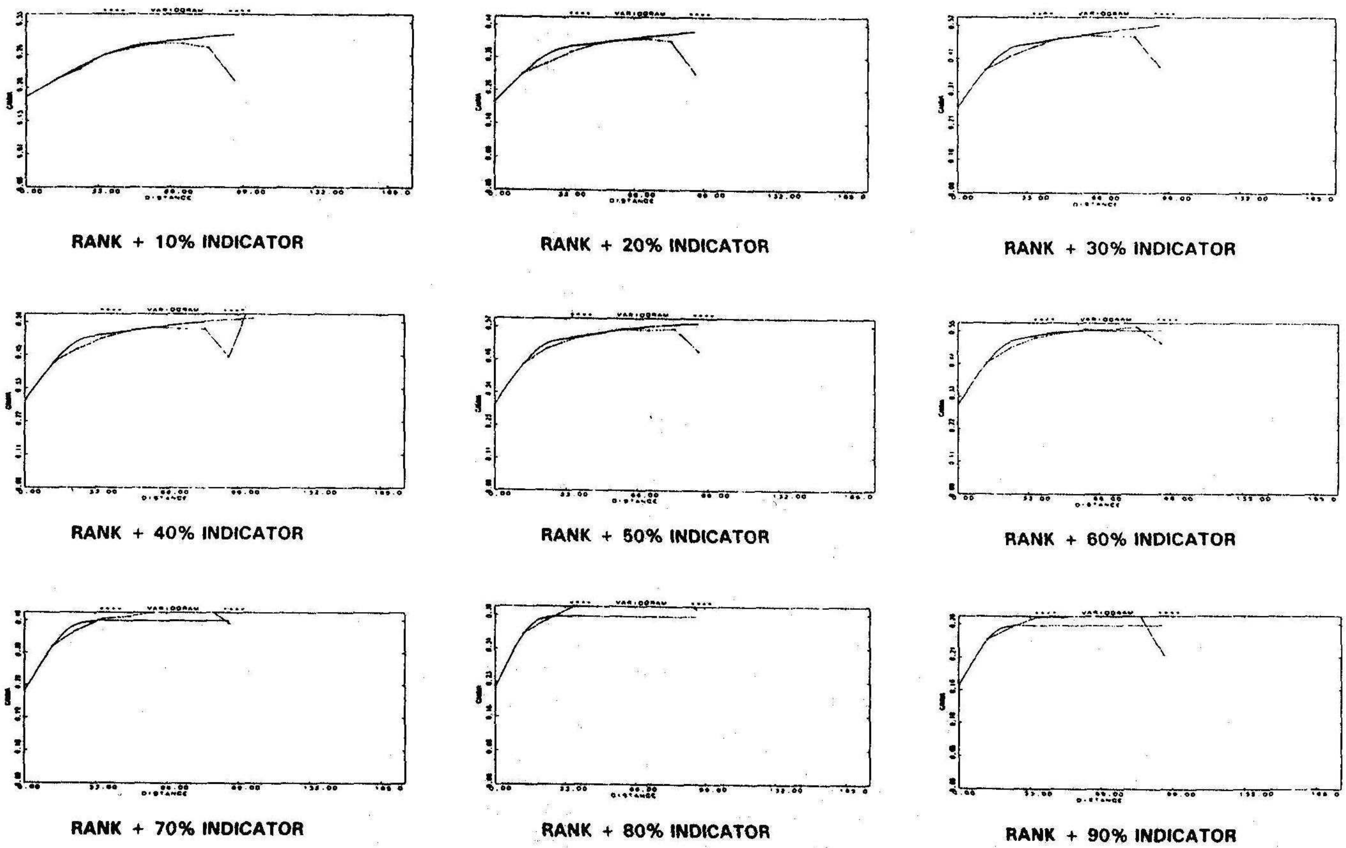

FIG 9 - Directional (rank + indicator) semivariograms for Caunter lodes down dip.

