SYSTÈMES GEOSTAT INTERNATIONAL INC.

Montreal October 1st, 1990

Mr. Dave Tenney
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Dear Dave,

Please find herewith a final version of the report on the geostatistical analysis of Faro drill hole and blast hole data. Our conclusions and recommendations are at the very beginning of the report. Basically we have identified 3 sources of differences between estimates and true values:

- + spatial inference errors: they can only be reduced with more drill holes - numbers are in the report - kriging does not improve estimates that much over inverse distance.
- + oversmoothing of block estimates: a simple "lognormal shortcut" correction of the regular block estimate can reduce this type of error very significantly.
- + uncertainties of the geological model: we found many inconsistencies between the ore type classification of drill hole samples and blast holes specially in types 20 and 30. We can see room for much improvement in a better geological model.

We also show that it is worth implementing a fairly simple (absolute variograms with ordinary kriging) blast hole kriging plan in order to improve recoveries at various cut-offs. In the example that we ran, we have found a 12% increase of recovered tonnage at the 6% cut-off with estimated grade right on target.

I hope that this study can help you improve ore reserve estimation at Faro and its related deposit. I will of course answer any question that you may have or any clarification that you may need.

Yours sincerely,

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for
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GEOSTATISTICAL ANALYSIS OF FARO DRILL HOLE AND BLAST HOLE DATA
PART 2 : ANALYSIS

Respectfully submitted to Curragh Resources Inc.
by Geostat Systems International Inc.
Montreal , October 3rd, 1990

FOREWORD

This is the second part of the geostatistical analysis of Faro drill hole and blast hole data. First part of the study was presented in a report of July 27th, 1990. It defined the objective of that second part of the study namely 1) determine the magnitude of estimation errors for various block sizes and drilling grids 2) determine ways to reduce those estimation errors 3) evaluate other alternatives for processing blast hole data to categorize ore in blasts. This work is covered by the P.O.# D-129004 of August 10th, 1990, from Curragh Resources Inc., to Geostat Systems Int'l Inc.

CONCLUSIONS AND RECOMMENDATIONS

1- In the calculation of tonnes and grade above cut-off, we have identified 3 major sources of differences between estimates derived from D.H. data and values derived from B.H. data in the same area: spatial interpolation errors, oversmoothing of distance weighted estimates and uncertainty of the geological model.

2- **The spatial interpolation errors** can be quantified means of variograms calculated on drill hole bench composite values in the various ore types. If we stick to the current segregation of the quartzite ores (20, 30) and sulfide ores (40 - 70), then the average precision of 25' x 35' x 20' block % Pb + Zn grade estimates at a 95% confidence level are: ± 67% in 20-30 and ± 50% in 40-70 from drill holes on a 140' grid, ± 47% in 20-30 and ± 37% in 40-70 from drill holes on a 70' grid.

3- The above confidence intervals are quite large but they apply to rather small blocks. If we now consider groups of blocks which may represent a month, a quarter or a year production, we have the following average precision (still at a 95% confidence level) for tonnage and %Pb + Zn grade estimates above cut-offs : for a month and with the 140' grid: from ± 44% for tonnage above 6% cut-off to ± 14% for grade above 6% - for a month but with the 70' grid: from ± 22% to ± 7% - for a year with the 140' grid: from ± 13% to ± 4% - for a year with the 70' grid: from ± 6% to ± 2%. Previous figures assume a production made 50% from 20-30 and 50% from 40-70.

4- Precision of estimates for large volumes depends of drilling grid, ore type and cut-off. Uncertainty on tonnage above cut-off increases with cut-off and, at the 6% cut-off, is higher in 20-30 than in 40-70. Uncertainty on % Pb + Zn grade above cut-off is not as bad. It now decreases with cut-off and is less in 20-30 than in 40-70. Also, to get a ± 5% precision on all monthly estimates, we need a drilling grid between 35' and 40' at 3% cut-off and between 15' and 20' at 6% cut-off. The ± 2% yearly precision is easier to achieve: we can get it with just a 50' grid at the 3% cut-off but we need a 25' grid at the 6% cut-off.

more?

5- The above quantification of spatial interpolation errors rests on variograms of D.H. bench composite grades in the two groups of ore types. With close to a thousand data points in each group, those variograms are well defined : relative nugget effects range from 35% (40-70) to 50% (20-30) of total variation, in 40-70, horizontal variations are isotropic with a maximum range of 600'; in 20-30, range along N-S (400') is much longer than along E-W (150'); in both group, there is a strong vertical anisotropy with vertical range not exceeding 60' in 20-30 and 180' in 40-70. Variogram features and the resulting assessment of the magnitude of spatial interpolation errors are confirmed by a D.H. bench composite reuse study. For example, in 20-30, out of 719 reestimated composites, 480 (67%) have an estimation error less than the predicted standard error and 683 (95%) have an estimation error less than twice the predicted standard error: this is an almost perfect fit of estimated and actual errors.

6- Variograms of D.H. bench composites also indicate only minor differences between kriged estimates and inverse distance estimates for the same blocks. The power of inverse distance which gives results closer to kriging is 1.4 in 20-30 and 1.75 in 40-70.

7- The oversmoothing of distance weighted block estimates is quite noticeable in the Faro long term block model: if you apply a cut-off on block estimates derived from D.H. bench composites, you always find more tonnes and a lower grade then what is indicated by the distribution of blast holes in the same area. In 20-30, tonnage differences are as much as 30% (5% cut-off) and grade differences reach 17%. In 50-70, maximum tonnage and grade differences are respectively 14% and 7%.

8- A way to overcome the oversmoothing of straight block estimates is to infer the likely proportion and grade of blast holes above the cut-offs in each block. A simple correction of block estimates dubbed "lognormal" short-cut reduces maximum tonnage differences to 8% in 20-30 and 3% in 50-70. With that correction, maximum grade differences are only 5% in 20-30 and 2% in 50-70.

9- All the above conclusions assume that the "geological model" is correct e.g. when we assign a code 20 to a block (and thus, we infer its grade from just 20-30 D.H. bench composites around), the type of ore in that block is actually 20 (or 30). To validate that assumption, we have compared the ore type of a D.H. bench composite to the ore type of the nearest B.H. (in the same bench and at a distance of less than 20'). We found that the classification of the predominantly high grade types 50 + 60 + 70 is consistent from drill holes to blast holes since nearly 70% of the D.H. composites of that type have a B.H. of the same type next to them. However, we have more problems with types 20 and 30: in that case, more than 50% of the D.H. composites of those types have a B.H. of type 50-70 nearby. We suggest that the criteria used to classify D.H. samples and B.H. of type 20-30 be revised so that we have more consistency in the classification of the two types of samples.

10- Another suggestion related to the geological model is to separate type 40 from types 50, 60 and 70 in the estimation of blocks even if they all refer to sulfide ore. Statistics of type 40 D.H. composite grade values indicate that they are much lower than for the other categories of sulfide ores. As a result, there is a danger to underestimate a type 50-70 block with a type 40 composite next to it and overestimate a type 40 block with a type 50-70 composite nearby. In fact, in the comparison of block estimates with B.H. values in those blocks, better results were achieved after isolating type 40 composites (and type 55 blast holes).

11- This geostatistical analysis of D.H. bench composites data can be extended to blast holes. The idea here is to see whether there is a better procedure to delineate ore limits in blasts than just contour individual blast hole grades. From the test data set of about 2000 blast holes in the south part of benches 3450, 3470 and 3490, we found that:

+ if we krige the grade of blast blocks from blast holes and then apply the cut-off on those blast block estimates, the actual grade of the material that we recover is the estimated grades.

+ if we contour individual blast hole values, the actual grade is less than the expected grade (in the example that we ran we noticed a 8.5% shortfall at the 6% cut-off). Moreover, we get less tonnes than if we do the selection on kriged estimates (12% in our example).

+ recovery based on kriged blast blocks estimates is even better if we process blast holes of type 20-30, 50-60-70 and 40-55 separately.

+ blast block kriging can easily be implemented with blast hole variogram models. Horizontal variograms of groups of a few hundred of blast holes around a blast are quite interpretable. They generally show the same features as the corresponding variograms of D.H. bench composites. In particular, their nugget effect is the same hence it looks like the sampling precision of blast holes is as good as that of drill holes.

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1-1 Statistical analysis of D.H. bench composite data

The current file of DH 20 ft bench composite data that we received from Curragh Resources Inc. has values for 7333 composites from 419 drill holes (from 65-53 to 90F93). For each composite, we have the 3 coordinates of the center point of the composite, its principal rock type (from 20 to 190 - 1608 composites have an undefined rock type of -1), the calculated grades for %Pb, %Zn and %Pb+Zn and the calculated specific gravity (with some undefined values of -1.0 too).

Out of this total, only 1730 composites are in the "mineralized" rock types i.e. 20,30,40,50,60,and 70 (3783 composites are in rock type 100 i.e. the top and bottom phyllites - 407 of them have a non-zero Pb+Zn value - surprisingly,31 composites in this supposedly "waste" rock type have a Pb+Zn grade above 6% with an overall maximum of 9.07 %) - In the current long term model, mineralized composites are grouped in two categories : "quartzite" ore (20+30) and semi-massive and massive sulfide ore (40+50+60+70) - Figure 1 is a map of those mineralized composites in one of the bottom bench of the pit, bench 3450, between elevations 3450 and 3470 '. On this map, we can see the 140' drilling grid in the center and north part of the pit (now mined-out) and the 70' drilling grid in the south part (now being mined). We see also that, as a general rule, the quartzite ore (20 = circles and 30 = triangles) is around the deposit whereas the sulfide ore (40 = plus, 50 = cross ,60 = diamond and 70 = arrow) is in the center. After producing this map from the composite file , we noticed many discrepancies between the rock type of composites in the file and the interpreted limits of the different ore types on the same bench as shown on a map received from the company. Staff at Curragh has been notified of these discrepancies (our fax of Aug. 21).

We can calculate summary statistics of composite values in the different mineralized rock types. They are shown on Table 1 for quartzite composites and table 2 for sulphide composites. Typical histograms of %Pb+Zn are on figures 2 (type 40 - skewed distribution) and 3 (type 50 - normal distribution). Our conclusions :

- distributions of Pb+Zn,Zn and Pb values are positively skewed and lognormal like in the low grade rock type 40 (Figure 2). Distributions are symmetric and normal like in the rather high grades rock types 50, 60 and 70 (Figure 3). Distributions of values are slightly skewed in 20 but rather normal in 30.

- except for the difference in shape described above, parameters of the distributions in 20 and 30 are fairly similar (there is a little more lead in 30) and it makes sense to group those two ore types in the estimation of blocks.

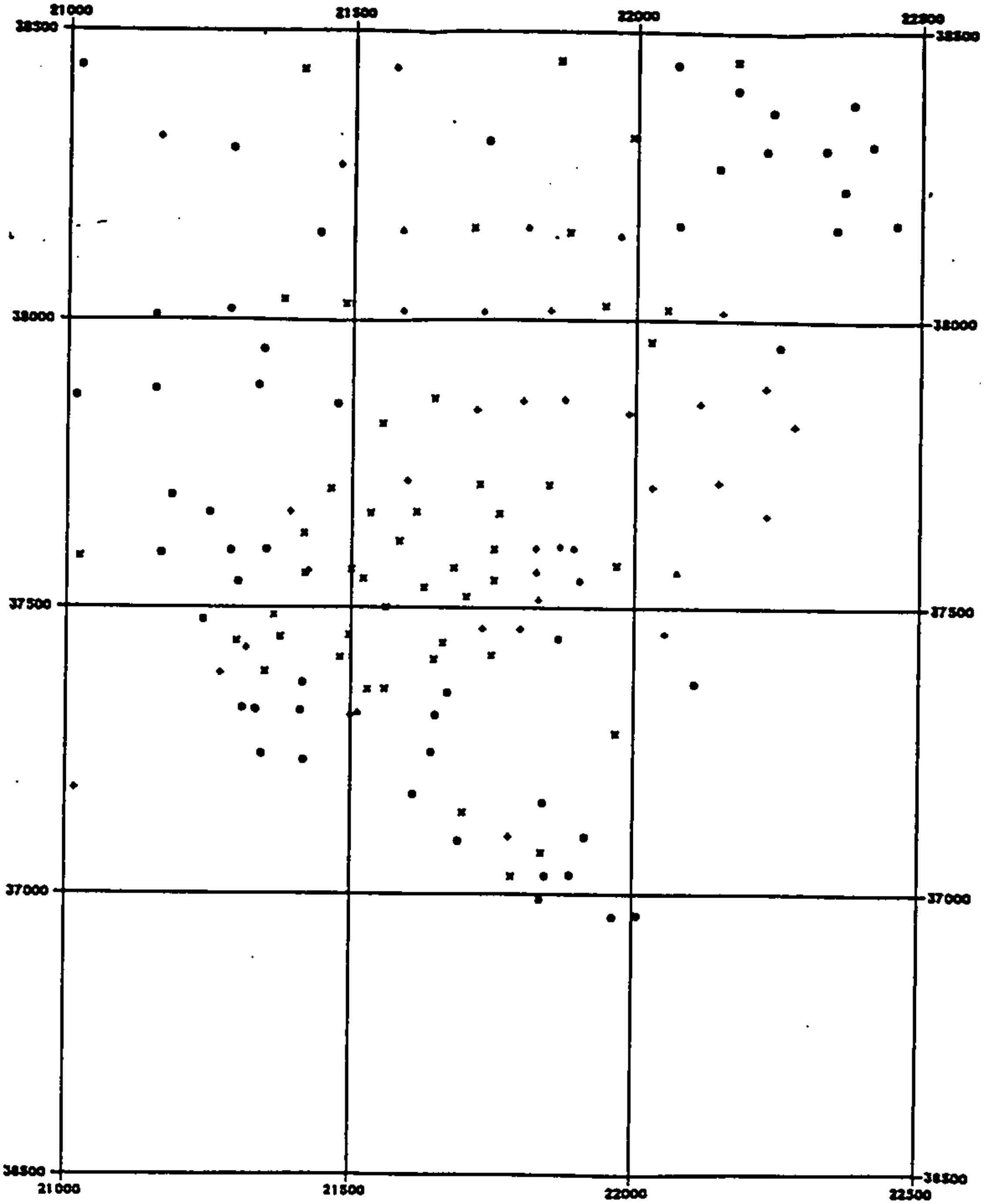
- on the other hand, the distributions of values in 40 are quite different from those in 50, 60 and 70 and it does not seem logical to put all those composites in the same group. 40 has the lowest values of all ore types whereas 50, 60 and 70 have the highest values. With this scheme, we may have potential problems when a high grade block 50 is estimated with a low grade composite 40 nearby and vice-versa

- the highest relative dispersions (coefficients of variation above 60 %) are in the low grade 40 . Then we have about the same dispersion in 20 and 30 (coefficients of variation between 55 and 60 %) . The lowest dispersion is in the high grades 50 , 60 and 70 (coefficients of dispersion between 30 and 40 %) . Hence , for the same drilling grid , precision of block estimates is expected to be better in high grade ore (50+60+70) than low grade ore (20+30) .

- production Pb+Zn cut-off grades (3,4,5 and 6%) are quite high compared to mean values of Pb+Zn in some ore types . The high grade cut-off of 6% is above the median of distributions in 40 , 20 and 30 . Then we can expect more difficulties in locating the high grade ore in those ore types .

There is a high degree of correlation between %Zn and %Pb in all ore types . Correlation coefficients range from 0.75 in 50 (Figure 4) to 0.86 in 20 (Figure 5) . Type 20 is also the ore type where the average ratio %Zn/%Pb is the highest (2.0 vs 1.3 to 1.6 in the other ore types) .

Figure 1 Map of "mineralized" DH composites in bench 3450. (20 = circle, 30 = triangle, 40 = plus, 50 = cross, 60 = diamond, 70 = arrow)



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	REVISED BY	DATE	CURRAGH RESOURCES INC.
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	DWG		

Figure 2 Histogram of Pb+Zn grades of composites in type 40

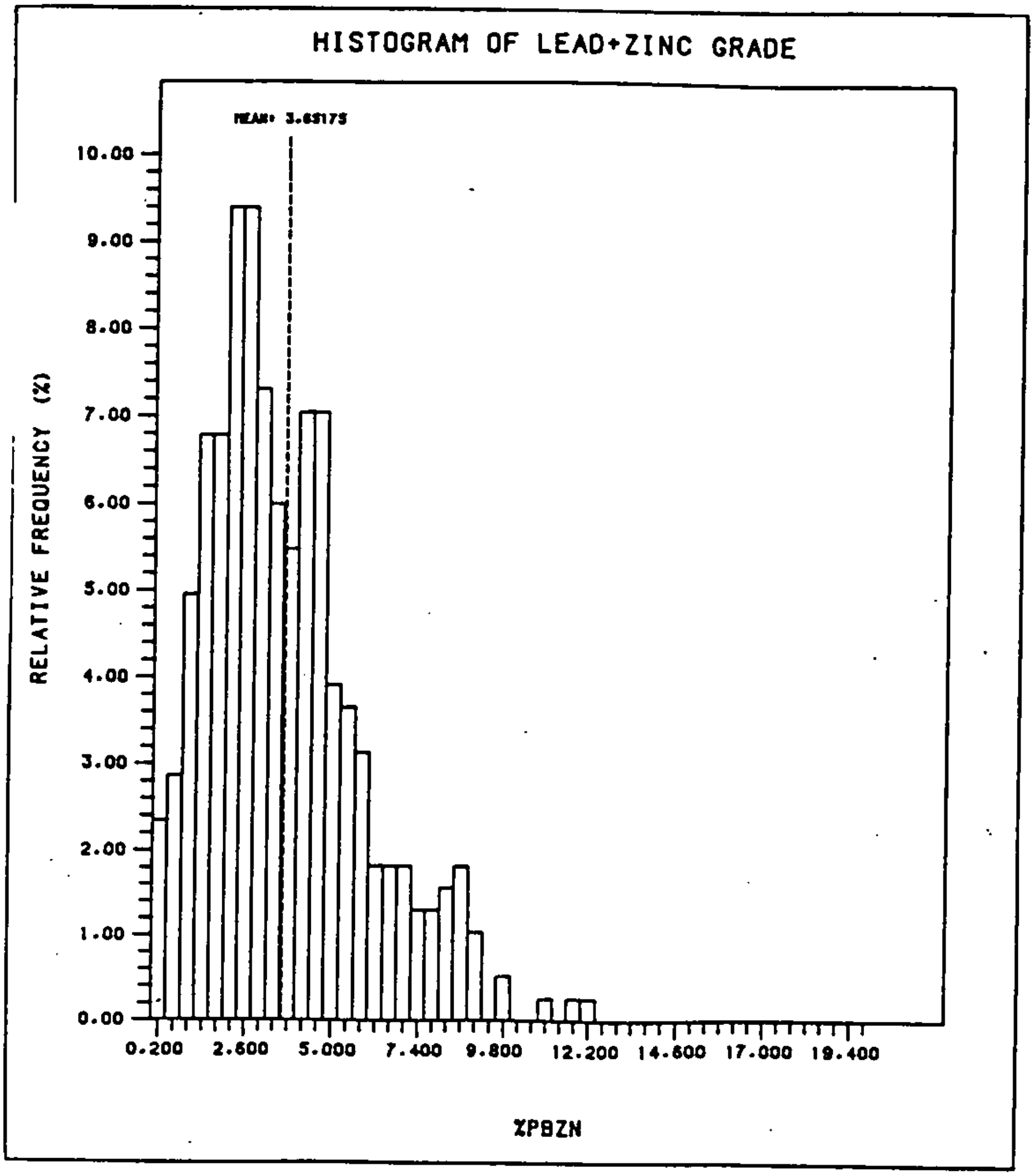


Figure 3 Histogram of Pb+Zn grades of composites in type 50

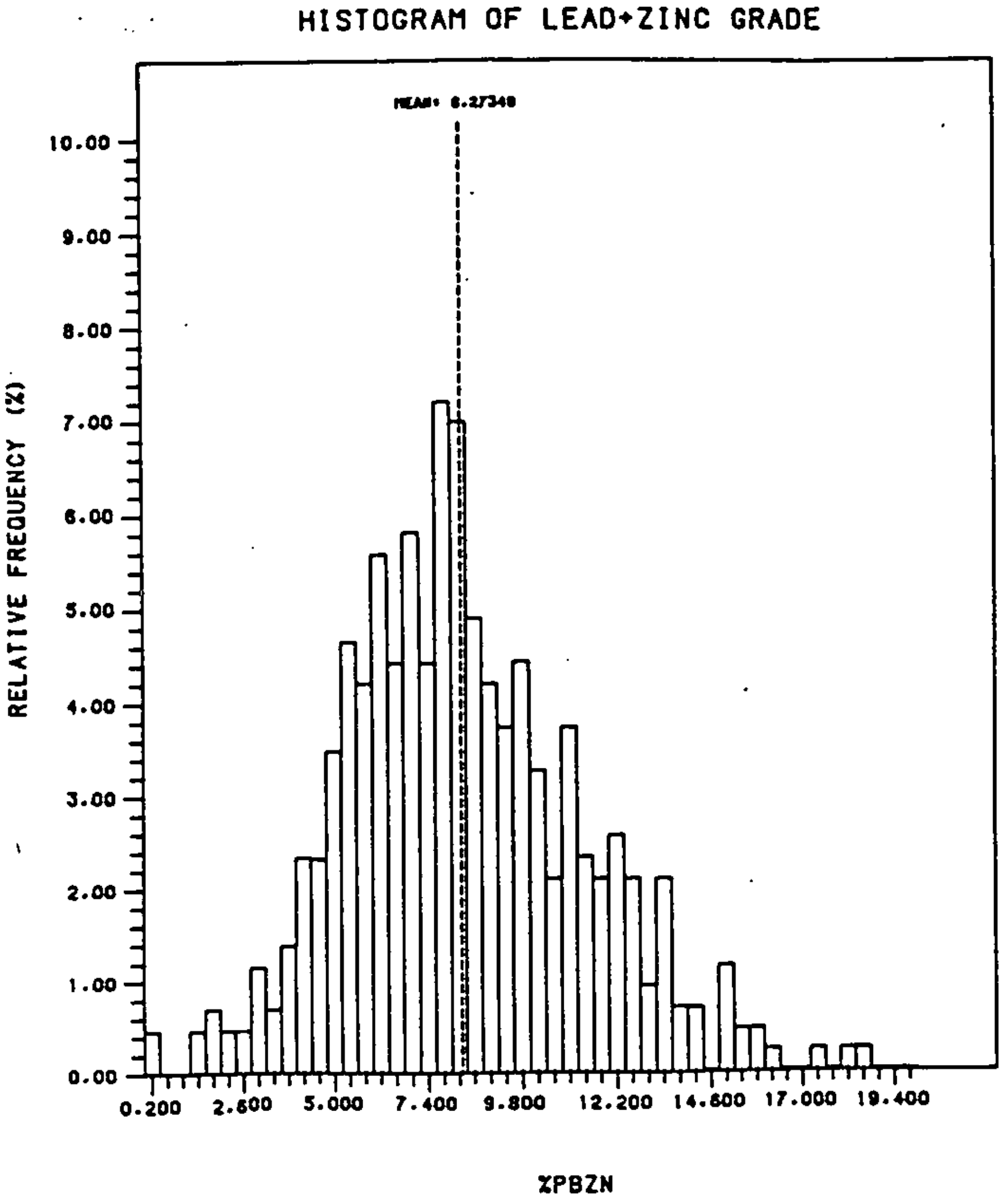


Table 1 Statistics of %Pb+Zn composite data

	20	30	20+30	40	50	60	70	40-70
Number	639	103	742	383	430	109	66	988
Minimum	0.0	0.0	0.0	0.0	0.0	3.0	1.84	0.0
Percentile 5%	1.12	1.36	1.04	0.77	3.84	4.75	3.64	1.32
Percentile 16%	2.40	2.19	2.38	1.56	5.42	6.40	5.75	2.62
Percentile 50%	4.73	5.33	4.81	3.22	7.98	9.40	9.33	6.47
Percentile 84%	7.84	8.62	7.96	5.71	11.45	12.06	12.37	10.40
Percentile 95%	10.12	11.09	10.23	8.17	13.48	14.70	14.39	13.12
Maximum	16.10	12.97	16.10	12.34	18.64	17.49	15.63	18.64
Mean	5.10	5.55	5.16	3.65	8.27	9.44	9.12	6.67
Standard deviation	2.81	3.17	2.87	2.22	3.04	2.98	3.11	3.67
Coefficient of variation	55	57	55	61	37	31	34	55