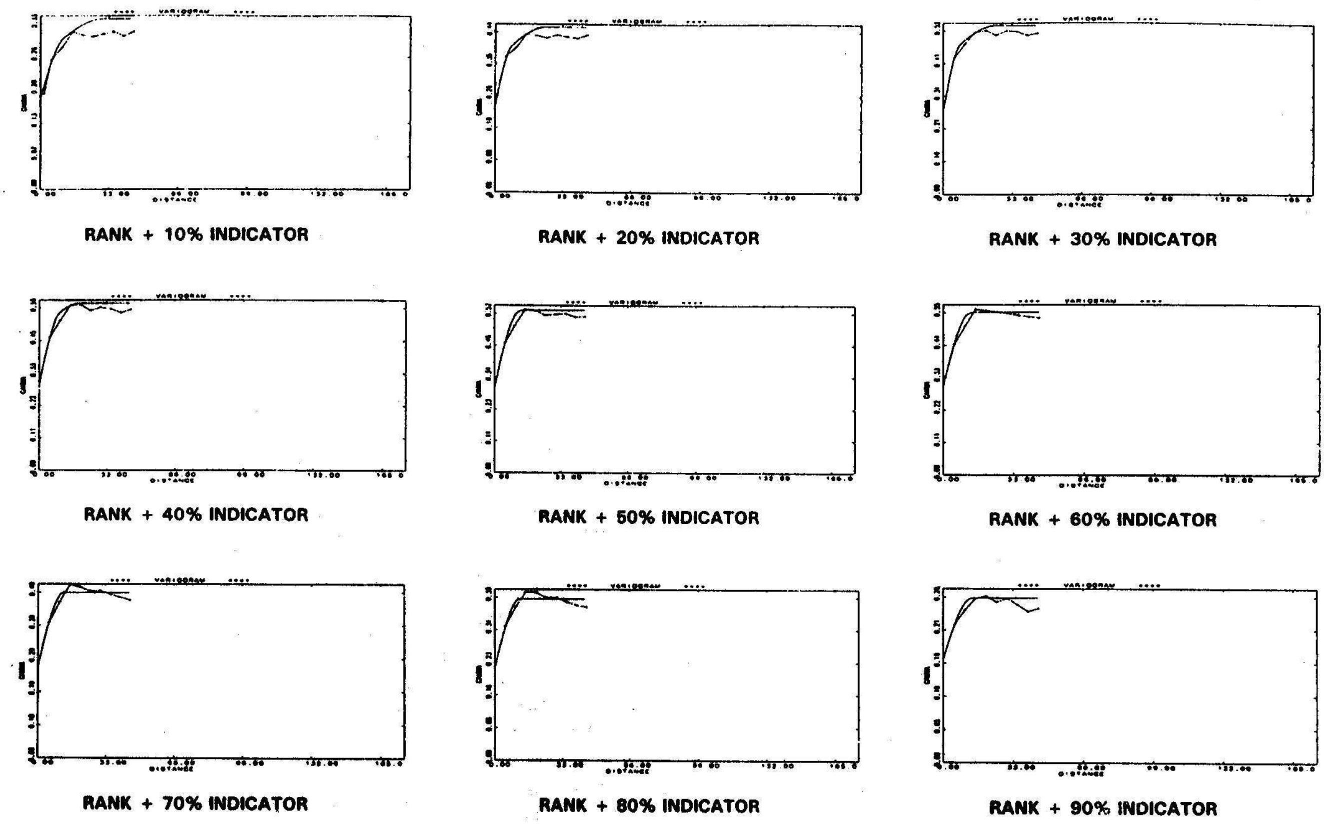

FIG 10 – Directional (rank + indicator) semivariograms for Caunter lodes across strike

TABLE 7
Caunter lodes probability kriging parameters.

Parameter	Indicator + Rank									Rank
	10%	20%	30%	40%	50%	60%	70%	80%	90%	
Nugget	0.53	0.51	0.49	0.51	0.52	0.54	0.50	0.57	0.62	0.48
Sill 1	0.23	0.27	0.30	0.31	0.31	0.30	0.57	0.26	0.21	0.31
Range 1	25 x 27 x 10									27 x 27 x 5
Sill 2	0.24	0.22	0.21	0.18	0.17	0.16	0.19	0.17	0.17	0.21
Range 2	130 x 130 x 15				100 x 100 x 15		36 x 48 x 15			90 x 115 x 16

Note: Ranges are down dip x along strike x across strike.

TABLE 8
Main Lode South probability kriging parameters.

Parameter	Indicator + Rank									Rank
	10%	20%	30%	40%	50%	60%	70%	80%	90%	
Nugget	0.43	0.40	0.44	0.59	0.59	0.62	0.55	0.55	0.63	0.48
Sill 1	0.40	0.47	0.42	0.24	0.24	0.26	0.30	0.29	0.16	0.22
Range 1	25 x 27 x 10									23 x 20 x 6
Sill 2	0.17	0.13	0.14	0.21	0.17	0.12	0.15	0.16	0.21	0.30
Range 2	50 x 70 x 15					40 x 50 x 12				23 x 47 x 12

Note: Ranges are down dip x along strike x across strike.

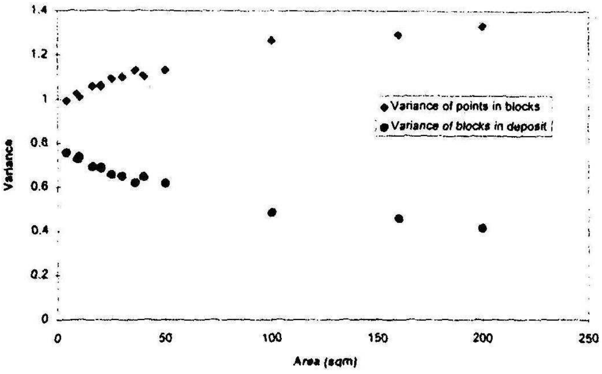

FIG 11 - Block area versus variance within and between blocks.

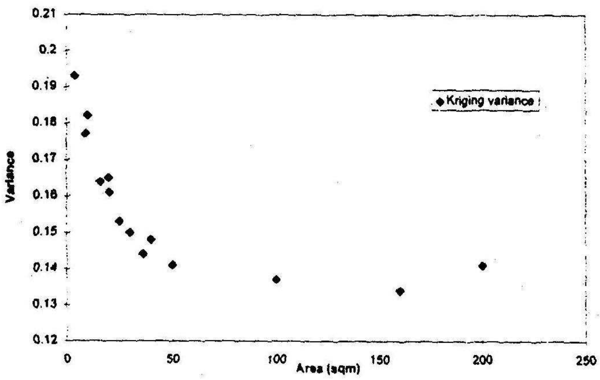

FIG 12 - Block area versus kriging variance.

one variable is fully sampled and a correlated variable is partially sampled. Co-kriging takes advantage of the correlation to compensate for the paucity of data in one of the variables. Probability kriging is a special case of co-kriging which takes advantage of the rank transform to add more control to the indicator case.

The following series of interpolations were undertaken:

1. Indicator kriging (IK)
2. KCGM Method – 1993 10m bench parameters (OKCGM)
3. Ordinary Kriging with 97.5 percentile top cut (C97OK)
4. Probability Kriging (PK)

The following versions of indicator kriging were tested:

	Regular	Nested
Full	IKFR	IKFN
Median	IKMR	IKMN

Full indicator kriging (IKFR and IKFN) uses a different semivariogram for each cut-off whereas median indicator kriging (IKMR and IKMN) uses the median semivariogram for each kriged cut-off. Block proportions are calculated either for the regular case (IKFR and IKMR) whereby the proportion is simply the probability above cut-off or for the nested case (IKFN and IKMN) in which the proportion calculated is the probability above cut-off for the remaining part of the block above the previous cut-off (Dagbert, 1990).

The probability kriging technique used is a full regular (PKFR) technique which employs the indicator semivariograms, the semivariogram of the rank of the grade and the semivariograms of the indicator + rank. Only bench –140 mRL was interpolated using probability kriging.