Table 2 Statistics of %Zn composite data

	20	30	20+30	40	50	60	70	40-70
Number	639	103	742	383	430	109	66	988
Minimum	0.0	0.0	0.0	0.0	0.0	1.77	1.23	0.0
Percentile 5%	0.68	0.09	0.58	0.36	2.00	2.29	1.85	0.82
Percentile 16%	1.59	1.26	1.57	0.99	3.13	3.52	3.30	1.63
Percentile 50%	3.16	3.19	3.16	2.00	4.97	5.41	5.57	3.90
Percentile 84%	5.15	5.66	5.21	3.48	7.26	6.77	7.02	6.30
Percentile 95%	7.01	6.92	7.00	5.14	8.57	8.25	8.76	8.17
Maximum	10.27	9.03	10.27	7.56	12.04	10.40	9.38	12.04
Mean	3.40	3.40	3.40	2.25	5.10	5.33	5.42	4.04
Standard deviation	1.90	2.03	1.92	1.39	2.03	1.79	1.88	2.27
Coefficient of variation	56	59	56	62	40	33	34	56

Table 3 Statistics of %Pb composite data

	20	30	20+30	40	50	60	70	40-70
Number	639	103	742	383	430	109	66	988
Minimum	0.0	0.06	0.0	0.0	0.0	1.07	0.61	0.0
Percentile 5%	0.36	0.79	0.33	0.21	1.35	2.07	1.23	0.34
Percentile 16%	0.74	1.26	0.74	0.42	2.06	2.79	2.36	0.95
Percentile 50%	1.50	2.09	1.56	1.23	3.05	3.95	3.70	2.57
Percentile 84%	2.65	3.31	2.80	2.38	4.33	5.50	5.18	4.11
Percentile 95%	3.55	4.07	3.69	3.14	5.32	6.71	5.78	5.32
Maximum	5.83	5.96	5.96	4.78	7.35	7.59	7.11	7.59
Mean	1.69	2.15	1.76	1.40	3.17	4.11	3.70	2.63
Standard deviation	1.00	1.29	1.05	0.96	1.21	1.38	1.40	1.54
Coefficient of variation	59	60	60	68	38	33	38	58

Figure 4 : Scattergram of Zn and Pb composite values in ore type 50

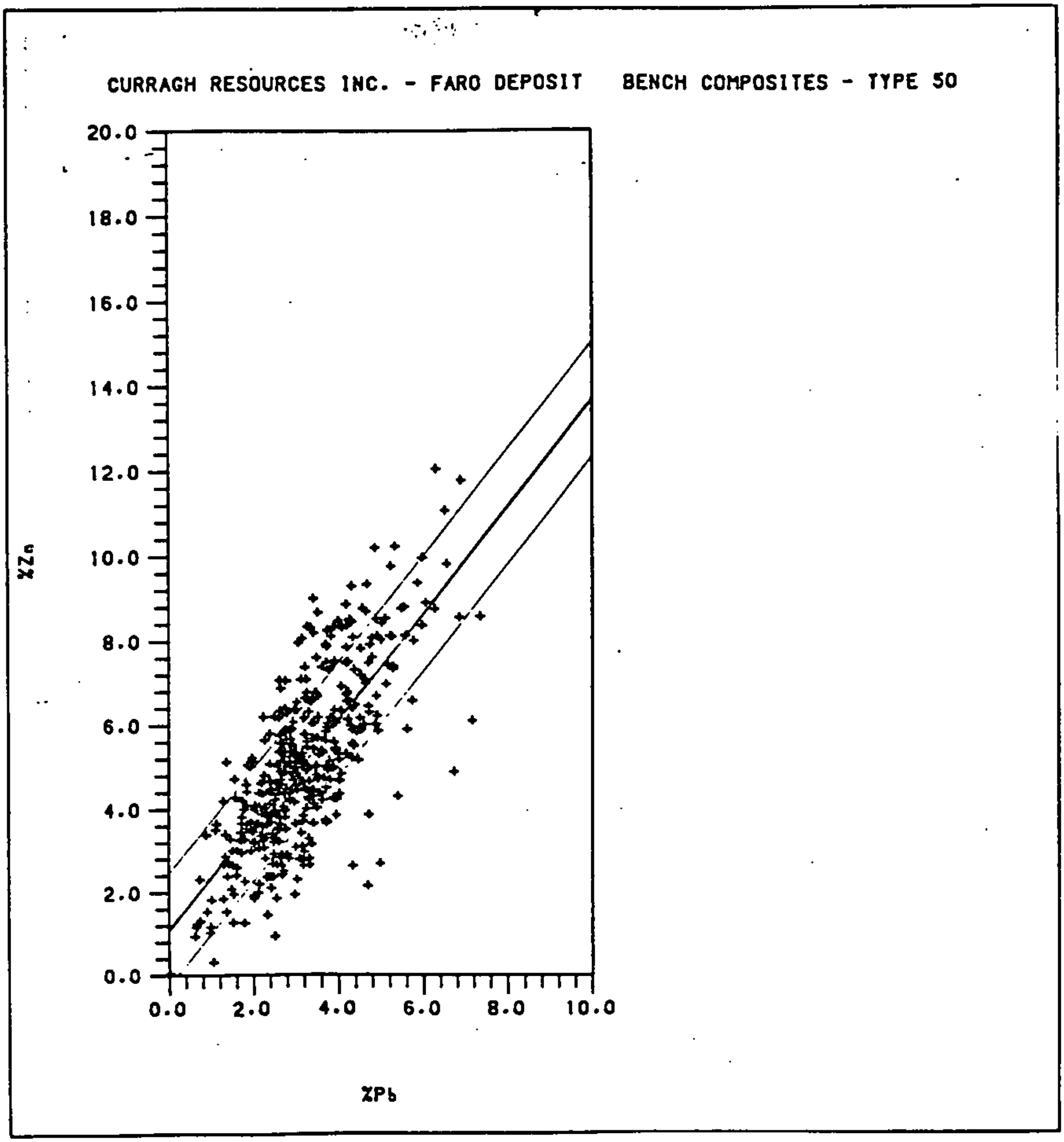
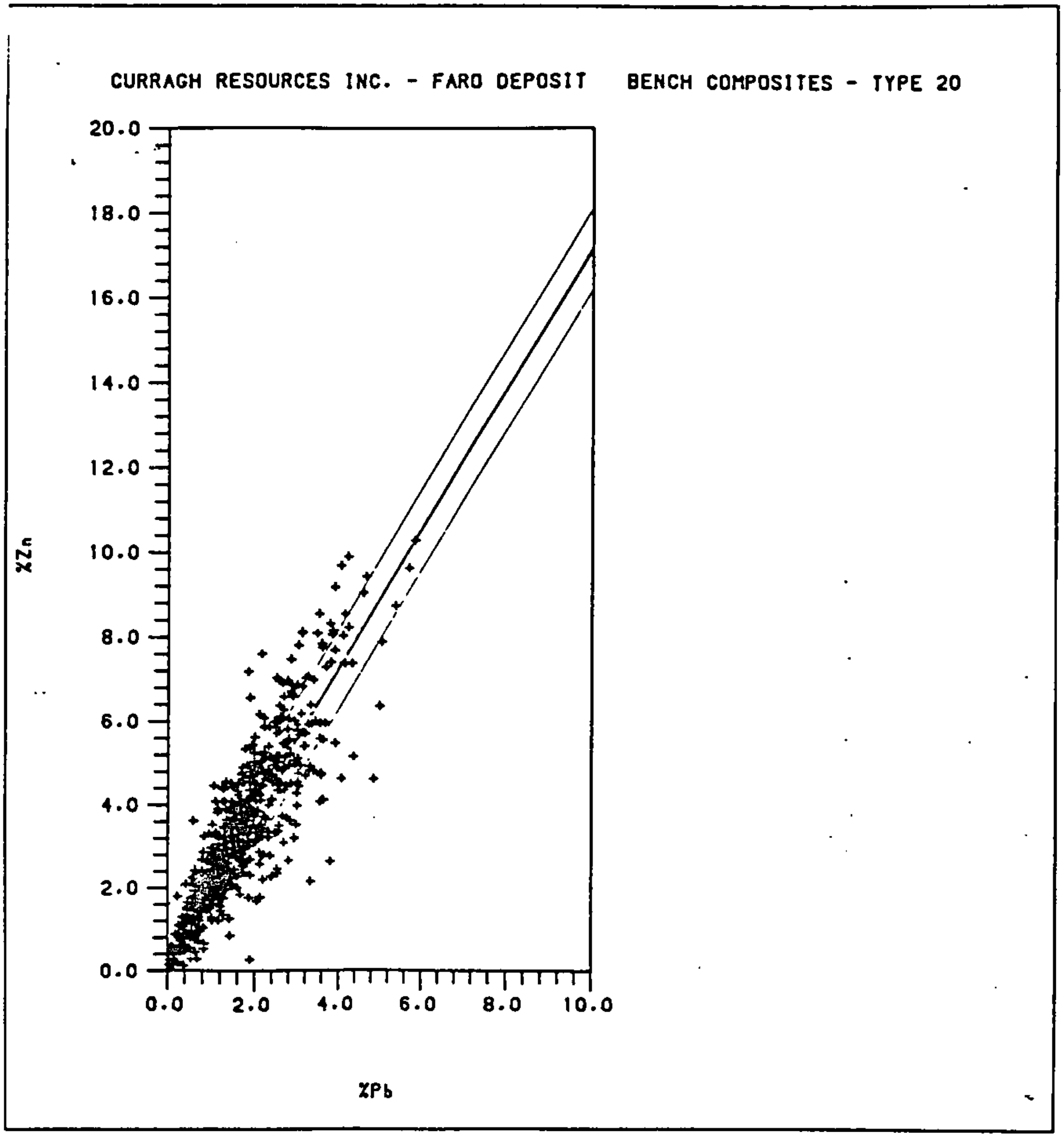


Figure 5 : Scattergram of Zn and Pb composite values in ore type 20



1-2 Variogram analysis of D.H. bench composite data

Variograms are diagrams showing the average difference between sample values as a function of the distance between samples . Variograms are computed along specific directions since the rate of increase of differences with distance may not be the same in all directions . Variograms are helpful in 1) assessing the magnitude of errors in the estimation of blocks 2) determining the most suitable estimation method for the blocks (e.g. choosing between 1/d or $1/d^2$) .

To keep consistent with the estimation method currently used at Faro , we have computed variograms of the grades and SG of bench composites in ore types 20-30 and 40-70 separately . Note that there is not enough composites in types 30, 60 and 70 to derive meaningful 3D variograms specifically in those ore types . However , it is quite feasible to have specific variograms for type 40 (and others for types 50,60 and 70 together) .

In both cases , variograms are computed along the vertical direction of most D.H. (angular tolerance 10 degrees - step for distances 20 ') and the four principal directions of the horizontal benches i.e. E,NE,N and NW (tolerance 45 degrees - step for distances 75 ') . In addition the omnidirectional variogram (tolerance 180 degrees) and an average horizontal variogram are computed . Variograms are of the absolute type with no transformation of raw data nor clipping of some high values .

Figure 6 shows the vertical variogram of %Pb+Zn together with the omnidirectional variogram in ore type 20-30 . We can notice an apparent nugget effect of about 4 (50% of overall variation) and higher differences along vertical than average (anisotropy) . Vertical range does not seem to exceed 60' . On figure 7 , we have the horizontal variograms of the same data : nugget effect is still very much apparent as well as some anisotropy . In this case , for short distances , the lowest curve (best continuity) is along N-S and the highest one (worst continuity) is along E-W . Also , NE is below average and NW is above average . A suitable model for the variogram of %Pb+Zn in 20-30 would be the sum of a nugget effect of 4 and a spherical function of sill 4.2 , long range 400' along N-15°-E , intermediate range of 150 ' along E-15°-S and short range of 60' along vertical . Variograms for the %Zn and %Pb grades in 20-30 are of the same type (Table 4) : the only noticeable difference is for %Pb with a truly N-S long range of 500'.

In 40-70 , the vertical variogram of %Pb+Zn is also above the omnidirectional variogram (Figure 8) . Apparent nugget effect is less than in 20-30 (35 % of overall variation) and vertical range is longer (180 ') . Along horizontal directions of the benches (Figire 9), variograms are almost linear with no apparent anisotropy . Model used is the sum of a nugget effect of 4 , a short range spherical function (60' horizontal and 40 ' vertical) and a long range spherical function (600' horizontal and 180 ' vertical) . Models for %Pb and %Zn are very much similar (Table 4) .

In conclusion , for both groups of ore types , it is feasible to define meaningful variograms for DH bench composite data . Horizontal ranges are generally several times the drill hole spacing . The only exception is with 20-30 where the E-W range is of the same order of magnitude as the original spacing between holes . Hence for this type of ore , additional holes at 70' distance on E-W section lines is quite an improvement . Also relative nugget effects are higher in 20-30 than in 40-70 which means that grade interpolation is more difficult in this type of ore (in other words , for the same drilling grid and block size , relative errors are likely to be higher)

Figure 6 Vertical and omnidirectional variogram of %Pb+Zn in type 20-30

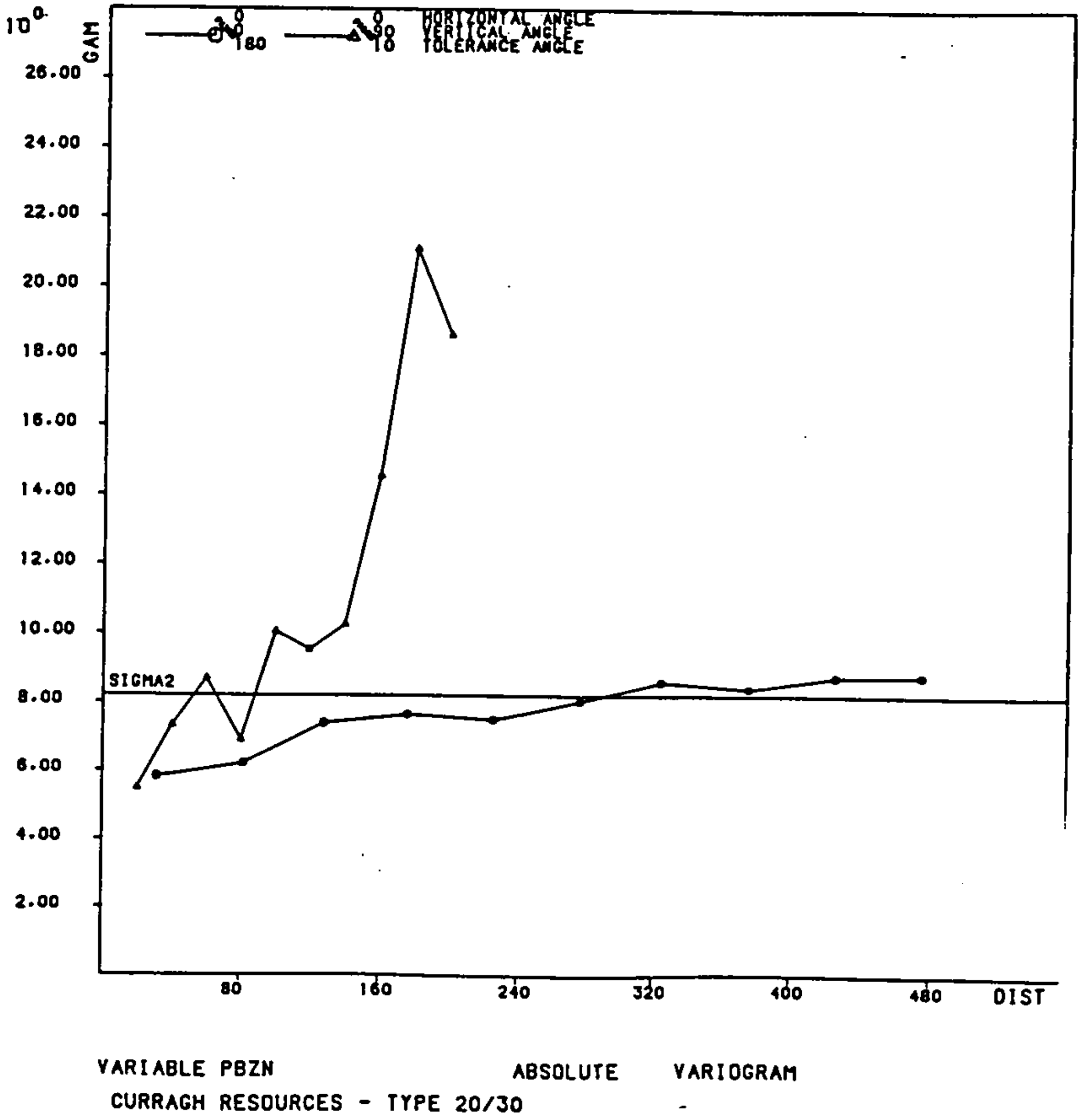
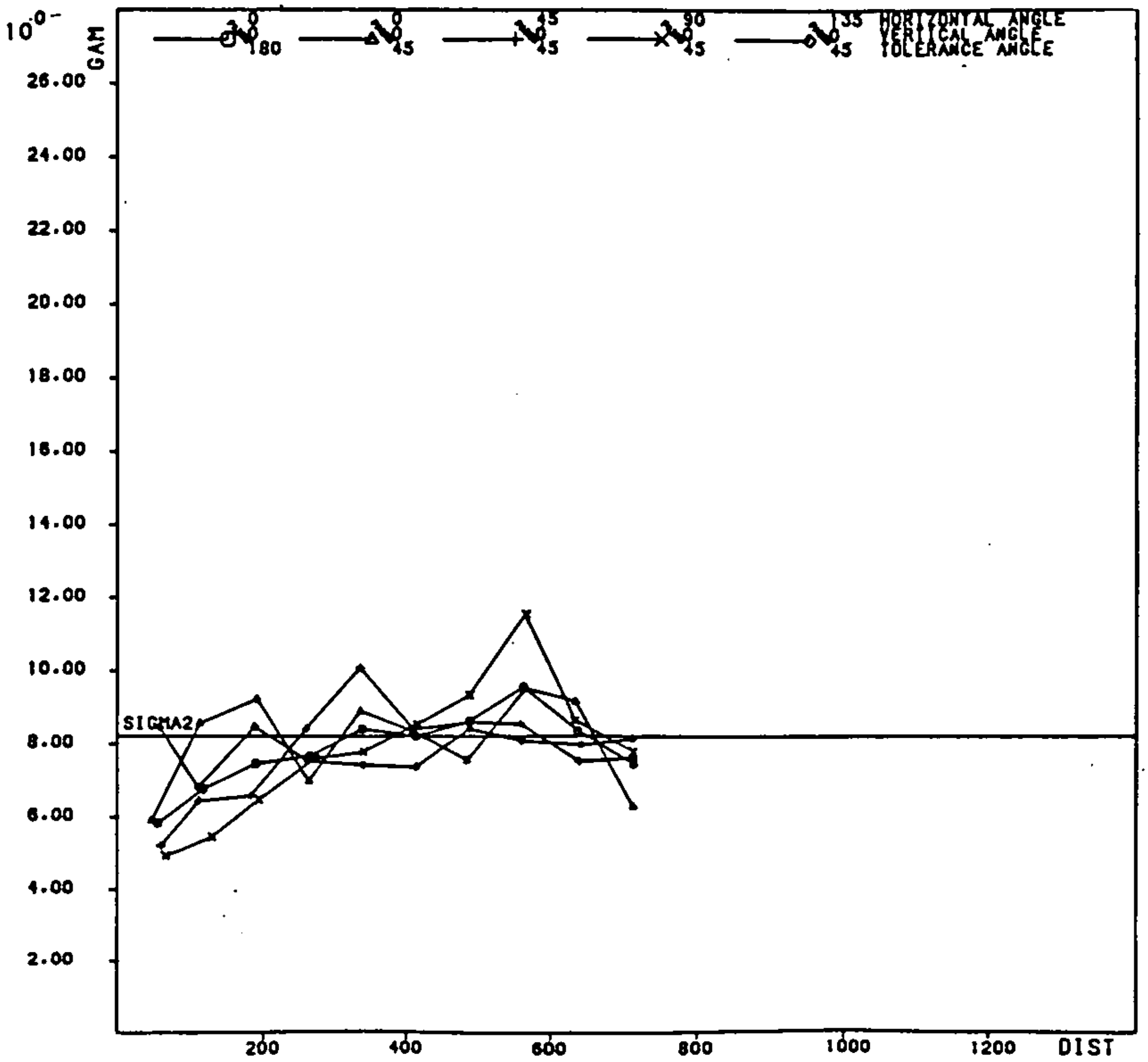