Secondary runs for C97OK and IKFR using all the data >0.001 g/t in each lode type zone (not constrained within 0.3 g/t envelopes) were also tested. These included:

- Constrained blocks, unconstrained grades (CBUG)
- Unconstrained blocks, unconstrained grades (UBUG)

Indicator kriging

A Datamine macro to allow the various types of indicator kriging was developed by Snowden Associates for KCGM.

Indicator cut-offs are set up for each lode domain considered. Each population is represented by decile bins giving nine cut-offs in all. Indicator semivariogram parameters are required for each decile for each lode type for full indicator kriging. Only the median indicator is used for median indicator kriging.

Bin grades are assigned by the arithmetic mean of composites within the bin. The uppermost bin is assigned the geometric mean (median) or a nominal assigned grade if data is absent. Any other bin containing no data within the search is assigned the mean of its bounding cut-offs. The bin grades are weighted by the kriged indicator proportions between cut-offs to establish the average grade of the block.

Probability kriging

Probability kriging was undertaken using a co-kriging option recently implemented by Geostat Systems International in their kriging program KRIGE3. This allows co-kriging of the indicator and the rank order variable, hence allowing probability kriging. For co-kriging the program requires the semivariogram model for variable #1, variable #2 and variable #1 + #2. This is slightly different from other programs whereby the cross semivariogram between variables #1 and #2 is required.

The indicator and rank variables are co-kriged for each cut-off resulting in the probability of the block above each of the nine cut-offs. The proportion of the block within cut-off bins is used to weight the bin grade to derive an average block grade. Part of the macro used for the indicator kriging process is used to generate the block grade from the probability kriging output of block proportions.

KCGM method

The KCGM system controls high grade outliers by a two-phase cutting process.

Grades are initially cut to the 95th percentile. Blocks are kriged using a search radius of 1.25 times the range of influence (up to four benches ie 40m vertically). In a second run, grades are set to an indicator of 1 between the 95th and 99th percentiles and 0 elsewhere. The 1's and 0's are used to interpolate an indicator flag using a search ellipse of 0.5 times the range of influence. All blocks with kriged flags >0.0001 g/t are re-interpolated using grades cut to the 99th percentile with a restricted search ellipse of 0.5 times the range of influence.

Ordinary kriging (C97OK)

Ordinary kriging employs the absolute semivariogram or a similarly scaled semivariogram to obtain the kriging weights to apply to raw data. It assumes a normal distribution. Skewed data should be cut or high grades restricted in influence to avoid smearing of grade by ordinary kriging.

Grades have been cut to the 97.5 percentile to simulate the true average grade of a lognormal distribution.

KRIGING RESULTS

Results were reported either for blocks constrained within the perimeters for each of the three lodes types studied in detail or for all blocks within a given ‘lode type’ zone.

When full regular indicator kriging is compared with 97.5 percentile cut ordinary kriging, each lode type shows close similarity between the grade/tonnage curves for both constrained and unconstrained blocks regardless of estimation method. At low cut-offs the 97.5 percentile cut ordinary kriging defines less tonnes at similar to higher grades than full regular indicator kriging. The curves converge at higher cut-offs and, for Main Lodes, they cross over so that ordinary kriging defines less tonnes at higher grades than indicator kriging. Indicator kriging at a cut-off of 1.5 g/t is similar to cut ordinary kriging above a cut-off of 1.3g/t for Main Lode South but for the other lodes both methods give the same tones and grade above a cut-off of 1.5g/t.

Indicator kriging results, cut ordinary kriging and probability kriging results for constrained blocks and constrained grade are compared in Figure 13. Nested indicator kriging is slightly more conservative than full regular indicator kriging which, in the case of Caunter lodes, is reasonably similar to probability kriging. In Main Lode South probability kriging gives higher grades than all the other indicator kriging methods. This may be a reflection of the large number of order relation problems observed during the probability kriging of Main Lode South and is not likely to be representative of the method in general. Results for Caunter Lode appear reasonable in terms of the full indicator kriging results. Main Lode North and Caunter Lode appear very stable in terms of their comparative results.

Cut ordinary kriging gives similar results to full regular indicator kriging for Caunter lodes but overestimates Main Lode South and underestimates Main Lode North slightly. Only Main Lode South appears to be significantly sensitive to methodology. This may be due to the high nugget effect measured by variography in this area. There is a high degree of unpredictability and therefore sensitivity to kriging parameters. The behaviour of the comparative results for Main Lode South suggests a possible sampling problem in this area.

Figure 14 compares the results of the KCGM kriging method (10 m variogram parameters) for constrained blocks and constrained grade with full regular indicator kriging and ordinary kriging cut to the 97.5 percentile. Once again, Main Lode South shows more sensitivity to methodology than the other lodes, both of which have good agreement between full indicators and ordinary kriging cut to the 97.5 percentile. In Caunter lodes full indicators and ordinary kriging are both more conservative than the KCGM method but in Main Lode North there is little difference between all three methods above the 1.5g/t ROM cut-off where results are virtually co-incident.

Figure 15 show the tonnage differences between constrained and unconstrained kriging. The curves converge towards higher cut-offs. Significant increases in tonnage are found for unconstrained kriging at cut-offs below 1g/t.

The 97.5 percentile cut constrained ordinary kriging falls between the constrained and unconstrained block, unconstrained grade results. It tends towards slightly higher tonnages for the same (to slightly higher) grade as the constrained results. There is very little difference between constrained blocks with unconstrained grade and constrained blocks with constrained grade for 97.5 percentile cut ordinary kriging.

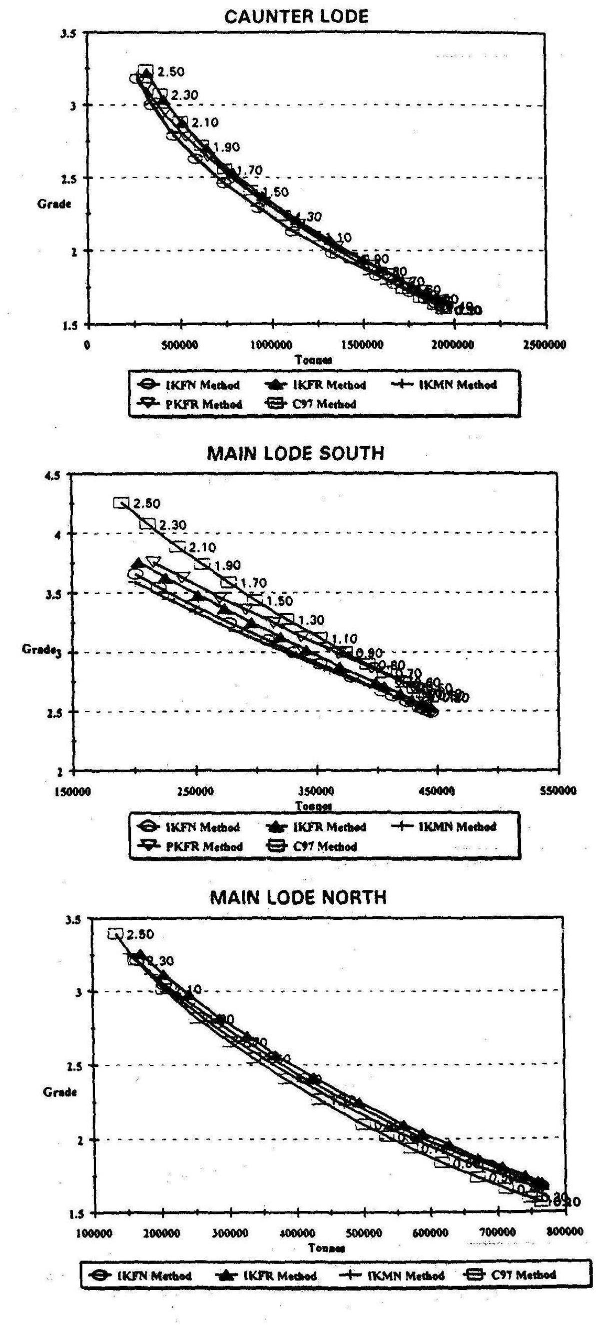

FIG 13 – Grade/tonnage relationships for constrained blocks and constrained grade IKFN, IKFR, IKMN and C970K