Figure 7 Horizontal variograms of %Pb+Zn in type 20-30



VARIABLE PBZN ABSOLUTE VARIOGRAM
CURRAGH RESOURCES - TYPE 20/30

Figure 8 Vertical and omnidirectional variogram of %Pb+Zn in type 40-70

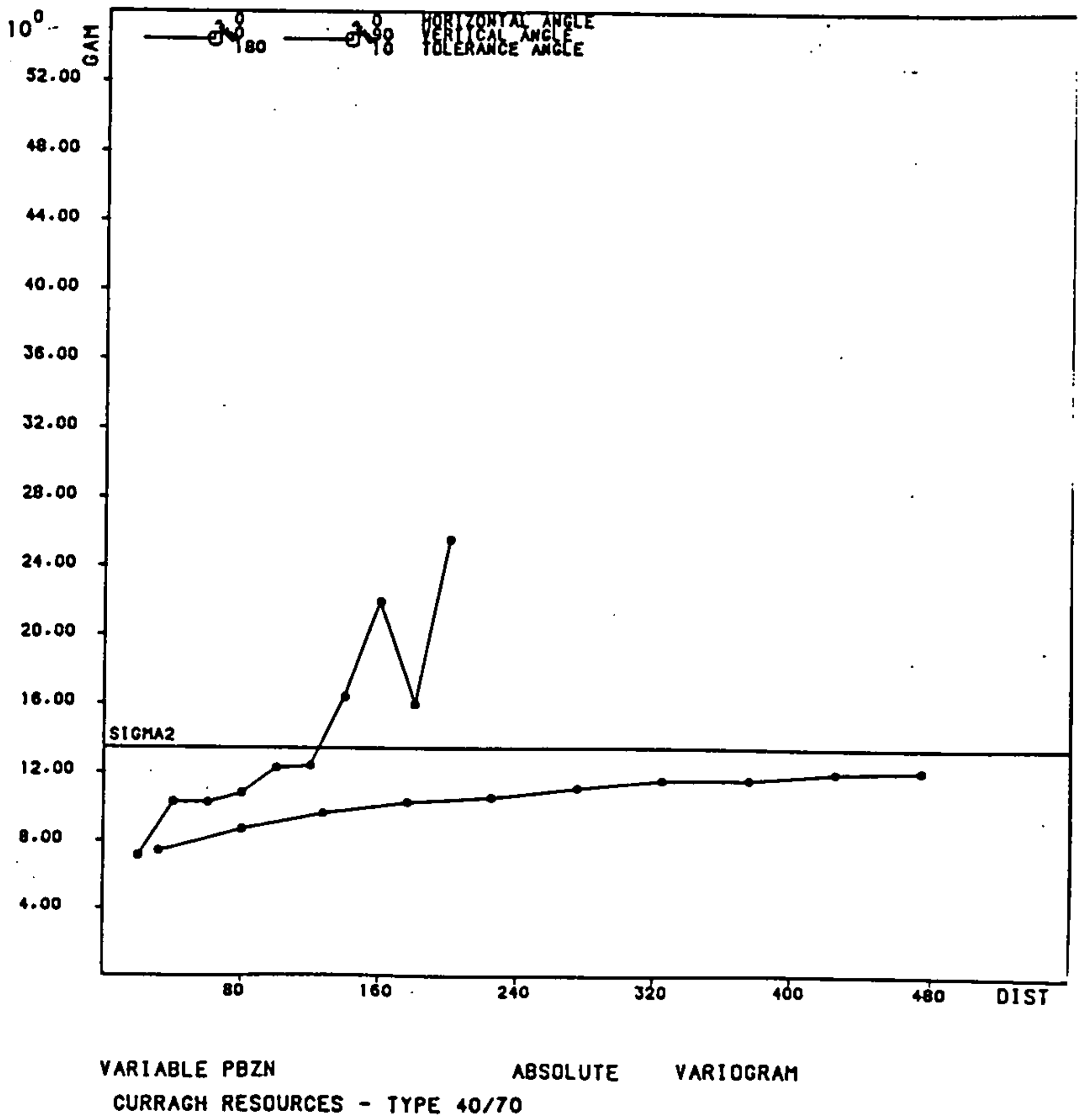


Figure 9 Horizontal variograms of %Pb+Zn in type 40-70

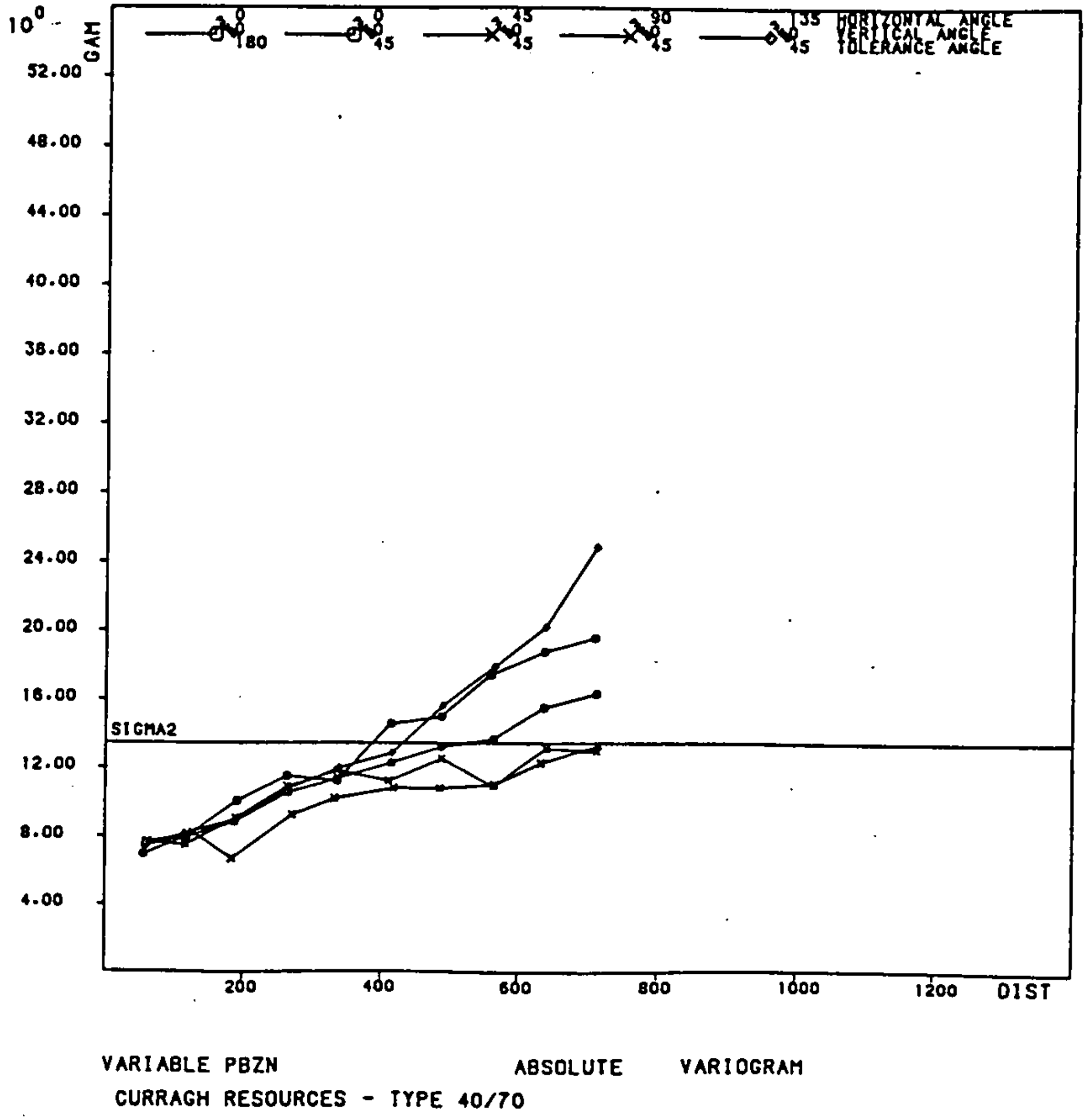


Table 4 Variogram model parameters

Ore type	20-30		40-70			
Parameter	%Pb+Zn	%Pb	%Zn	%Pb+Zn	%Pb	%Zn
Nugget effect	4.0	0.5	1.5	4.0	0.8	1.3
Spherical 1						
Sill	4.2	0.6	2.2	2.0	1.6	1.5
Long range	400'	500'	400'	60'	600'	120'
Int. range	150'	150'	150'	60'	600'	120'
Short range	60'	60'	60'	40'	200'	80'
Spherical 2						
Sill				2.5		2.4
Long range				600'		600'
Int. range				600'		600'
Short range				40'		80'
Spherical 3						
Sill				5.0		
Long range				600'		
Int. range				600'		
Short range				180'		
Total sill	8.2	1.1	3.7	13.5	2.4	5.2

1-3 Standard errors for block estimates from D.H. composites

In the current block estimation method , the average grades and SG of 25' x 35.35' x 20' blocks are estimated by inverse distance using the bench composites of the similar ore type around the block . As explained above , matching of block and composite ore types is done with only two categories : 20+30 and 40+50+60+70 .

With the variogram models of bench composite data in the two categories , it is possible to quantify the precision of such block estimates . The common practice is to measure precision by a standard error . If the block estimate is 7.53 %Pb+Zn and the standard error is 1.40% Pb+Zn , then :

- there is a 68% probability that the true block grade lies somewhere between 7.53 - 1.40 = 6.13 %Pb+Zn and 7.53 + 1.40 = 8.93 %Pb+Zn
- there is a 95% probability that the true block grade lies somewhere between 7.53 - 2x1.40 = 4.73 %Pb+Zn and 7.53 + 2x1.40 = 10.33%Pb+Zn

Probabilities of 68% (+/- 1 standard error) and 95% (+/- 2 standard errors) are derived from a normal model applied to the distribution of errors . In that case , we could say that the precision of the estimate at a 68% confidence level is 1.40/7.53 = 18.5% and the precision at a 95% confidence level is 2x1.40/7.53 = 37% .

If we do the kriging of the average Pb+Zn grade of the blocks using the variogram models described in the previous section , we get the following standard errors :

-if the drilling grid is 70' x 70' , standard errors vary from 0.80%Pb+Zn (block centered on a drill hole) to 1.20%Pb+Zn (block in between drill holes) in types 20-30 and from 1.13%Pb+Zn to 1.25%Pb+Zn in types 40-70 .

-if the drilling grid is 140' x 140' , standard errors vary from 1.17%Pb+Zn (block centered on a drill hole) to 1.73%Pb+Zn (block in between drill holes) in types 20-30 and from 1.36%Pb+Zn to 1.68%Pb+Zn in types 40-70 .

In type 20-30 , because of the horizontal anisotropy of variograms , blocks between two holes on a N-S line are better estimated than blocks between two holes on an E-W line (standard errors of 1.06% and 1.18% respectively for the 70' grid and 1.28% and 1.73% for the 140' grid).

If we just keep the worst case block to get a single precision attached to a given drill hole grid , we have the following <u>95% confidence precisions :</u>

- in type 20-30 : 67% precision for 140' grid and 47% precision for 70' grid .
- in type 40-70 : 50% precision for 140' grid and 37% precision for 70' grid .

In order to illustrate the distribution of standard errors in blocks , we have kriged the %Pb+Zn grade of blocks in two test zones of bench 3450 . First , we plotted all the composites 20-30 and 40-70 in the bench and we defined approximate enveloppes around each type of composite (Figure 10) . We filled those enveloppes with the 25' x 35.35' blocks and we kriged the average %Pb+Zn grade of each block using composites of the same type around . The search ellipsoid used in each case is defined from the anisotropy of variograms : in 20-30 , the long radius is 400' along N-15-E , the intermediate radius is 150' along E-15-S and the short radius is 60' along vertical . In 40-70 , the long radius is 300' along any horizontal direction and 90' along vertical . Figure 11 is a map of block estimates . Figure 12 is a map of block standard errors . The average standard error is 1.59 %Pb+Zn in 20-30 and 1.73 %Pb+Zn in 40-70 . Those numbers confirm the precision values given above .

We can also use the same test zones to compare I.D. (inverse-distance) and kriged estimates . We have reestimated the %Pb+Zn of block in each ore category by inverse distance methods using various powers of the inverse distance composite-block . Each time we compared our I.D. estimates with kriged estimates for the same blocks and we can compute the average absolute difference for all blocks (Table 5) . We see that the average difference is minimal for a power of about 1.4 in type 20-30 (average difference = 0.37%) and for a power of about 1.75 in type 40-70 (average difference = 0.48 %) . We can also compare reserves above various cut-offs with the two methods (Table 6) .

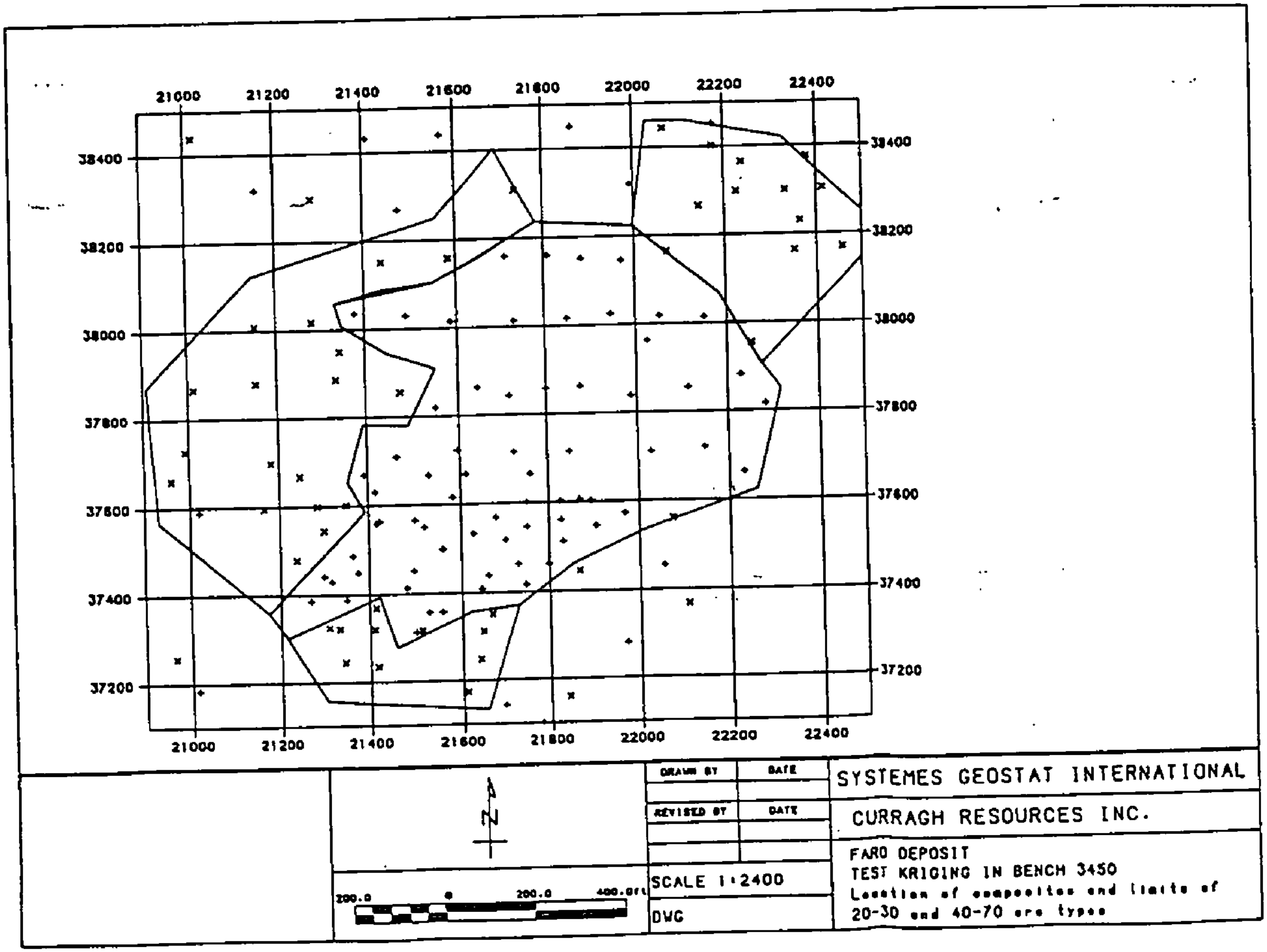


Figure 10 Test kriging in bench 3450 : map of 20-30 (cross) and 40-70 (plus) composites with limits of test zones for each type

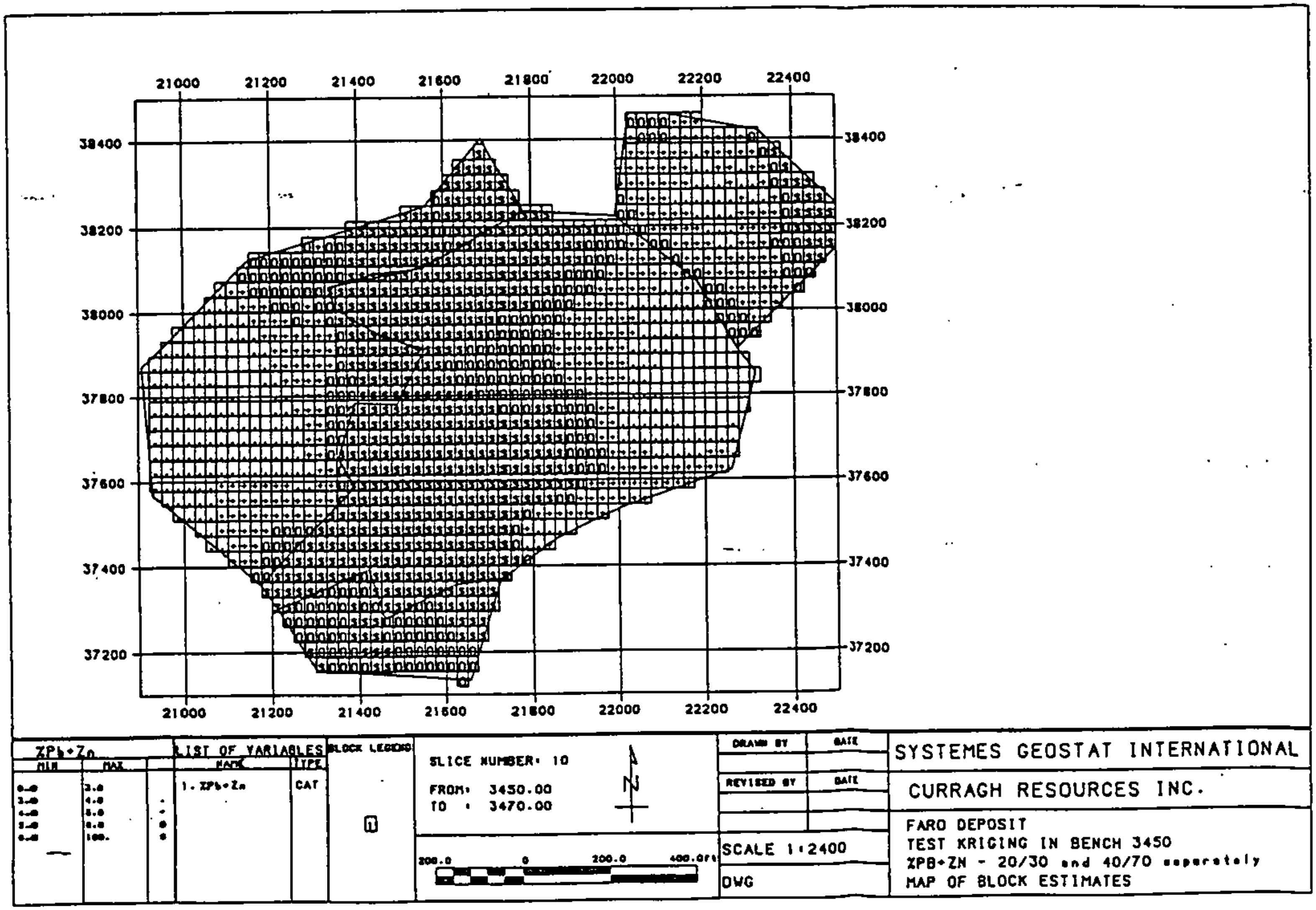


Figure 11 Test kriging in bench 3450 : map of block kriged estimates of %Pb+Zn (see legend for explanation of symbols)