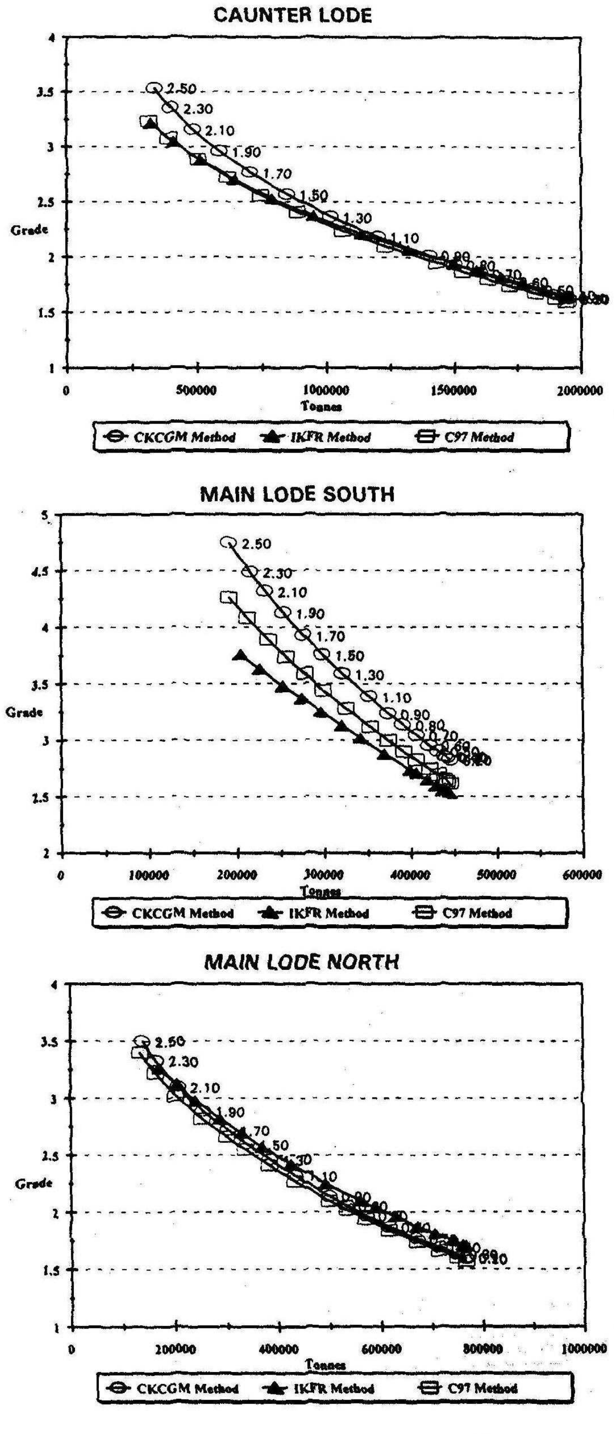

FIG 14 - Grade/tonnage relationships for constrained blocks and constrained grade OKCGM 10 m, IKFR and C970K.