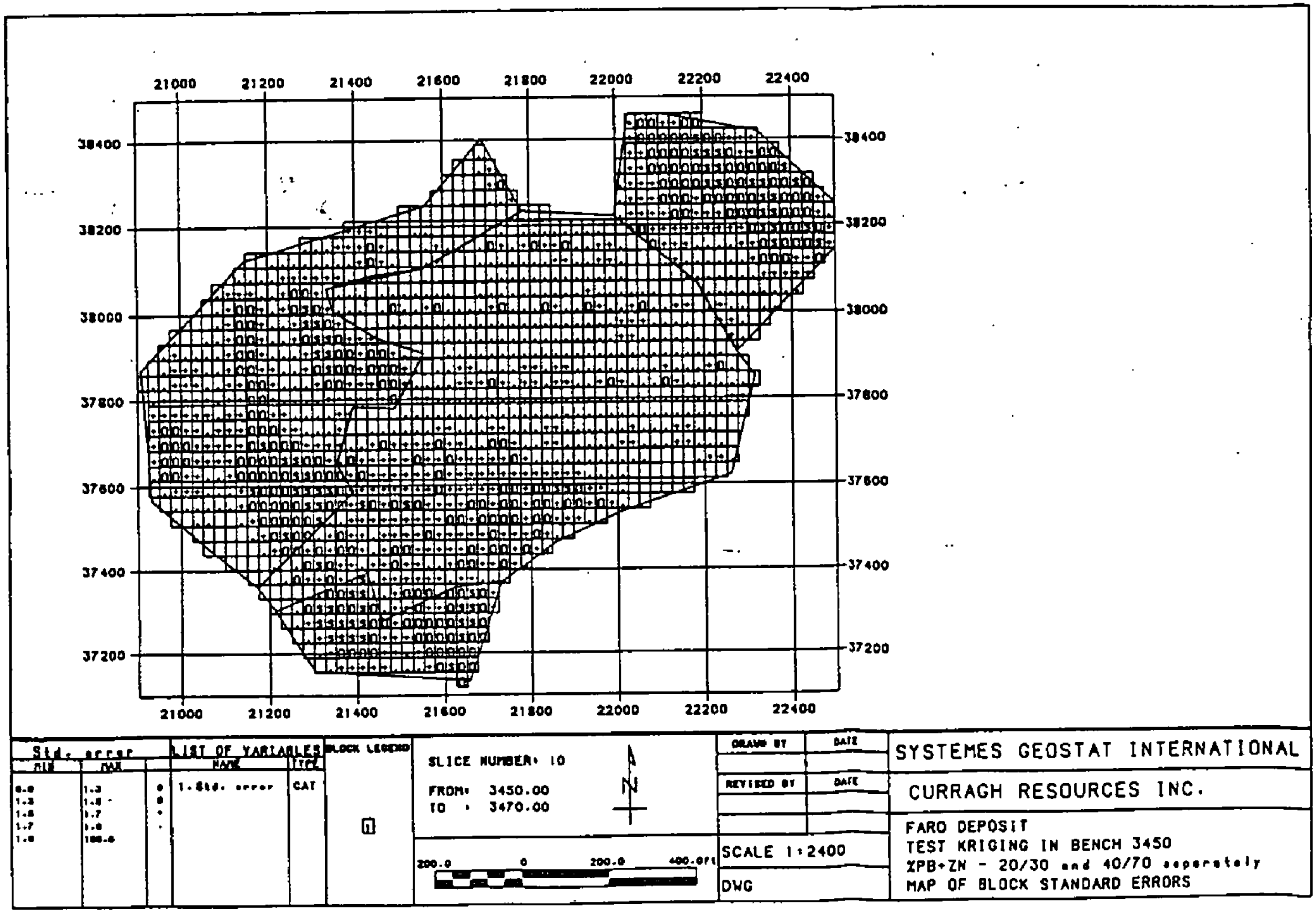


Figure 12:Test kriging in bench 3450 : map of block kriging standard error for estimates of %Pb+Zn (see legend for explanation of symbols)

Table 5 Average absolute difference between kriging and I.D. with various powers of inverse distance for block estimates of %Pb+Zn in the two ore types

Power	0.5	1.0	1.5	2.0	2.5
20-30	0.45	0.38	0.37	0.41	0.47
40-70	0.58	0.52	0.48	0.48	0.52

Table 6 Number of blocks above cut-offs with kriging and I.D. with various powers of inverse distance for block estimates of %Pb+Zn (Type 20-30 : total 699 blocks)

Estimate Cut-off	Kriging	I.D. 0.51.0	1.5	2.0	2.5	
3%Pb+Zn	675	695	687	675	667	654
4%Pb+Zn	517	565	553	523	503	491
5%Pb+Zn	324	333	350	359	359	350
6%Pb+Zn	144	122	132	140	149	164

Table 6 Number of blocks above cut-offs with kriging and I.D. with various powers of inverse distance for block estimates of %Pb+Zn (Type 40-70 : total 699 blocks)

Estimate Cut-off	Kriging	I.D. 0.51.0	1.5	2.0	2.5	
3%Pb+Zn	668	662	659	657	651	648
4%Pb+Zn	598	576	578	575	577	579
5%Pb+Zn	485	486	485	487	483	476
6%Pb+Zn	387	408	412	412	409	407

1-4 Standard errors for monthly , quarterly and yearly production estimates

From variograms , it is also possible to get the magnitude of errors for large block estimates i.e. volumes corresponding to one month , three months or one year production . The technique used to derive those standard errors is a little bit different than the one used before to get errors of small blocks estimates . We can't combine estimation errors of small blocks in a big block to get the estimation error of the big block since those estimation errors are not independent . We can however combine extension errors i.e. errors produced when the small blocks correspond to the drilling grid cell and the estimation of those small blocks is done with only the sample in their center (polygonal estimation) . In that case the estimation variance for the big block is :

$$V^2=v^2/n$$

where v^2 is the extension variance of one composite to its cell of influence (derived from variograms) and n is the number of drilling grid cells in the big block

At Faro , the big blocks that we have investigated correspond to the average monthly , quarterly and yearly production . To get those volumes , we have considered the production figures for the first four months of 1990 . Depending of cut-off , the flagged-in-pit volume of ore varies from 671,000 bcys at 3% Pb+Zn cut-off to 468,000 bcys at 6% Pb+Zn cut-off. Hence , the "ore bench surface" mined in a month is 226,460 ft2 at 3% and 157,950 ft2 at 6% . For a quarter it is 3 times as much and for a year , 12 times .

To determine the number of drilling grid cells of ore mined in a month , a quarter and a year , we have considered two basic drilling grids : 140' and 70' . Hence , at a 3% cut-off , there are 226,460/(140x140)=12 ore composites on a 140 ft grid in a month volume and 46 composites on a 70 ft grid . At 6% cut-off , number of composites are respectively 8 and 32 .

First uncertainty is on the estimated surface (or volume) of ore above cut-off . This uncertainty depends of the degree of "connectivity" of the ore above the cut-off and the overall proportion of ore above that cut-off in the ore type being mined . Obviously , we can be more confident on the estimate of volume of ore above cut-off if 80% of the samples are above that cut-off instead of just 20% . More precisely , the "relative" error (or precision) is likely to be higher in the second case . Then we can anticipate that the errors on volumes at 3% are less than at 6% and that we should do better in 40-70 than 20-30 because there is a higher proportion of composites above the usual cut-offs in this ore type . The connectivity of sample values above a cut-off can be measured through a variogram of indicator at that cut-off . The indicator value of a composite is 1 if the grade of the composite is above the cut-off and 0 otherwise . Figure 13 shows horizontal variograms of indicator at 3% Pb+Zn cut-off in 20-30 . Figure 14 has the same type of variograms but for cut-off 6% in 40-70 . As a general rule , indicator variograms have about the same features as the corresponding grade variograms . Once indicator variograms are modelled , we can determine v , the extension standard error of the indicator of a composite to its cell of influence . Then to get the relative standard error of the surface (or volume) above cut-off , we use a formula derived from the general one presented above :

$$V = v/(nxp)^{1/2}$$

Where p is the overall proportion of composites above the cut-off . This formula has been implemented in ore types 20-30 and 40-70 , at 3% and 6% Pb+Zn cut-offs , and for 70' and 140' drilling grids . Results are given in Table 7 . We can see that :

+ monthly standard errors vary from 4.6% (70 ft grid - 3% cut-off - 20/30) to 26.6% (140 ft grid - 6% cut-off - 20/30)
+ yearly standard errors vary from 1.3% (id) to 7.7% (id)
+ as expected , standard errors are increasing with cut-off .
+ as expected , at the 6% cut-off , standard errors in 20-30 are higher than in 40-70 because the proportion of values above that cut-off is less (34% vs 54%)
+ at the 3% cut-off , standard errors in 20-30 are slightly less than standard errors in 40-70 because of the better connectivity of data above that cut-off in that ore type .

As indicated in the previous section , the above standard errors correspond to a 68% confidence . For a 95% confidence , all numbers must be doubled .

The error on tonnage above cut-off is a combination of the error on volume and the error on the estimated average specific gravity above the cut-off . Relative variations of specific gravity are rather limited : in 20-30 , average SG of composites at 3% cut-off is 3.25 with a standard deviation of 0.35 . At 6% cut-off , average is 3.39 and standard deviation is 0.34 . In 40-70 , average SG varies from 4.14 to 4.17 whereas standard deviation stays at 0.42 with cut-off from 3% to 6% . Based on these statistics , we can determine that the relative standard error of estimated SG above cut-off are : 1.3% (70ft grid) and 2.5 % (140 ft grid) for monthly blocks , 0.3 % (70 ft grid) and 0.7 % (140 ft grid) for yearly blocks , at both cut-offs and in the two ore types . Theoretically , the relative error variance of tonnage would be the sum of the relative error variance of volume and the relative error variance of SG . Now there is some negative correlation between volume and SG above cut-off : if we underestimate the volume , we probably overestimate the SG . As a result of this negative correlation , we think that the relative standard errors for tonnage above cut-off should not exceed the relative standard errors for volume above cut-off in Table 7 .

The error on estimated average grade (Pb+Zn) above cut-off can be derived from the general formula . In that case , v^2 is the extension variance of the Pb+Zn grade of a composite above cut-off to its cell of influence . It is derived from a variogram of composite grades above cut-off . Figure 15 presents horizontal variograms of %Pb+Zn above 3% in 20-30 . On figure 16 , we have the same type of variograms for %Pb+Zn above 6% in 40-70 . It is interesting to note that , as we increase the cut-off , the dispersion of grade values is decreasing : in 20-30 , at a 3% cut-off , mean and standard deviation of %Pb+Zn values are respectively 6.21% and 2.45% ; at 6% cut-off , they are 8.39% and 1.96% . In 40-70 , as cut-off goes from 3% to 6% , mean %Pb+Zn above cut-off goes from 7.84% to 9.44% and standard deviation goes from 3.09% to 2.46% . Hence , for average grade , magnitude of estimation errors decreases with cut-off . Relative standard errors for grade are detailed in Table 8. Conclusions are :

+ monthly standard errors vary from 3.3 % (20/30 - 70' grid - 6% cut-off) to 8.7% (40/70 - 140' grid - 3% cut-off).
+ yearly standard errors vary from 1.0 % (id.) to 2.5% (id.)
+ as expected , relative standard errors decrease with cut-off
+ standard errors are slightly better in 20-30 than 40-70 at all cut-offs .

All the above errors are given for ore types 20-30 and 40-70 separately . If production in a given period is made of a mixture of the two ore types , the relative standard error is a weighted average of standard errors of each ore type in the same proportions . If production is made of 50% 20-30 and 50% 40-70 , we get the 95% confidence precision of Table 9. From that table it appears that relative errors are higher for tonnage than grade . Additional calculations show that :

+ in order to get 95% relative standard errors of less than 5% on monthly estimates , we need a drilling grid between 35' and 40' at 3% cut-off and between 15' and 20' at 6% cut-off

+ in order to get 95% relative standard errors of less than 2% on yearly estimates , we need a drilling grid of about 50' at 3% cut-off and 25' at 6% cut-off .

Figure 13 Horizontal indicator variograms (3% Pb+Zn cut-off) in 20-30

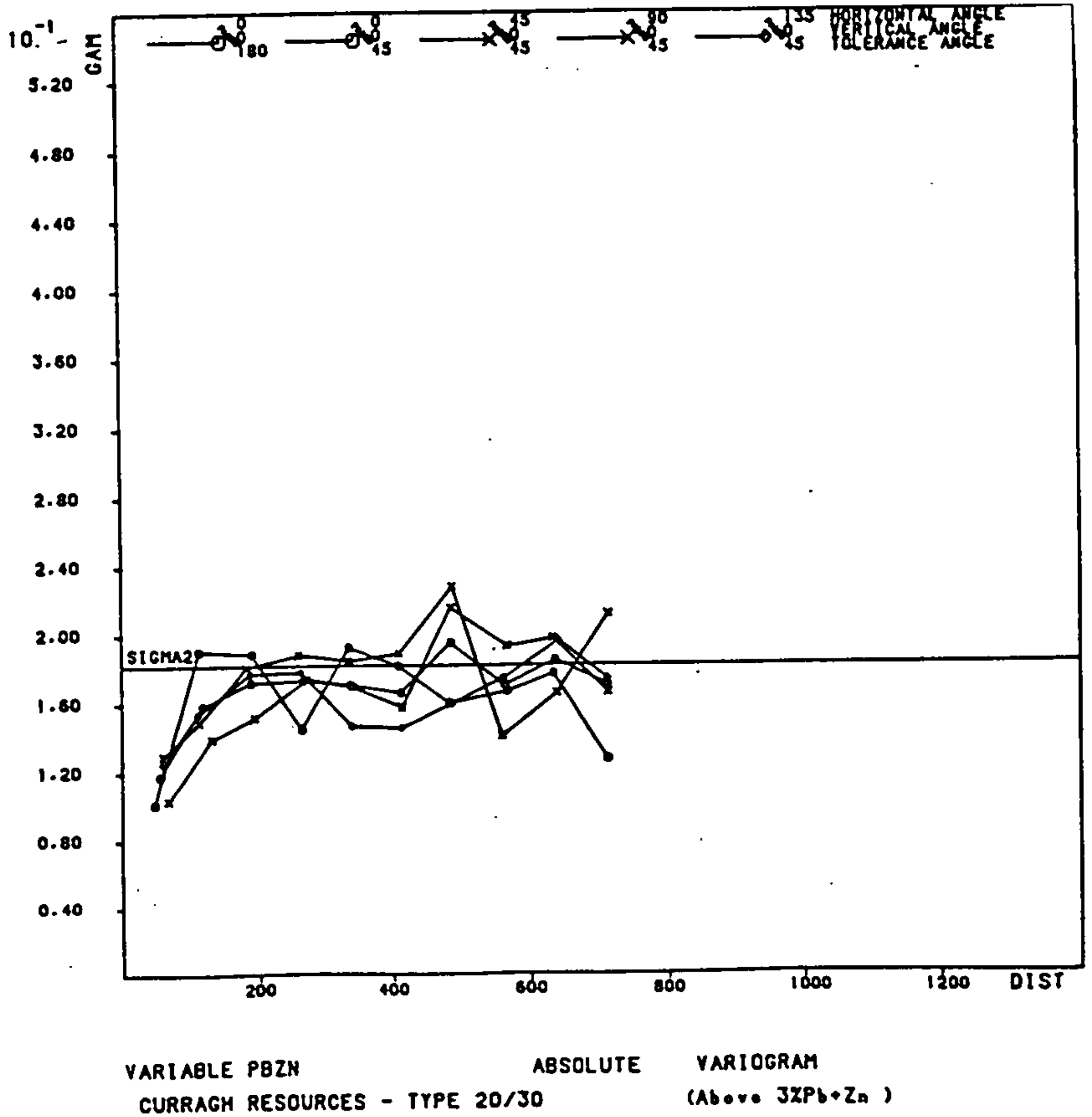


Figure 14 Horizontal indicator variograms (6% Pb+Zn cut-off) in 40-70

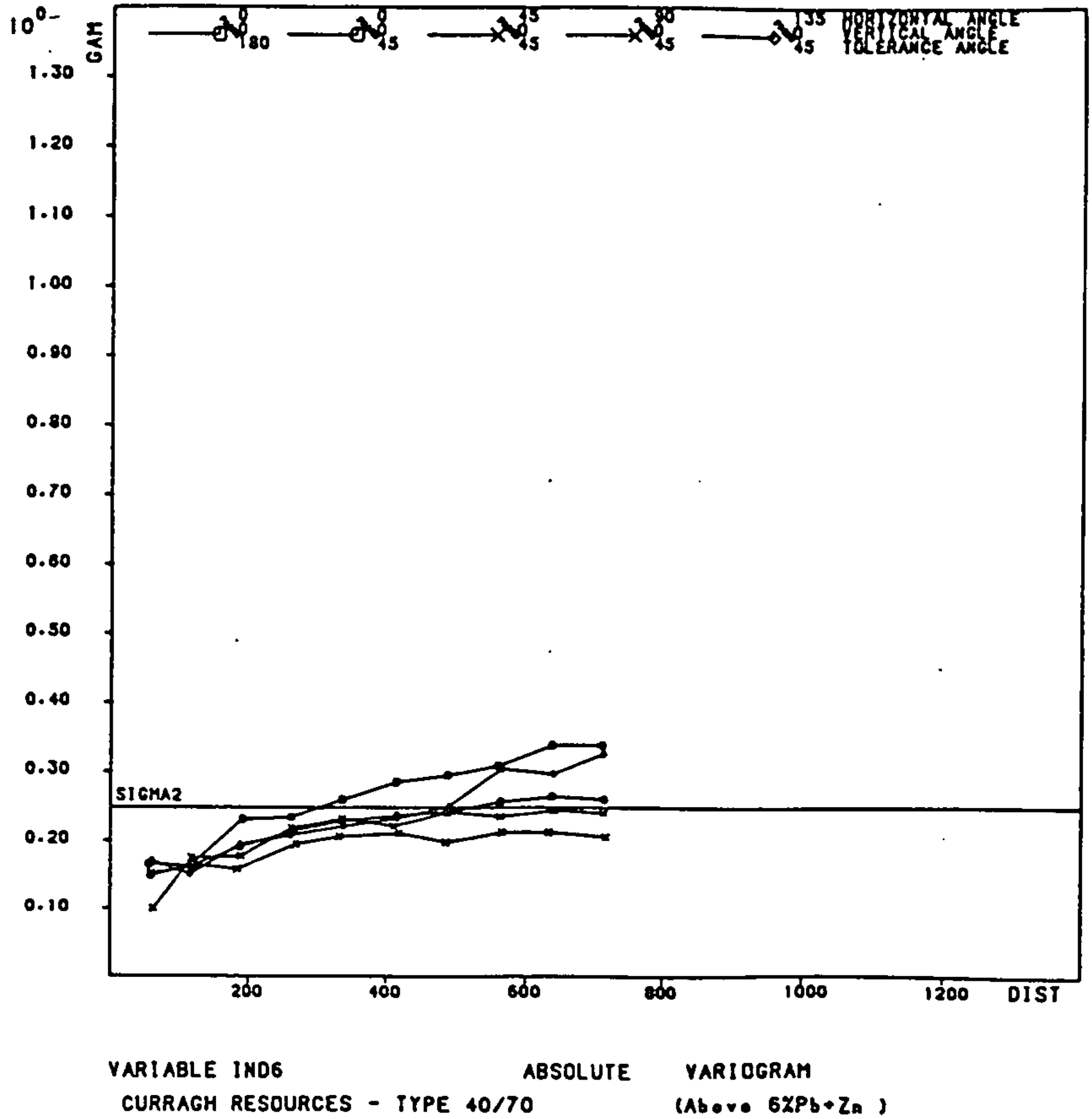
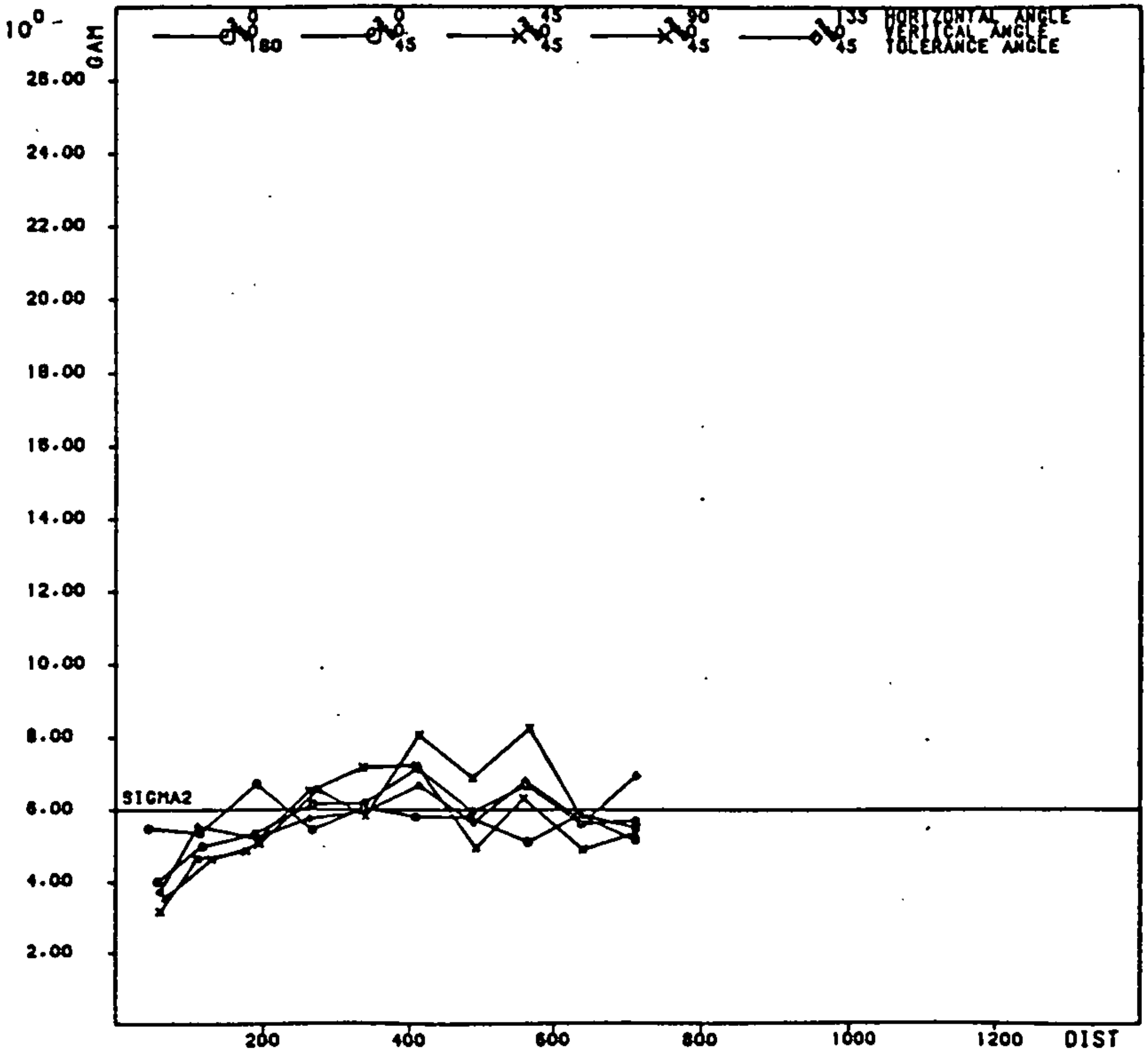


Table 7 Relative standard errors (%) on estimated surface (volume) above cut-off.

Cut-off	3%Pb+Zn		6%Pb+Zn	
Ore type	20-30	40-70	20-30	40-70
Proportion of composites above cut-off (p)	0.76	0.80	0.34	0.54
Extension standard error (v)				
70' grid	0.27	0.31	0.44	0.36
140' grid	0.30	0.32	0.44	0.37
Monthly standard error (V %)				
70' grid	4.6	5.1	13.2	8.6
140' grid	10.1	10.5	26.6	17.7
Quarterly standard error (V %)				
70' grid	2.6	3.0	7.6	5.0
140' grid	5.8	6.0	15.4	10.2
Yearly standard error (V %)				
70' grid	1.3	1.5	3.8	2.5
140' grid	2.9	3.0	7.7	5.1

Figure 15 Horizontal variograms of %Pb+Zn above 3% cut-off in 20-30



VARIABLE PBZN ABSOLUTE VARIOGRAM
CURRAGH RESOURCES - TYPE 20/30 (Above 3%Pb+Zn)

Figure 16 *Horizontal variograms of %Pb+Zn above 6% cut-off in 40-70*

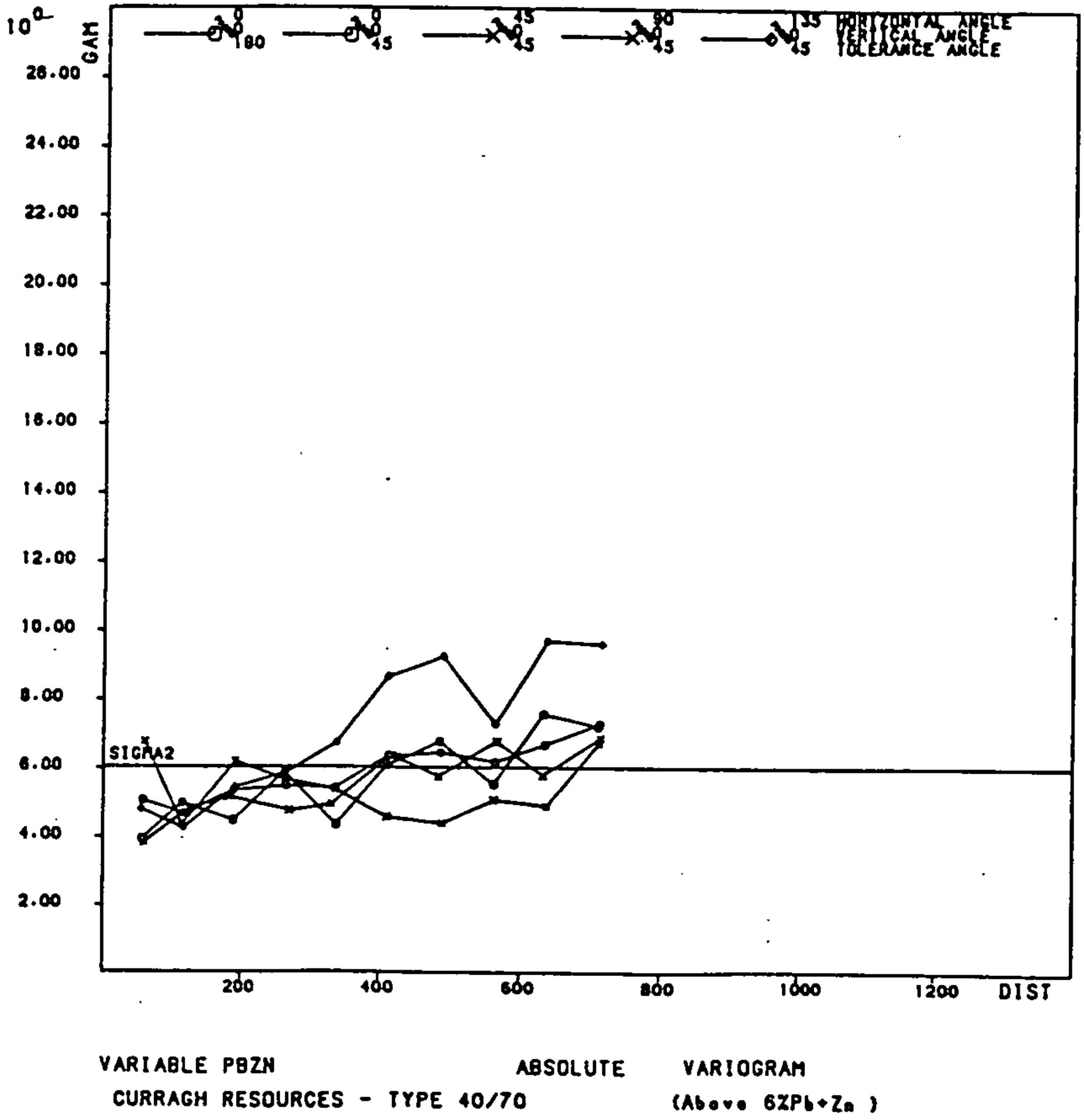


Table 8 Relative standard errors (%) on estimated %Pb+Zn grade above cut-off

Cut-off	3%Pb+Zn		6%Pb+Zn	
Ore type	20-30	40-70	20-30	40-70
Average grade above above cut-off (%Pb+Zn)	6.21	7.84	8.39	9.44
Extension standard error (v)				
70' grid	1.56	2.28	1.58	2.03
140' grid	1.70	2.32	1.61	2.06
Monthly standard error (V %)				
70' grid	3.7	4.3	3.3	3.8
140' grid	8.1	8.7	6.8	7.7
Quarterly standard error (V %)				
70' grid	2.1	2.5	1.9	2.2
140' grid	4.6	5.0	3.9	4.4
Yearly standard error (V %)				
70' grid	1.1	1.2	1.0	1.1
140' grid	2.3	2.5	2.0	2.2

Table 9 Average 95% confidence precisions (50% 20-30 + 50% 40-70)

Period	Month		Year	
Drilling grid	70'	140'	70'	140'
Tonnage				
3% cut-off	9.7	20.6	2.8	5.9
6% cut-off	21.8	44.3	6.3	12.8
Pb+Zn grade				
3% cut-off	8.0	16.8	2.3	4.8
6% cut-off	7.1	14.5	2.0	4.2

1-5 VALIDATION OF VARIOGRAMS AND ERROR PREDICTION

One way to check the validity of the prediction model is to reestimate samples from samples around. Estimates are compared to true values and actual errors with predicted errors.

For example, if we take the 742 bench composites of type 20 and 30, we can krige the % Pb + Zn grade of each of them using % Pb + Zn values of neighbor composites of the same type but in different holes. With the standard 400' x 150' x 60'search ellipsoid, we can reestimate 719 composites. Average estimate is 5.19% Pb + Zn which compares well with the mean value of the 719 data (5.18% Pb + Zn) i.e. the average error is virtually zero. The average absolute error is 2.35% Pb + Zn and the average squared error is 8.79 i.e. a standard deviation of 2.96% Pb + Zn. In other words, the average experimental uncertainty in the reestimation of samples from nearby samples is 2.96/5.18 = 57%. The average kriging variance is 8.02 or a standard deviation of 2.83% Pb + Zn, very close to the experimental value (individual standard errors vary from 2.35 to 4.05% Pb + Zn). These standard errors of about 2.9% Pb + Zn in the reestimation of composites at distances from 70' to 140' are consistent with the predicted standard errors of 1.20% to 1.73% Pb + Zn in the estimation of 25' x 35' blocks at about half those distances.

The same method can be used to test various features of the variogram model =

+ if we do the reestimation using a variogram model with no horizontal anisotropy (horizontal range = 300' in all directions), the absolute error is 2.34% Pb + Zn, the experimental error variance is 8.84 but the average kriging variance is only 7.50. Hence this model is giving estimates as good as the anisotropic model but the predicted error is too low.

+ if we do the reestimation with a model with no nugget effect, absolute error is 2.44% Pb + Zn, experimental error variance is 9.63 but average kriging variance is only 6.45. Hence a nugget effect gives better estimates and a more realistic predicted error.

+ if we do the reestimation using only the nearest composite in the 400' x 150' x 60' search ellipsoid, the average absolute error is 2.96% Pb + Zn hence distance weighting interpolation methods like kriging are preferable to polygon.

Back to the original prediction model, another way of checking the validity of error prediction with the sample reuse method is to count the number of times when the actual error is less than the predicted standard error or less than twice the predicted standard error. According to a normal model for the distribution of errors, we should have 68% of the errors less than the standard errors and 95% of them less them two standard errors. Actual numbers are 480 out of 719 i.e. 67% and 683 out of 719 i.e. 95%.

Even if the prediction of errors is correct, the estimates of composites are not that good as indicated by the correlation plot of figure 17. Correlation coefficient of estimated and true values is in fact only 0.18. What we can notice on this diagram is that estimates are smoother (less dispersed) then actual values. In fact the standard deviation of estimates is only 1.41% Pb + Zn whereas that of true values is 2.88% Pb + Zn.
A direct consequence of too smooth estimates is an overestimation of the proportion of values (tonnage) above a low cut-off and the underestimation of the proportion of values above a high cut-off (Table 10). Estimated grades above cut-off are always underestimated. Hence somekind of correction is necessary to "unsmooth" the distance weighted estimates. This would be considered in the next section.

In 40/70, the reestimation of composites is giving similar results: with the current variogram model, out of 985 reestimated samples, the average error is 0.07% Pb + Zn (mean of true values is 6.65% Pb + Zn, mean of estimates is 6.57% Pb + Zn), the average absolute error is 2.22% Pb + Zn, the experimental error variance is 8.43 (standard error: 2.90% Pb + Zn) and the average kriging variance is 8.89 (standard error 2.98% Pb + Zn). Also 73% of the actual errors are less than the predicted standard error and 95% of them are less then two standard errors. Correlation of estimates and true values is much better than in 20/30 (figure 18). Correlation coefficient is now 0.61. Oversmoothing of estimates is still present. As a result, since now all cut-offs are less than the mean grade, all the proportion of values above cut-off are overestimated and all grades above cut-off are underestimated (Table 11).

```
      PROGRAM PILLAR
$DEBUG
$DECLARE
C********************************************************************
C       PROGRAM FOR CALCULATING SAFETY FACTORS OF PILLARS USING PAGE/
C       LAUBSCHER EQUATION BASED ON HYDRAULIC RADIUS.
C       WRITTEN FOR CURRAGH RESOURCES LTD, FARO PROJECT
C       J.I. MATHIS 16/11/91
C********************************************************************

        REAL*4 PD(100,10)
        REAL*4 RDIP,SE,SEM,LA,PA,RATIO,PSTR,WEFF,PS,PH,SF

        INTEGER I,J,K
        INTEGER NP

        CHARACTER*4 PI(100)


C***    GET THE DATA

        WRITE(*,1)
   1    FORMAT(/,' ************* PILLORY POGRAM *************',/)

        NP=1

 100    WRITE(*,2)
   2    FORMAT(/,' PILLAR NAME (A4) ',\)
        READ(*,50) PI(NP)

        IF(PI(NP).EQ.'XXXX') GO TO 200

        WRITE(*,3) PI(NP)
   3    FORMAT(/,' INPUT FOR PILLAR ',A4,': ',/,
     1 ' AREA,PERIMETER,HEIGHT, LOAD AREA, V. STRESS, OREBODY DIP',/)
        READ(*,*) (PD(NP,J),J=1,6)

        WRITE(*,4)
   4    FORMAT(/,' PILLAR STRENGTH (MPa) ',\)
        READ(*,*) PD(NP,7)

  50    FORMAT(A4)

C***    AREA = FEET, PERIMETER = FEET, HEIGHT = FEET, LOAD AREA = FEET
C       V. STRESS = PSI, DIP = DEGREES FROM HORIZONTAL

C***    CALCULATE DIP STRESS CORRECTION, ASSUME HORIZONTAL STRESS =
C       TWO TIMES VERTICAL STRESS
C       SIGMAE=SIGMAV*COS^2(DIP)+SIGMAH*SIN^2(DIP)

        RDIP=PD(NP,6)/57.2958

        SE=(COS(RDIP)**2+2.*SIN(RDIP)**2)*PD(NP,5)

C***    CONVERT TO MPA
        SEM=SE/145.

C       WRITE(*,*) ' SEM ',SEM

C***    CONVERT LOAD AREA TO SQUARE METERS

        LA=PD(NP,4)/10.758

C***    CONVERT PILLAR AREA TO SQUARE METERS
```

Figure 18: Scattergram of real % Pb + Zn value and estimated % Pb + Zn value in 40/70.

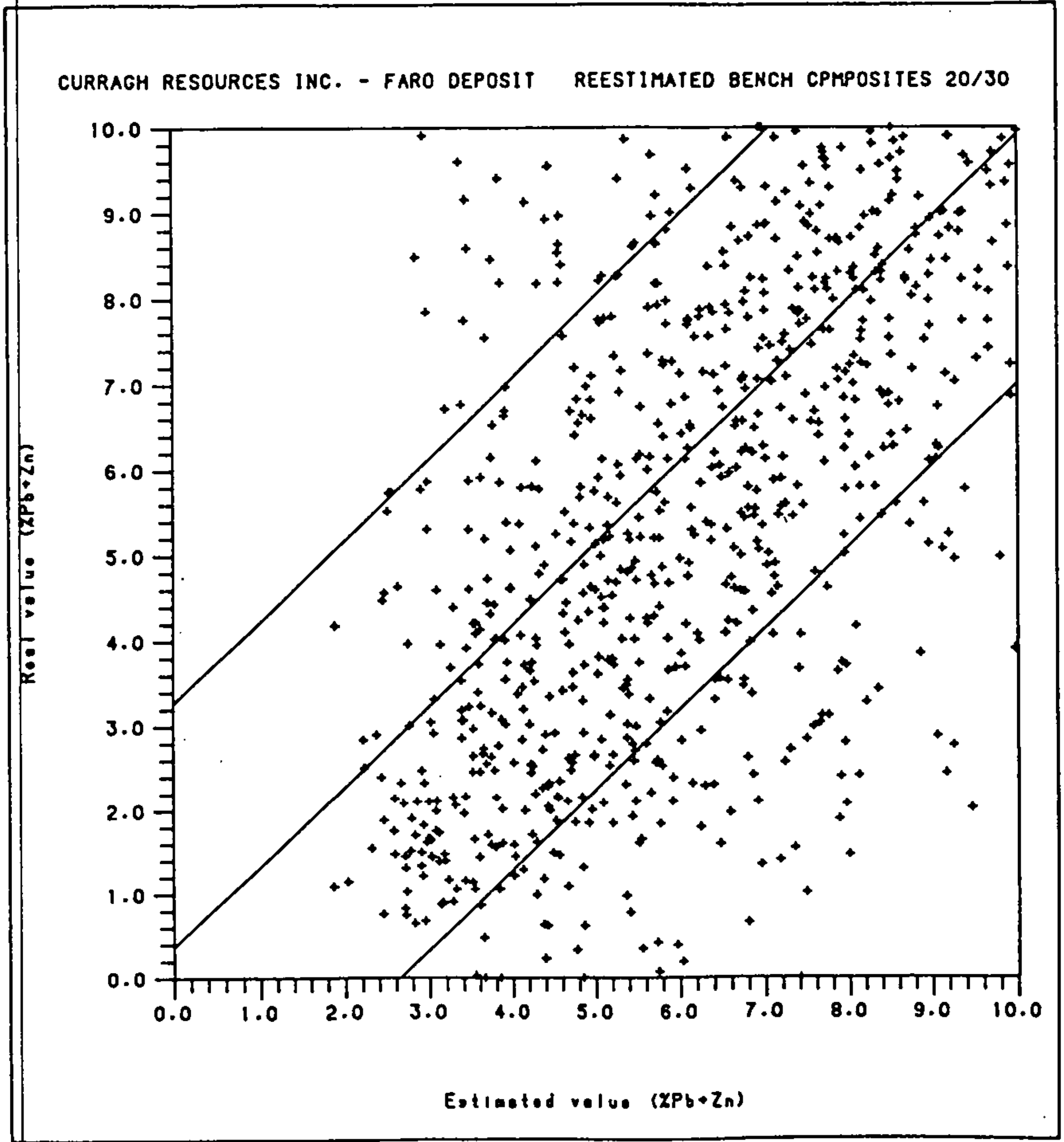


Figure 18

Table 10: Reestimation of composite % Pb + Zn grades. Proportion of actual and estimated values above cut-offs (% values).

Cut-off	20/30		40/70	
(% Pb + Zn)	Actual	Estimated	Actual	Estimated
3	76	95	80	95
4	61	79	73	84
5	48	55	63	72
6	34	27	54	57

Table 11: Reestimation of composite % Pb + Zn grades. Mean % Pb + Zn grade (no SG weighted) above cut-off: actual and estimated.

Cut-off	20/30		40/70	
(% Pb + Zn)	Actual	Estimated	Actual	Estimated
3	6.24	5.32	7.83	6.78
4	6.93	5.68	8.28	7.19
5	7.58	6.79	8.83	7.63
6	8.41	6.88	9.42	8.21

1-6 CORRECTION OF BLOCK ESTIMATES FOR PROPORTION OF BLAST HOLES IN BLOCKS

Another way to validate the long term prediction of block values from drill hole bench intercepts is to compare block estimates derived from those intercepts and blast hole grades in the same blocks.

We have % Pb, % Zn, % Pb + Zn as well as coordinates from 2083 BHs in benches 3490, 3470 and 3450 in the south phase of the pit. Table 12 lists some statistics of those blast hole values according to rock code. We can see that most of the blast holes that we have are in rock type 50. We have a significant group of "55" that we did not have before and which seems to have the same (low) means grades as type 40 in DHs. With the exception of 70, all mean B.H. grades in that zone are higher than the overall D.H. mean grades (Table 1-3), hence it is a relatively rich zone.

If we just consider the quartzite types, 20 and 30, we have 568 blast holes with % Pb + Zn values ranging form 0.10% to 14.83%, a mean of 6.39% and a standard deviation of 2.80%. Figure 19 is a map of those blast holes (x with size proportional to % Pb + Zn) in bench 3470. On the same map, we have the 20/30 D.H. composites in the same bench(0 also with size proportional to % Pb + Zn). We can notice that, overall, there is a good agreement between ore type characterization of D.H. composites and blast holes. There are however a few 20/30 D.H. composites which are more than 25' away from the closest 20/30 B.H., hence there are almost coincident with a B.H. which is not classified in type 20/30.

We can find all the blocks of the 25' x 35' model which contain a blast hole of type 20/30 and do the interpolation of the % Pb + Zn grade of those blocks from the drill hole composites (Figure 20). All together there are 413 blocks but since the blast hole grid is about 20', most of the time, there is only one blast hole in a block. The interpolation method that we use is kriging with the variogram model of % Pb + Zn for 20/30 D.H. composites (Table 4) and the 400' x 150' x 60' search ellipsoid.

If we compare the mean kriged grade of the 413 blocks with the mean grade of the 568 blast holes in those blocks, they are reasonably close: 6.24% Pb + Zn vs 6.38% Pb + Zn. The difference of 0.14% Pb + Zn (or relative difference of 2.2%) is consistent with the monthly and quarterly precision figures of % Pb + Zn estimates in 20/30 of table 10 (413 blocks represents about 1.5 months of production.