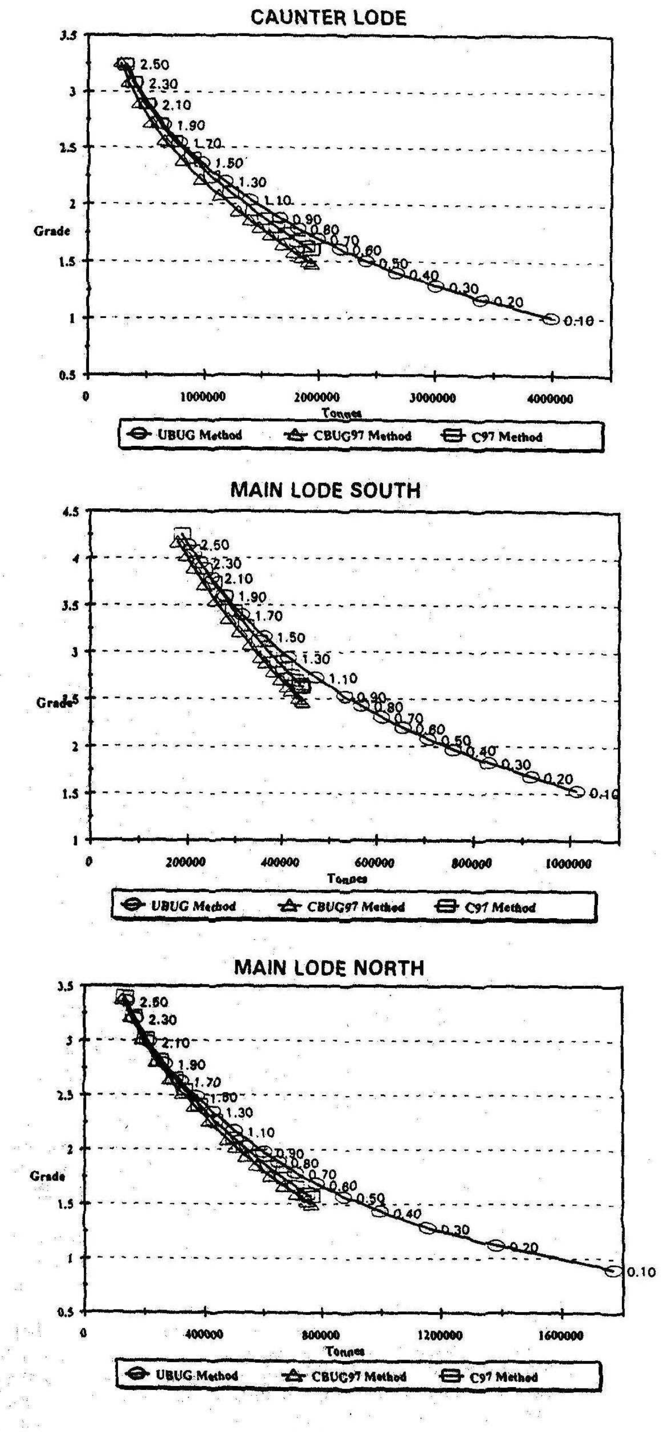

FIG 15 - Grade/tonnage relationships for 97.5 percentile methods UBUG, CBUG97 and C97OK.

Summary of comparative kriging results

- Full regular indicator kriging is closely represented by ordinary kriging (cut to the 97.5 percentile) for all lodes.
- Probability kriging gives comparable results to full regular indicator kriging for Caunter lodes but overestimates Main Lode South.
- Median indicator kriging is more conservative than full regular indicator kriging.
- Except for Main Lode North, changing to 97.5 percentile cut ordinary kriging will drop the grade estimate about 0.2 g/t compared with the KCGM method using the new 10 m bench.
- Main Lode South is sensitive to kriging methodology, highlighting a potential problem related to this style of mineralisation.
- 97.5 percentile cut constrained blocks with constrained grade ordinary kriging gives a result similar to blocks using unconstrained grades (at cut-offs greater than 1g/t).
- Constrained blocks using 97.5 percentile cut ordinary kriging give similar results whether or not grades are constrained. Unconstrained blocks display significant increases in tonnage at cut-offs below 1g/t.

CONCLUSIONS

Updating parameters to 10 m benches but retaining the KCGM kriging method does not affect Caunter lode estimates (except at cut-offs greater than 1.5g/t) or Main Lode North.

Changing to either 97.5 percentile cut ordinary kriging or full regular indicator kriging would have the effect of dropping the grade estimate above 1.5 g/t by 0.25 g/t for Main Lode South (to an expected average grade of 3.25g/t using indicator kriging) and by about 0.2g/t for Caunter lodes. There is no change for Main Lode North.

Following this technical evaluation, KCGM has implemented the 10 m bench semivariogram parameters (resulting in a marked improvement in reconciliation with production) and is evaluating changing from the KCGM kriging method to indicator kriging while continuing to use nominal 0.3 g/t perimeters.

Ultimate performance appraisal will be done by reconciliation with production which will highlight which method is best in terms of predictive capabilities.

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