Even if means are close, the correlation between kriged D.H. grade of a block and mean B.H. grade of that block is not that great (Figure 21): correlation coefficient is only 0.11. The main reason for that poor correlation is the <u>oversmoothing of kriged block values;</u> kriged values range from 3.31 to 9.59% (standard deviation: 1.02%) whereas B.H. values range from 0.10 to 14.83% (standard deviation of 2.68%).

As a direct consequence of that oversmoothing, <u>if we apply the usual cut-offs to the kriged block values, tonnages are too high and grade too low</u> (Table 13). Tonnage difference is as much as 30% (5% cut-off) and grade difference as much as 17%.

If we repeat the same exercise in 40-70 (excluding 55), we end up with 795 blocks that contain at least one blast hole of either 40, 50, 60 or 70 type. Mean of kriged values for those blocks is 8.16% Pb + Zn whereas the mean of blast holes in these blocks is 8.84%. This almost 10% difference is more than what can be expected. A closer look at the location of blast holes with type 55 indicates that they are in regions with D.H. composites of type 40 (Figure 22). Hence it seems more reasonable to krige all blocks that contain blast holes of type 40, 50, 60, 70 and 55 with the 40/70 D.H. composites. In that case, we end up with a mean of 909 blocks equal to 7.75% Pb + Zn whereas the mean of the BHs in those blocks is 8.12% Pb + Zn.

Difference is less than before but still fairly high. It shows that when a few low grade D.H. composites of type 40 are used in the estimation of mostly high grade 40-70 blocks, there is some overall underestimation of grade.

If we restrict ourselves to types 50-60-70, we have 1148 blast holes with % Pb + Zn values ranging from 3.13% to 18.21%, a mean of 9.07% and a standard deviation of 2.73%. Map of those blast holes in bench 3470 (together with the D.H. composites in the same bench) is on figure 23. In that case, we see that all D.H. composites are surrounded by BHs of the same type. However, we can see extensive zones of blast holes 50/70 with no 50/70 D.H. composites around = D.H. composites in those zones have probably been assigned a different rock type.

There are now 765 blocks with 50/70 BHx in them (Figure 24). The average kriged % Pb + Zn of those blocks is 9.02% which compares well with the mean B.H. of 9.07% Pb + Zn.

However, like in 20/30, correlation of D.H. estimate with B.H. value is not good (Figure 25). Correlation coefficient is a mere 0.31. Like before, this poor correlation is derived from the oversmoothing of block estimates: kriged values range from 5.70 to 10.94% (standard deviation: 1.11%) whereas B.H. values go from 3.13% to 18.21% (standard deviation: 2.52%). Again, because of that oversmoothing, if we apply a cut-off to the kriged block values, tonnages are too high and grades are too low (Table 14). Tonnage difference is as much as 14% (6% cut-off) and grade difference, 7% (same cut-off).

A way to overcome the oversmoothing of straight block estimates is to estimate the likely proportion and grade of blast holes above the cut-off in each block.

We can take the kriged estimate as the mean of that distribution. Its variance can be derived from the variogram of D.H. composites: it is simply the average value of the horizontal variogram in a rectangle 25' x 35'. It is 4.41 in 20/30 and 4.53 in 40/70. The shape of the distribution can be assumed to be a simple model, normal or lognormal (considering the histograms of D.H. bench composites, the best assumption is probably lognormal in 20/30 and normal in 40/70).

We have tried a "lognormal short cut" correction of the kriged block values in both 20/30 and 50/70 with the above variances. This means for example that if we have a kriged block estimate of 5.54% in a 20/30 block, we estimate that:

6.8% of the BHs in that block are below 3% with a grade of 2.58% Pb + Zn.

17.2% of the BHs are between 3 and 4% with a grade of 3.54% Pb + Zn.

22.1% of the BHs are between 4 and 5% with a grade of 4.50% Pb + Zn.

19.5% of the BHs are between 5 and 6% with a grade of 5.48% Pb + Zn.

34.4% of the BHs are above 6% with a grade of 7.82% Pb + Zn.

This is far different from the answer that you get if you apply the cut-off directly on the block estimate. In that case the estimated proportions for the same grade categories are simply:

0, 0, 0, 100% and 0. If we sum all the estimated proportions and grades above cut-off in each block, we get the results of Table 15.

We can see that the correction is achieving its goal: reduce tonnage and increase grade. Maximum tonnage difference is now 8% in 20/30 (6% cut-off) and 3 % in 50/70 (6% cut-off maximum grade difference is 5.4% in 20/30 (3% cut-off) and 2.4% in 50/70 (6% cut-off).

Table 12: Summary statistics of B.H. data available.

Rock type	Number of BHs	Mean % Pb	Mean % Zn	Mean% Pb + Zn
0	37	1.09	1.03	2.12
10	12	1.56	2.47	4.03
20	398	2.16	3.75	5.92
30	170	2.85	4.65	7.50
40	55	2.21	3.35	5.56
50	1061	3.46	5.60	9.05
55	263	1.66	1.99	3.65
60	6	4.61	7.33	11.96
70	81	3.75	5.25	9.00
20 + 30	568	2.37	4.02	6.39
40 + 50 60 + 70	1203	3.42	5.49	8.91
40 + 50 60 + 70 + 55	1466	3.11	4.86	7.96
50 + 60 + 70	1148	3.48	5.59	9.07
All	2083	2.86	4.55	7.41

Table 13: Resources above cut-off from D.H. kriged block estimates and blast holes in those blocks. Type 20/30 - 413 blocks.

Cut-off	Kriged D.H. values		B.H. values	
% Pb + Zn	% above	% Pb + Zn above	% above	% Pb + Zn above
3%	100	6.24	91	6.81
4%	98	6.28	82	7.17
5%	91	6.42	70	7.63
6%	59	6.86	53	8.33

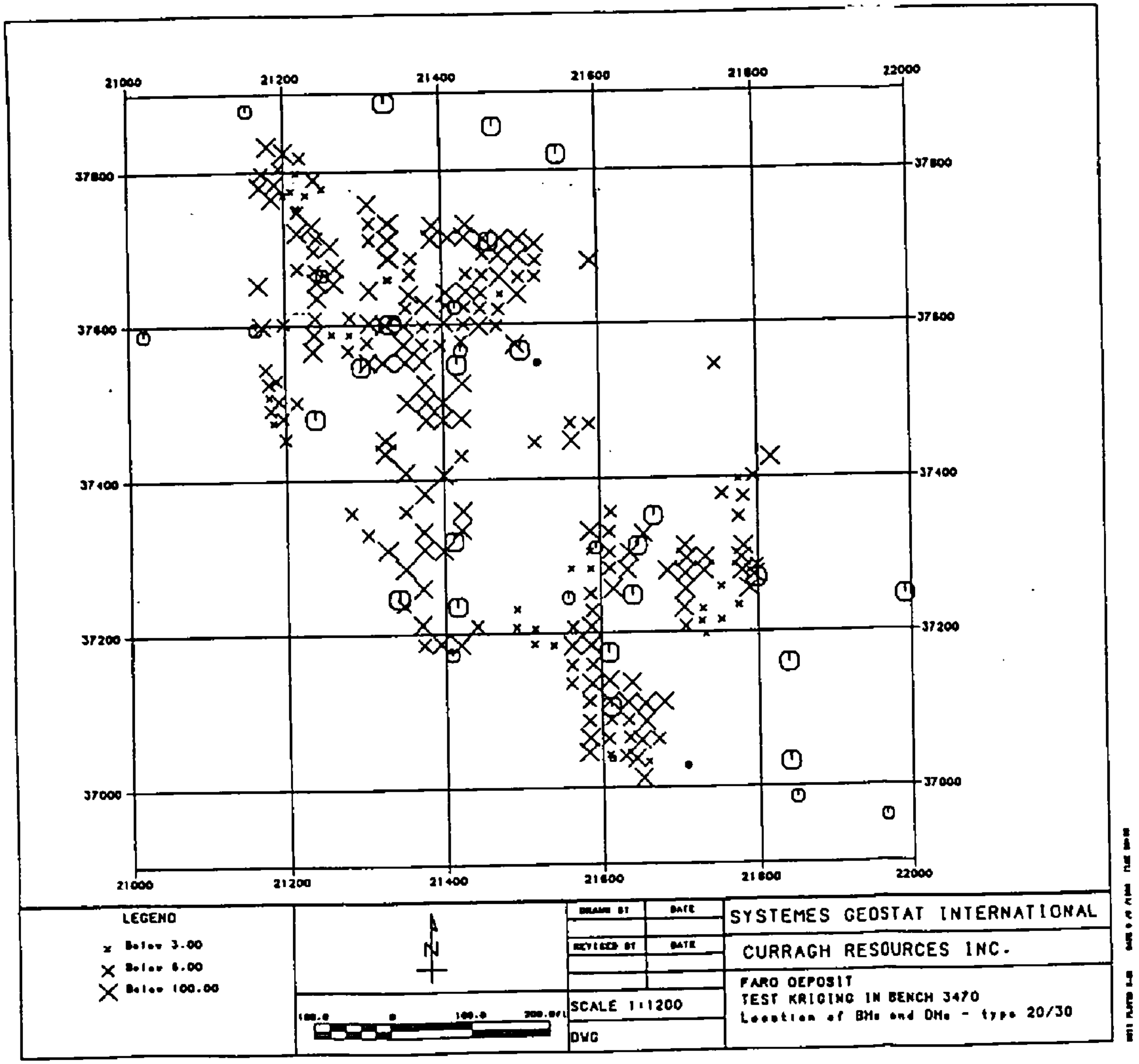
Table 14: Resources above cut-off from D.H. kriged block estimates and blast holes in those blocks. Type 50/70 (excluding 55) - 765 blocks.

Cut-off	Kriged D.H. values		B.H. values	
% Pb + Zn	% above	% Pb + Zn above	% above	% Pb +Zn above
3%	100	8.90	100	9.02
4%	100	8.90	99	9.07
5%	100	8.90	97	9.18
6%	100	8.90	87	9.56

Table 15: Resources above cut-off after correction of oversmoothing by lognormal short-cut (dispersion variances of 4.41 and 4.53 in 20/30 and 50/70 respectively).

Cut-off	Type 20/30		Type 50/70	
% Pb + Zn	% above	% Pb + Zn above	% above	% Pb + Zn above
3%	95	6.44	100	8.90
4%	84	6.81	99	8.94
5%	67	7.38	96	9.06
6%	49	8.09	90	9.33

Figure 19: Map of 20/30 DHs and BHs in bench 3470.



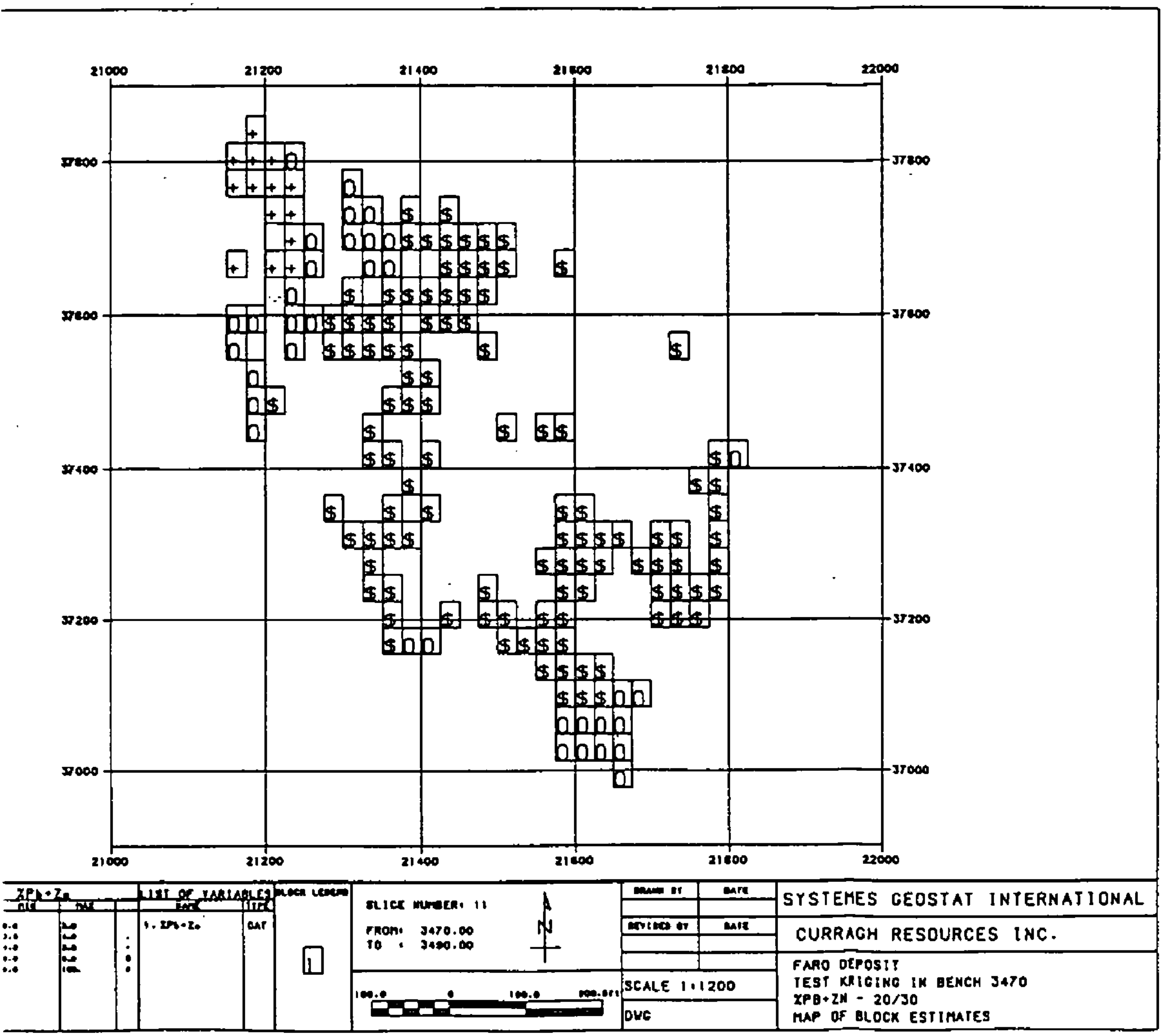


Figure 20: Map of estimated 20/30 blocks in bench 3470.

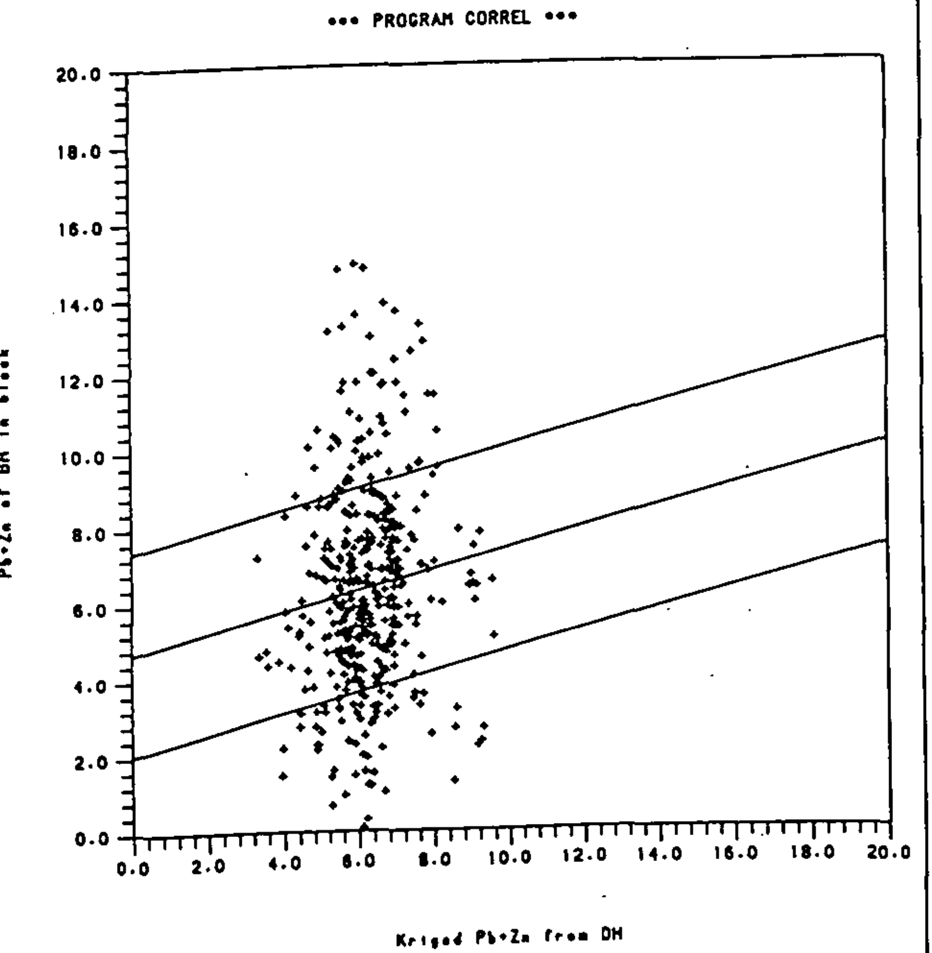
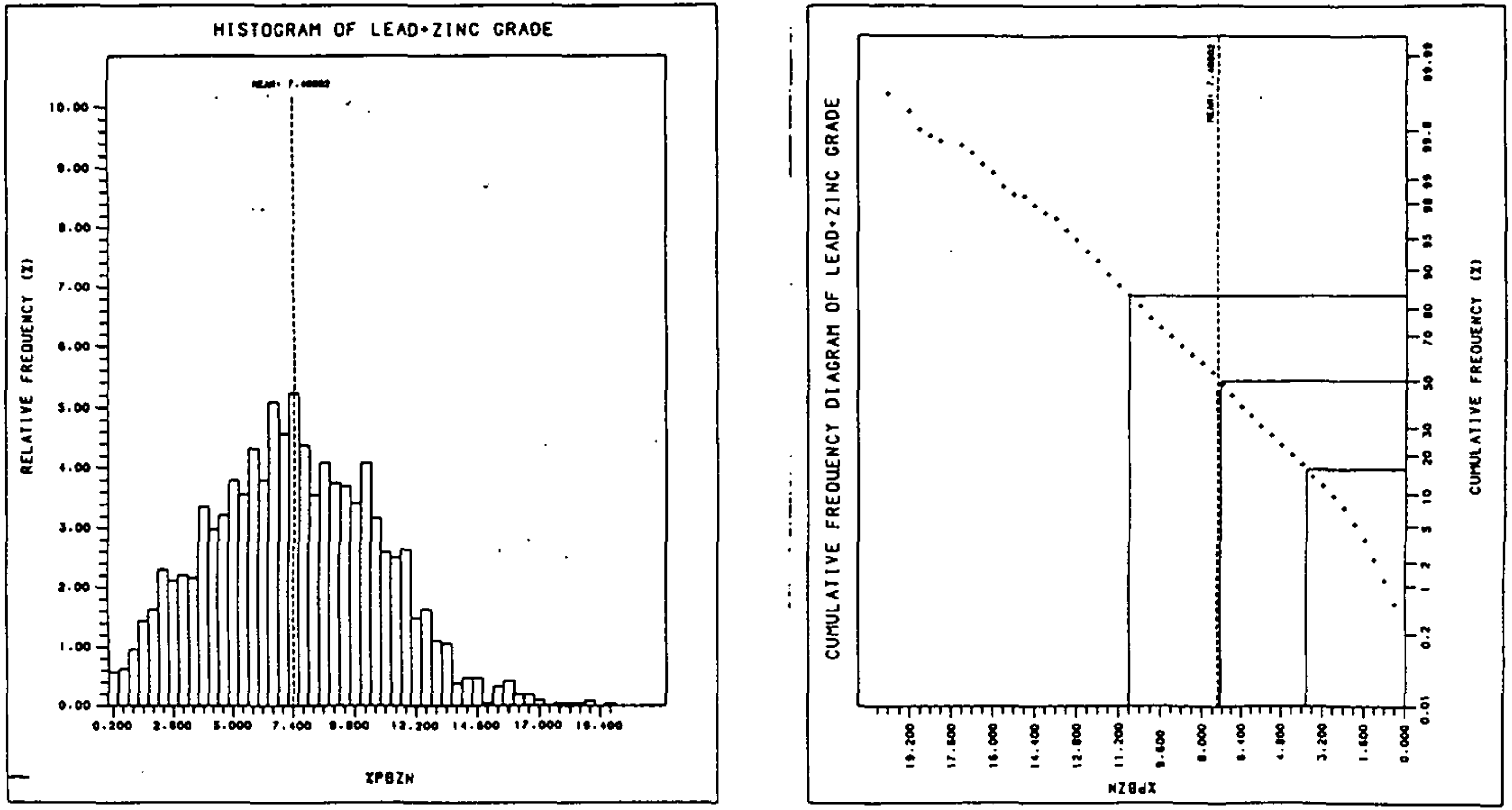


Figure 21: Correlation of kriged DH block and mean BH % Pb + Zn in 20/30.

Figure 26: Histogram of all B.H. % Pb + Zn available.



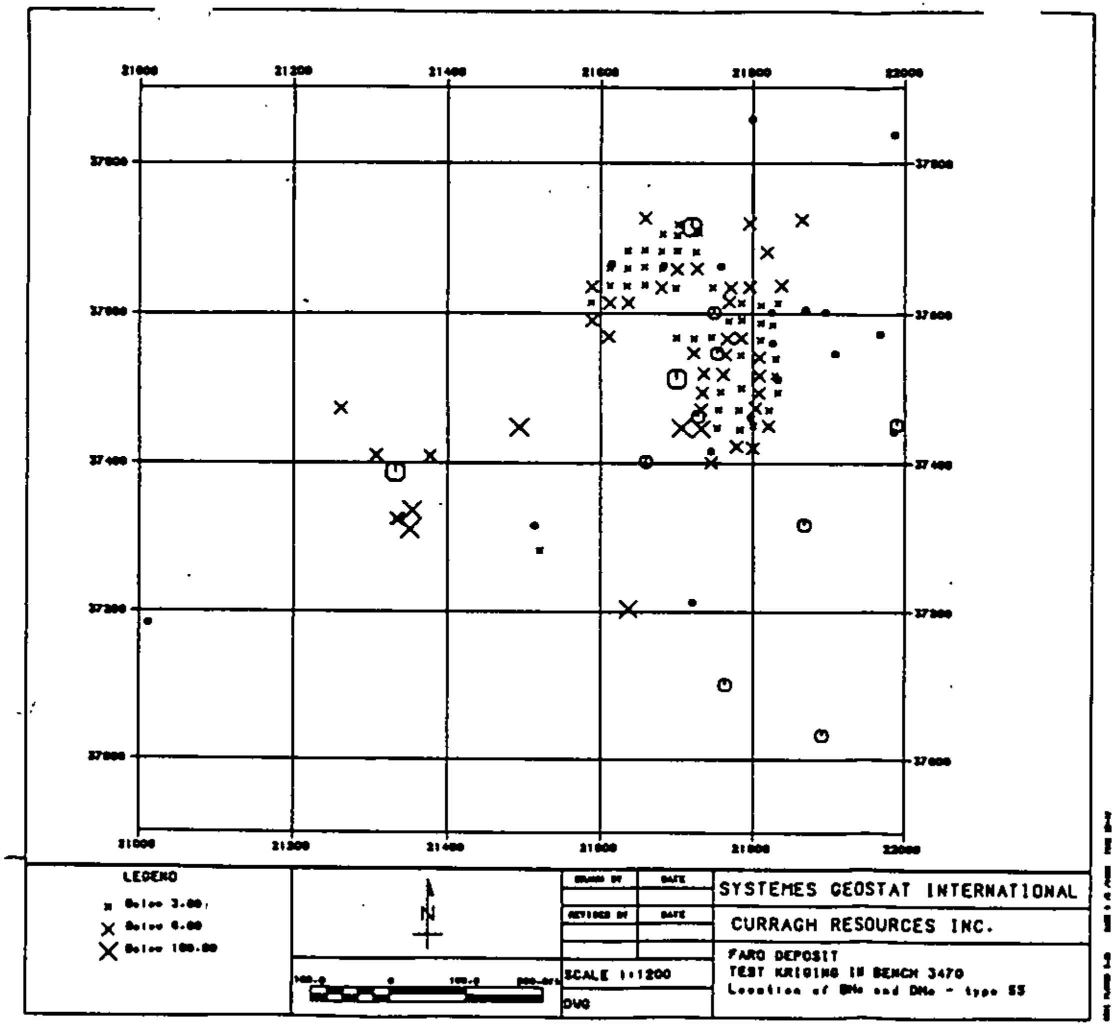


Figure 22: Map of 40 DHs and 55 BHs in b
3470

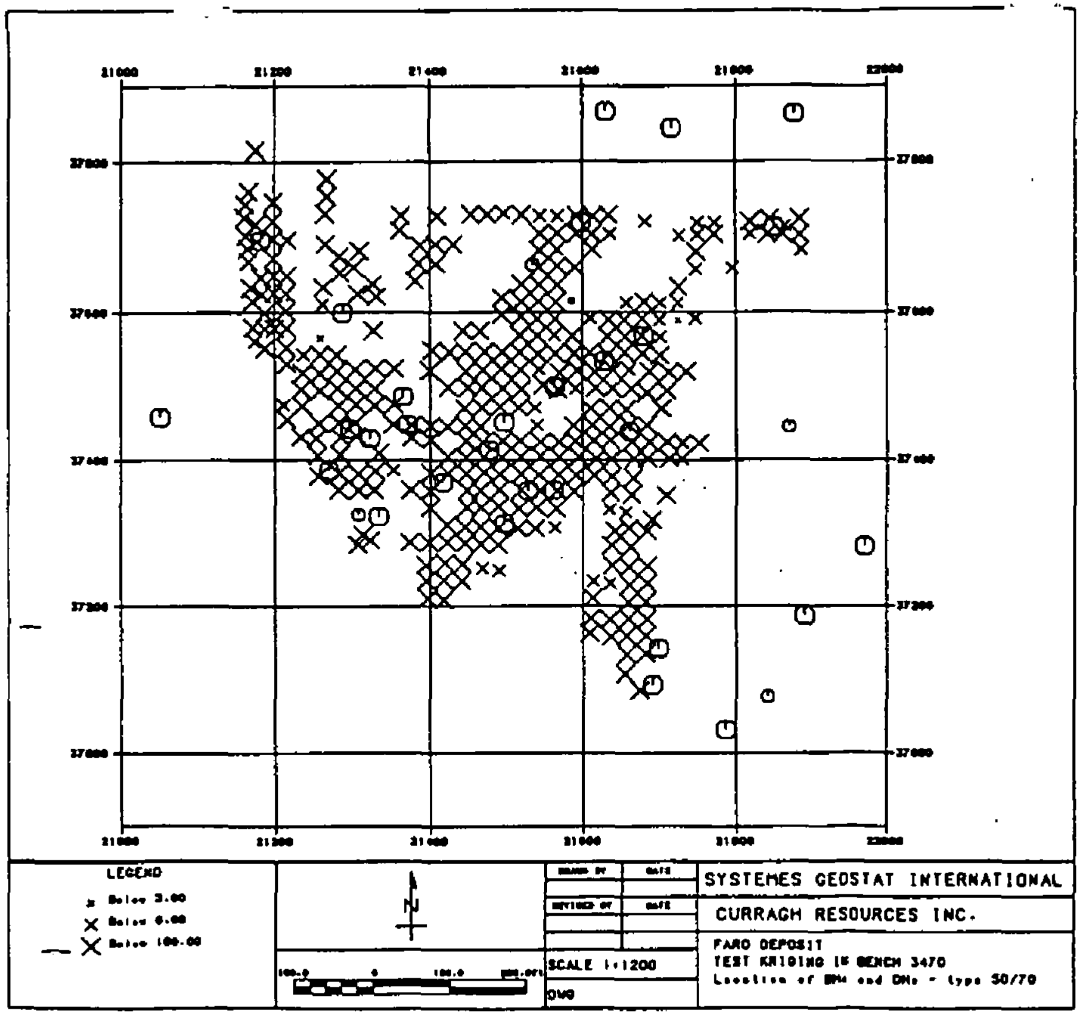
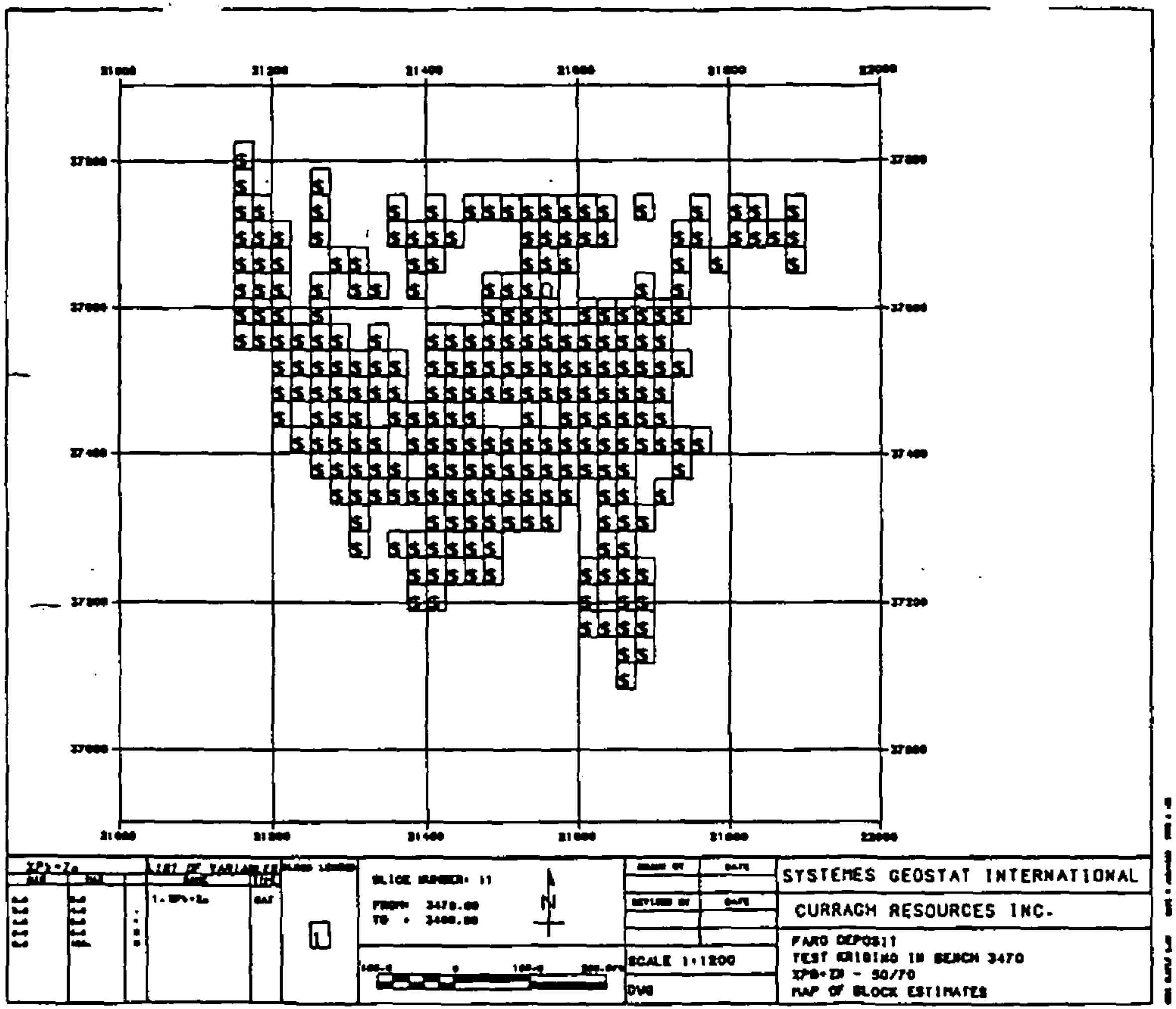


Figure 23: Map of 50/70 DHs and BHs in bench 3470

Figure 24: Map of estimated 50/70 blocks in bench 3470



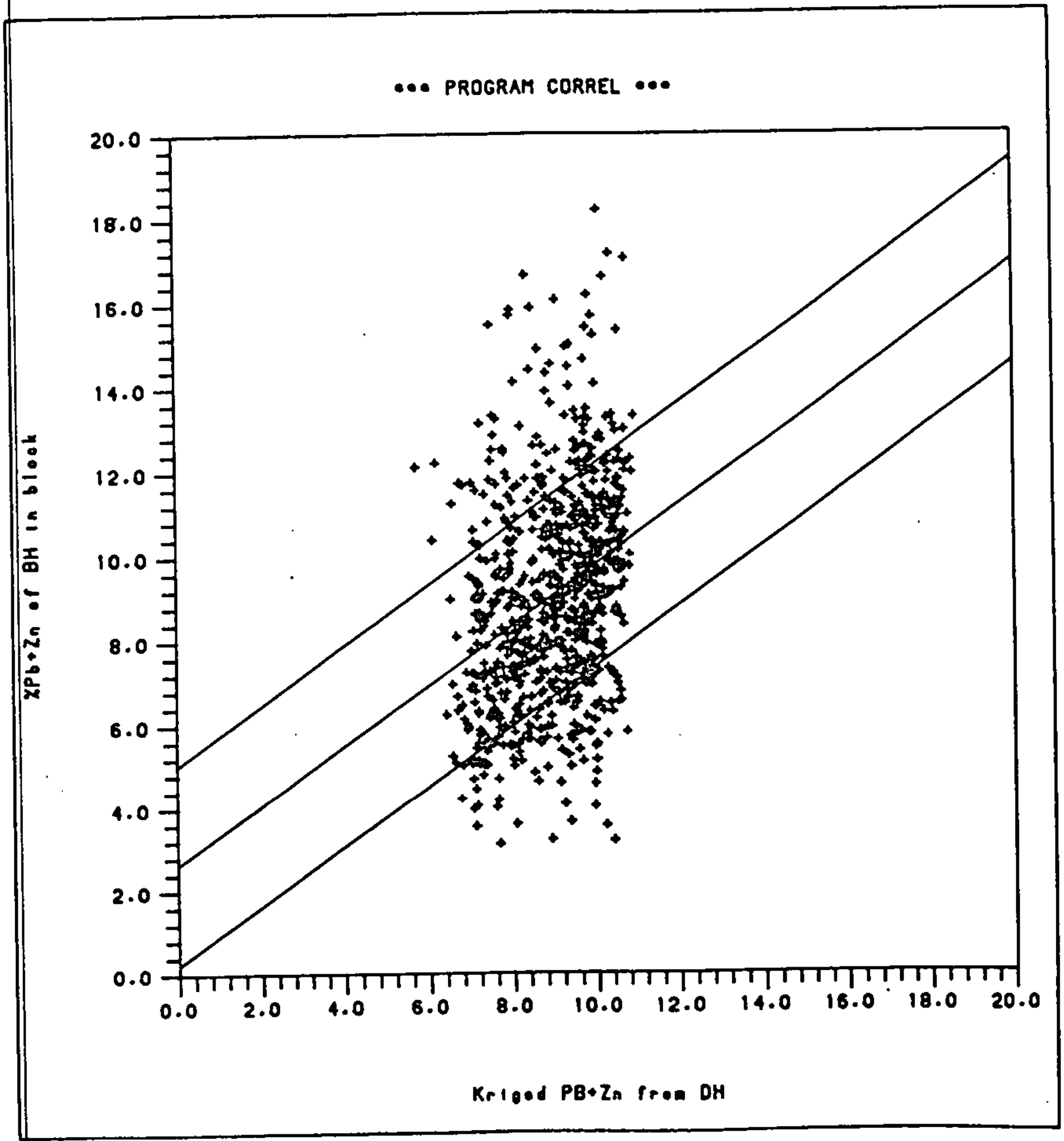


Figure 25: Correlation of kriged DH block and mean BH block % Pb + Zn in 50/70.

1.7 VALIDATION OF THE GEOLOGICAL MODEL

In the current long term prediction model, blocks are first classified according to their ore type, then their average grade is derived from drill hole bench composites of the same ore type around the block. In addition to the grade inference error which has been covered in the previous section, another source of error might be a wrong ore type assignment for the block. To get an idea of the degree of misclassification of blocks according to their ore type, we have checked the assignment of the ore code of drill hole bench composites against the assignment of the same ore types to blast holes nearby (assuming that the categorization of blast holes is more precise than that of drill hole bench composites since we can map ore type limits in a blast). In that part of the study, we have looked at the ore type of the nearest blast hole (within a 20' distance) to each drill hole composite in the test benches 3490, 3470 and 3450. Results are summarized on Table 16. Our comments are:

- more than 50% of the drill hole bench composites of type 20 + 30 (Total: 55) have a blast hole of type 50 + 60 + 70 nearby.

- more than 50% of the drill hole bench composites of type 40 (Total: 26) have a blast hole of type 55 nearby.

- about 70% of the drill hole bench composites of type 50 + 60 + 70 (Total: 96) have a blast hole of the same type nearby.

Hence it appears that the classification of the predominantly high grade types 50 + 60 + 70 is consistent from drill holes to blast holes.

Also, if we pool together the mostly low grade types 40 and 55, classification of these types is also adequate. We have more problems with types 20 and 30 : most of the drill hole bench composites of those types are surrounded by generally higher grade blast holes of type 50 , 60 or 70. In fact, out of the total 177 pairs of D.H./B.H., 55 (31%) involve a D.H. composite of type 20 + 30 whereas only 37 (21%) involve a B.H. of the same type. Hence types 20 and 30 seem to be underrepresented in drill hole composites compared to blast holes.

Table 16: Ore type of the nearest blast hole (within a 20' distance) to drill hole bench composites of various types.

Ore type of D.H.	Ore type of nearest B.H.									
	0	10	20	30	40	50	55	60	70	Total
20	0	0	17	5	1	24	1	0	1	49
30	1	0	1	1	0	3	0	0	0	6
40	1	0	1	0	1	8	14	0	1	26
50	0	0	4	3	1	56	9	0	2	75
60	2	0	0	0	3	3	2	0	0	10
70	0	0	4	1	0	6	0	0	0	11
Total	4	0	27	10	6	100	26	0	4	177

2 SHORT TERM PREDICTION FROM BLAST HOLE DATA

We have already introduced the reference blast hole data set in section 1-6 with summary statistics of their % Pb + Zn data on Table 12. Those blast holes are categorized according to the predominant ore type. Since some of the ore types are mostly low grade (55) and others are high grade (50-70), the distribution of all their % Pb + Zn values is rather heterogeneous. Histogram is a "fat" bell shaped curve with its peak at about 7.30 % Pb + Zn and large quantities of low and high grades (Figure 26). There is also a tail of very high grade data (above 15%). The coefficient of variation, 45% is fairly high considering that data come from a fairly restricted zone. If we look at distributions of values according to ore types, we also see some heterogeneities within each group:

x Distribution of the 37 %Pb + Zn values in type "0" is positively skewed with most values below 2% and other values up to 7%.

x Out of the 12 blast holes classified as "10", 2 are above 12% whereas the balance is 5% or less. As a result, the coefficient of variation for the 12 %Pb + Zn values in that group is 89%.

x Most of the 398 values classified in type 20 are within the range 2-10%. However, maximum reaches 17.68%. Coefficient of variation is similar to that for overall data 46%.

x The 170 data in type 30 are more homogeneous. Most values are within the interval 3 - 14%. Coefficient of variation is only 35%.

x In type 40, we just have 55 values ranging from 2 to 12%. Coefficient of variation is the same as overall (45%).

x Like in 30, the 1061 data in 50 are more concentrated: 90% of the values lie in the interval 5 - 14%. There are a few high outliers up to 20%. Coefficient of variation is a mere 30%.

x The 263 values in type 55 have the typical distribution of low grade material: lots of low values (median is just about 2%) and a few scattered high values (up to 13%). As a result, the coefficient of variation is pretty high: 62%.

x There is not much to say about the 6 blast holes classified in type 60. Values range from 6 to 16%. Coefficient of variation is 25%.

x Distribution of the 81 values in type 70 is well homogeneous with values from 5 to 13% and a coefficient of variation of 25%.

Formally, the current short term prediction model is also a block model with a distance weighting grade interpolation method: blocks are the 25 x 25 ft volume of influence of a blast hole and the interpolation method is nearest neighbor (or polygon). In other words, the grade estimate for a blast block is the grade of the single blast hole sample in the middle of the block. Like for the long term prediction model from drill holes, it is possible to assess the standard error a single blast-block grade estimate or a group of them. We just need compute and model variograms of blast hole grade.

At this point, we can calculate a) a global variogram of all the 2083 B.H. data available whatever their rock type assignment b) variograms in each rock type or combination of rock types.

Blast hole variograms are well defined provided they are computed on a few hundred data points. We have just computed horizontal variograms: with only data from 3 benches, we don't have that much information on B.H. grade variations through benches. Also, if we were to implement a blast hole distance weighting grade interpolation procedure (some form of blast hole kriging) we would tend to limit ourselves to blast holes on the same bench as the blast-block to estimate.

An example of blast hole variogram is given on Figure 27. It is for the % Pb + Zn of all available blast holes. In addition to the average variogram (circles), we have directional variograms along E-W (triangles) N-S (X) NE (+) and NW (diamond). Step to classify distances is 25' along E-W and N-S and 36' along NE and NW. All variogram points are defined from a large number of samples. There is no restriction on sample data. Those variograms show:

> + a well defined nugget effect of about 4 $(\%)^2$ i.e. about 35% of the variance of 11.5. Note that this is exactly the same as the nugget effect of % Pb + Zn of bench composite in both 20 + 30 and 40 + 70 ore types. Hence it looks like the sampling precision of blast holes is as good as that of drill holes.
>
> + a short range structure of about 100' (average variogram). For short distances, less than 100', we can detect some anisotropy pattern on directional variograms which is similar to the one observed on the bench composite variograms of type 20-30: top variogram (least continuity) is E-W and bottom variogram (best continuity) is N-S.
>
> + a long range structure of about 350' i.e. similar to what we had for the D.H. bench composites variograms.

Blast hole variogram models for various combinations of ore types are given on Table 17. We can see that:

> + the strong E-W/N-S anisotropy that we had for D.H. composites in 20/30 is still visible in the blast hole grades of the some ore type.
>
> + likewise, the variograms of blast holes in 50-60-70 is isotropic.

+ low grades 40 and 55 have been pooled together for variogram computation. The variograms show a strong trend at long distances due to the presence of isolated high grade blast holes categorized in those ore types. The model used does not take that trend into account.

To check the performance of various blast hole grade interpolation methods, we can use the same sample reuse method that we had for D.H. bench composites. The idea is to reestimate each of the 2083 B.H. % Pb + Zn grades from blast holes around using various interpolation methods and segregation of blast holes by ore type. Results are in Tables 18 and 19.

For example, if we do the reestimation with no segregation at all, we get a pretty good correlation between original and reestimated B.H. grade if we use kriging (r = 0.70 - Figures 28). It is not so good if we just use the nearest neighbor method (r = 0.56 - Figure 29) even if the dispersion of estimates perfectly matches that of the original data (see table 28). In fact, even if kriged estimates are smoother than real values, we can see one advantage of kriging over nearest-neighbor: the regression line of real on estimate is almost an y = x line. This means that if we mine all blast holes with an estimate of 6% the true average of these blast holes is 6% : we mine what we anticipate. There is no shortfall of grade above cut-off. On the other hand, if we use the nearest-neighbor approach, the regression line is like y = 0.56 x + 3.2. If we enter estimates (x) of more than 3.2/(1.056) = 7.27% Pb + Zn in this equation, the corresponding mean true value (y) is less than the estimate. Hence we overestimate high grade. For example, if we apply a cut-off of 6% Pb + Zn to the nearest-neighbor estimates, we get 1367 blast holes (66%) with an average estimated grade of 9.37% Pb + Zn but an average true grade of 8.57%. If we apply the same cut-off to the kriged estimates, we get 1560 blast holes (75%) with an average estimated grade of 8.46% Pb + Zn and an average true grade of 8.52%. Hence with kriging, we recover more tonnes (12%) at the expected grade. With nearest neighbor we have a grade shortfall of 8.5%.

We get even better results if we do the kriging of blast holes independently in 20-30, 50-60-70 and all the low grades 55-40-00-10 together. Correlation coefficient of real data and estimates is now 0.74 (Figure 30), regression line of real on estimate is virtually y = x. As a result, if we apply the 6% Pb + Zn cut-off on the estimates, we recover 1519 data (73%) with an average estimated value of 8.65% Pb + Zn and an average true value of 8.64%. We get a little less tonnage than in the case when we use all blast holes together but with a higher recovered grade. Our selectivity has improved.

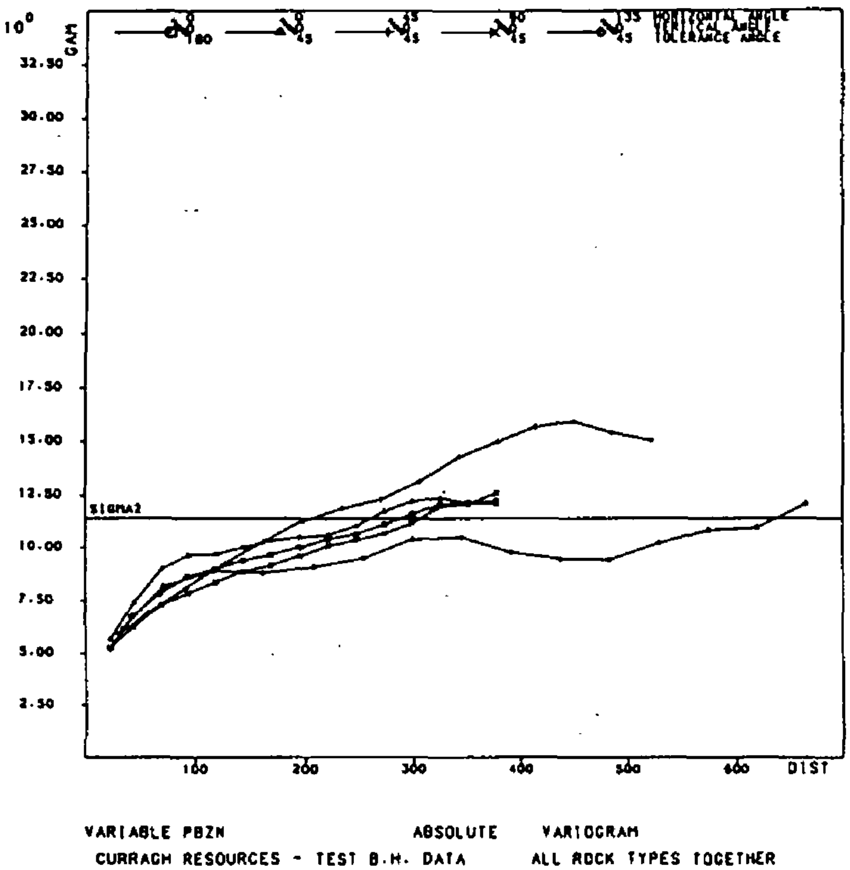


Figure 27: Horizontal variograms of all B.H. % Pb + Zn available.

Figure 28: Correlation plot of real vs reestimated B.H. % Pb + Zn kriging. All B.H.s together.

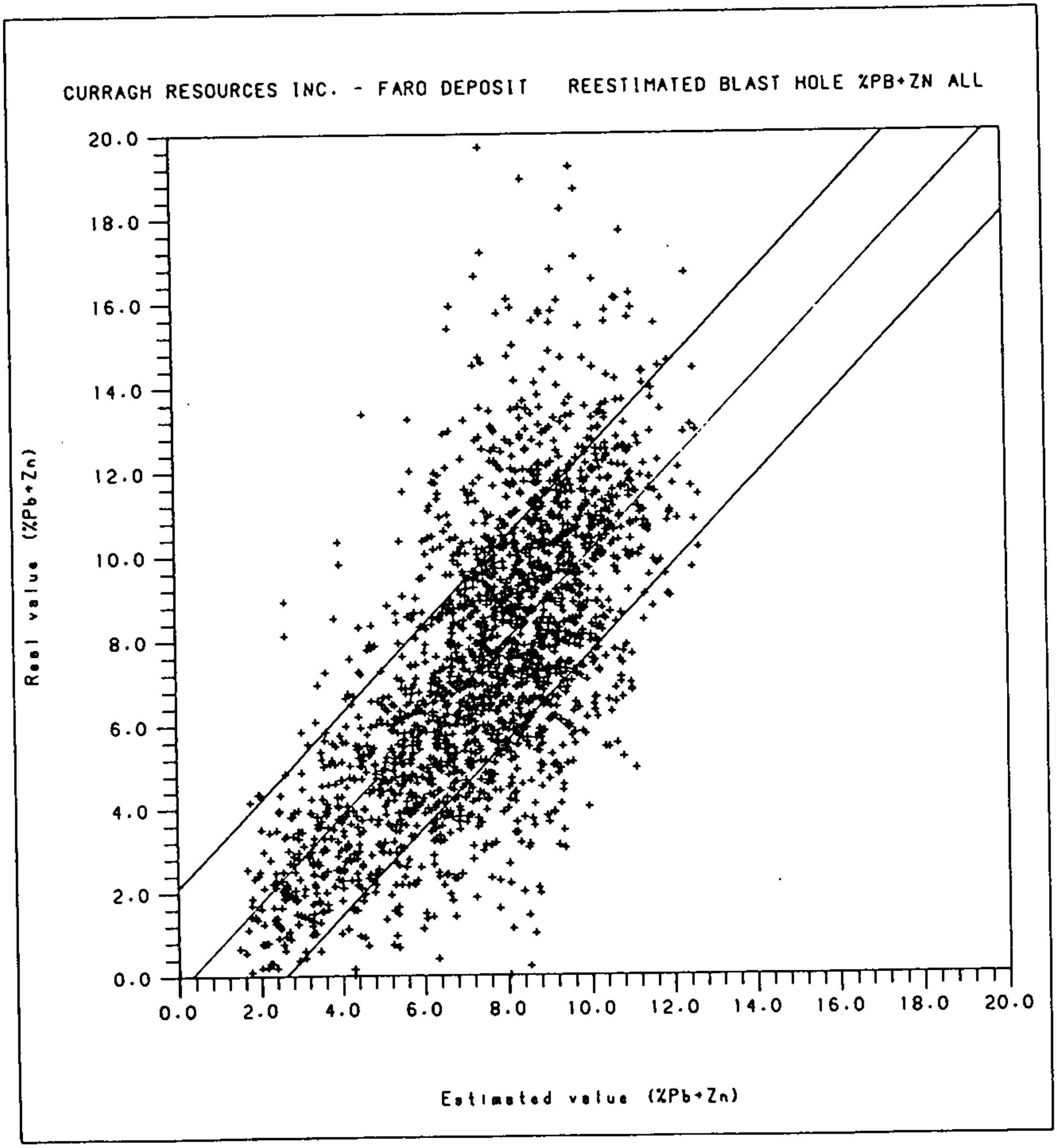


Figure 29: Correlation plot of real vs reestimated B.H. % Pb + Zn nearest neighbor. All B.H.s together.

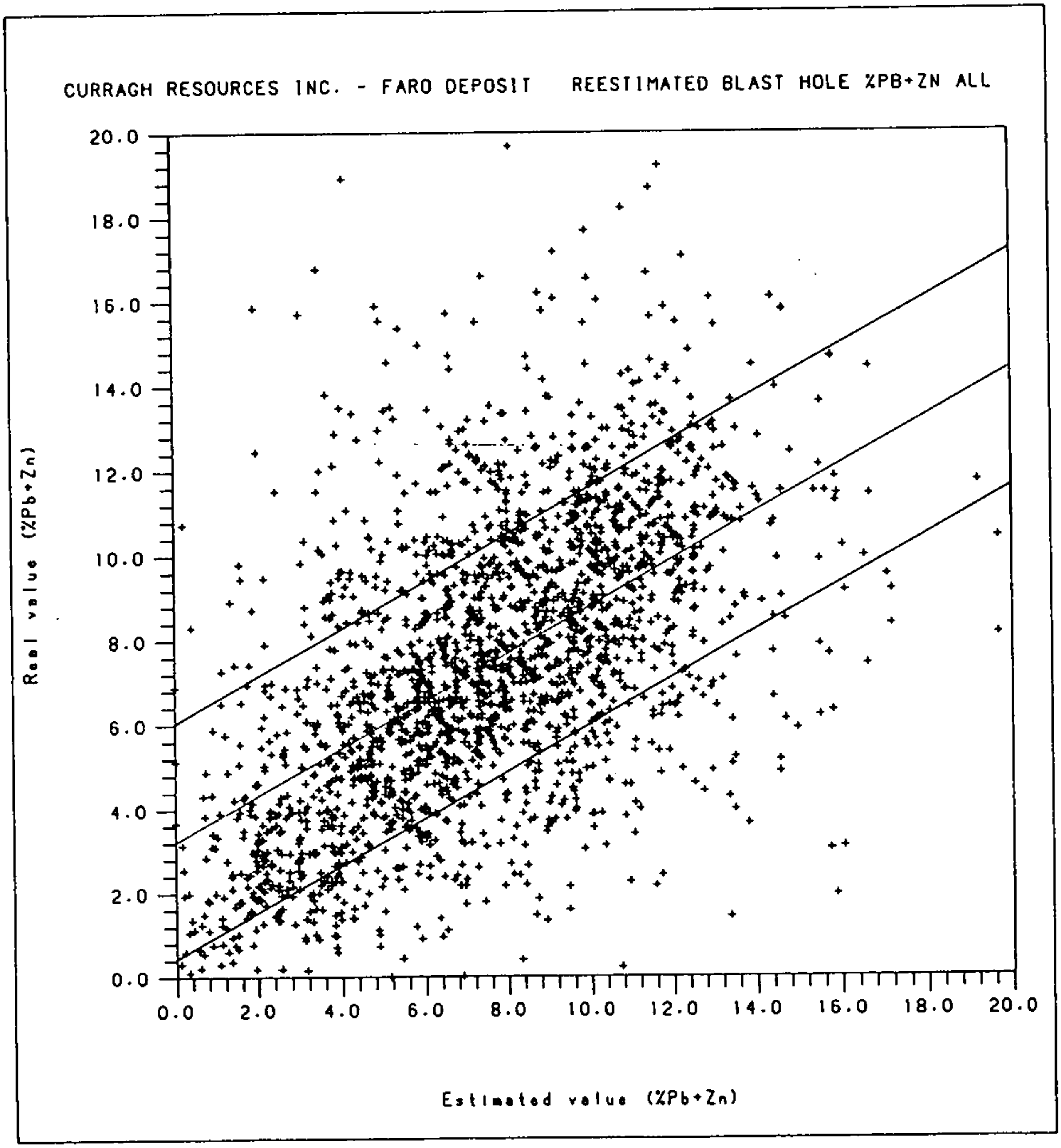


Figure 30: Correlation plot of real vs reestimated B.H. % Pb + Zn kriging. 3 separate ore types.

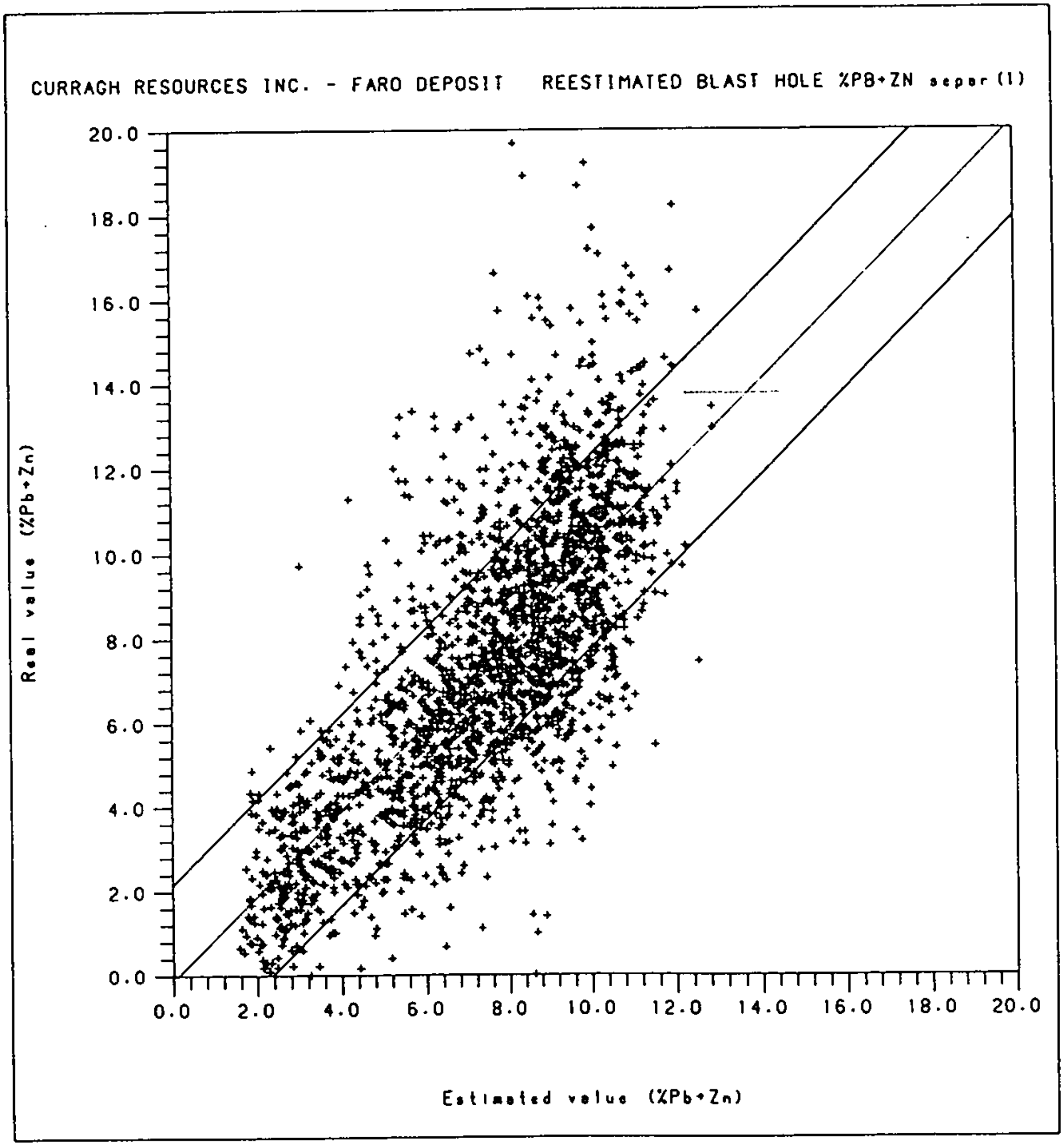


Table 17: Models of % Pb + Zn horizontal variograms for blast holes.

Blast holes	Nugget Effect $(\%)^2$	Sill $(\%)^2$	Spherical 1 Ranges (ft)	Sill $(\%)^2$	Spherical 2 Ranges (ft)	Sill $(\%)^2$	Spherical 3 Ranges (ft)
All (N = 2083)	4	3.5	100	4.0	350	-	-
20 + 30 (N = 568)	3.5	2.0	50	2.5	75 (E-W) 500 (N-S)	-	-
50-60-70 (N = 1148)	4.0	0.5	50	3.0	300	-	-
40 + 55 (N = 318)	1.5	0.5	50	1.0	250	-	-

Table 18: Statistics of errors in the reestimation of % Pb + Zn grade of B.H.s for B.H.s around (on the same bench).

B.H. grouping	Interpolation method	Number of reestimations	Error (%)	Average Absolute error (%)	Experimental error variance $(\%)^2$	Theoretical error variance $(\%)^2$
All	Kriging	2078	-0.017	1.84	5.83	6.07
All	Nearest Neighbor	2078	-0.071	2.34	10.04	9.43
20-30 50-60-70 00-10-40-55	Kriging	2078	0.00	1.72	5.12	4.95

Table 19: Correlation of estimates and real values in the reestimation of % Pb + Zn grade of B.H.s from B.H.s around (on the same bench).

		Standard deviations		Correlation coefficient	Regression real = f (estimates)
B.H. grouping	Interpolation method	Real	Estimates		
All	Kriging	3.37	2.26	0.70	y = 1.04 x - 0.3
All	Nearest Neighbor	3.37	3.36	0.56	y = 0.56 x + 3.2
20-30 50-60-70 00-10-40-55	Kriging	3.37	2.46	0.74	y = 1.015 x - 0.11

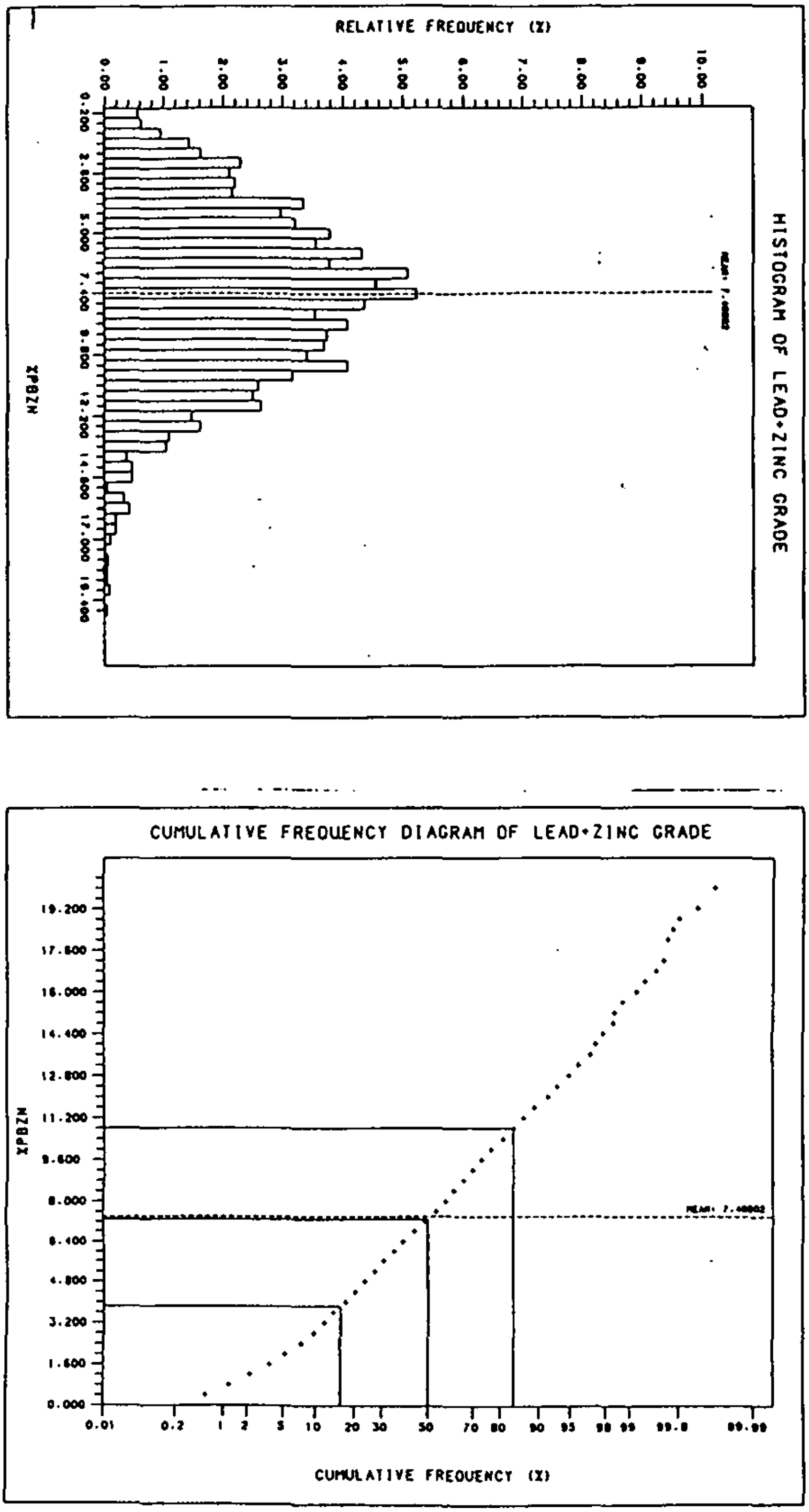


Figure 26: Histogram of all B.H. % Pb + Zn available.