Calculations of grade and tonnage for two co-products from a projected South African gold mine

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SYNOPSIS

Consideration is given to the problem of the estimation, from limited data, of the likely grade and tonnage for a new mining property that is to be exploited by the selective mining of two metals that have substantial contributions to make to the total revenue. In particular, the case of a new gold and uranium mine in South Africa is analysed as follows.

(1) The applicability of the underlying lognormal bivariate model for different support (i.e. ore unit) sizes is examined.

(2) The necessary parameters for the bivariate lognormal models for different block sizes are estimated from abundant chip-sampling data from a section of the Hartebeestfontein Gold Mine using alternative approaches, and the results are compared.

(3) A method is given for obtaining the necessary parameters for a tonnage-grade relationship relative to a joint pay limit from the very limited information likely to be available at the end of the exploration stage of a gold mine, and the results are compared with those obtained from the large volume of data available from a mined-out area.

SAMEVATTING

Oorweging word geskenk aan die probleem van die beraming, aan die hand van beperkte data, van die waarskynlike graad en tonnemaat van 'n nuwe mynbou-eiendom wat ontgin moet word deur die selektiewe ontginning van twee metale wat aansienlike bydraes tot die totale inkomste kan lewer. Veral die geval van 'n nuwe goud-en-uraanmyn in Suid-Afrika word soos volg ontleed:

(1) Die toepaslikheid van die onderliggende lognormale bivariantmodel vir verskillende steungroottes (d.w.s. ertseenheidgroottes) word ondersoek.

(2) Die nodige parameters vir die lognormale bivariantmodelle vir verskillende blokgroottes word met gebruik van alternatiewe benaderings aan die hand van volop spaandermonsternemingsdata van 'n seksie van die Hartebeestfontein-goudmyn geraam en die resultate vergelyk.

(3) Daar word 'n metode aangegee om die nodige parameters vir 'n tonnemaat-graadverhandeling relatief tot die rendeergrens te kry van die uiters beperkte inligting wat waarskynlik aan die einde van die eksplorasiestadium van 'n goudmyn beskikbaar sal wees, en die resultate word vergelyk met dié wat verkry is van die groot volume data wat vanaf 'n uitgewerkte gebied beskikbaar is.

Applicability of Bivariate Lognormal Model

The model used for the grade–tonnage calculation for ore above a joint pay limit is the bivariate lognormal model as outlined in Fig. 1 (Krige[2]). The important features to keep in mind are that the marginal distributions and the correlation coefficient are applicable to ore block values that are considered to be of an appropriate size for selective mining.

At the inception of a project, the model usually has to be applied directly to grades obtained from ore units of small support, i.e. chip-sampling sections or boreholes; also, the data are not abundant enough to prove in a practical way the applicability of the model to larger ore units.

In addressing this problem, the author used 3991 chip-sampling values from a reasonably homogeneous section of the Hartebeestfontein gold mine measuring some $1\frac{1}{2}$ by 2 km. The values were gathered individually with coordinates from 1978 onwards (Magri[3]).

As a test of the applicability of the bivariate lognormal model for different support sizes, the following procedure was used.

Chip-sampling Data

Histograms and cumulative frequency plots were constructed for the 3991 gold and uranium values in cm.g/t and cm.kg/t respectively. These are shown in Fig. 2. It can be seen that the three-parameter lognormal model is a good approximation for the marginal distributions.

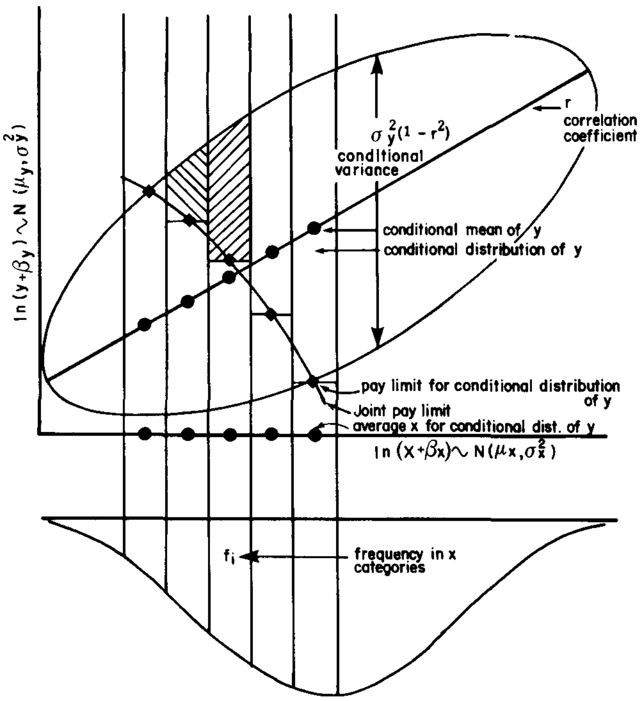

Fig. 1—Outline of tonnage-grade calculation relative to a joint pay limit

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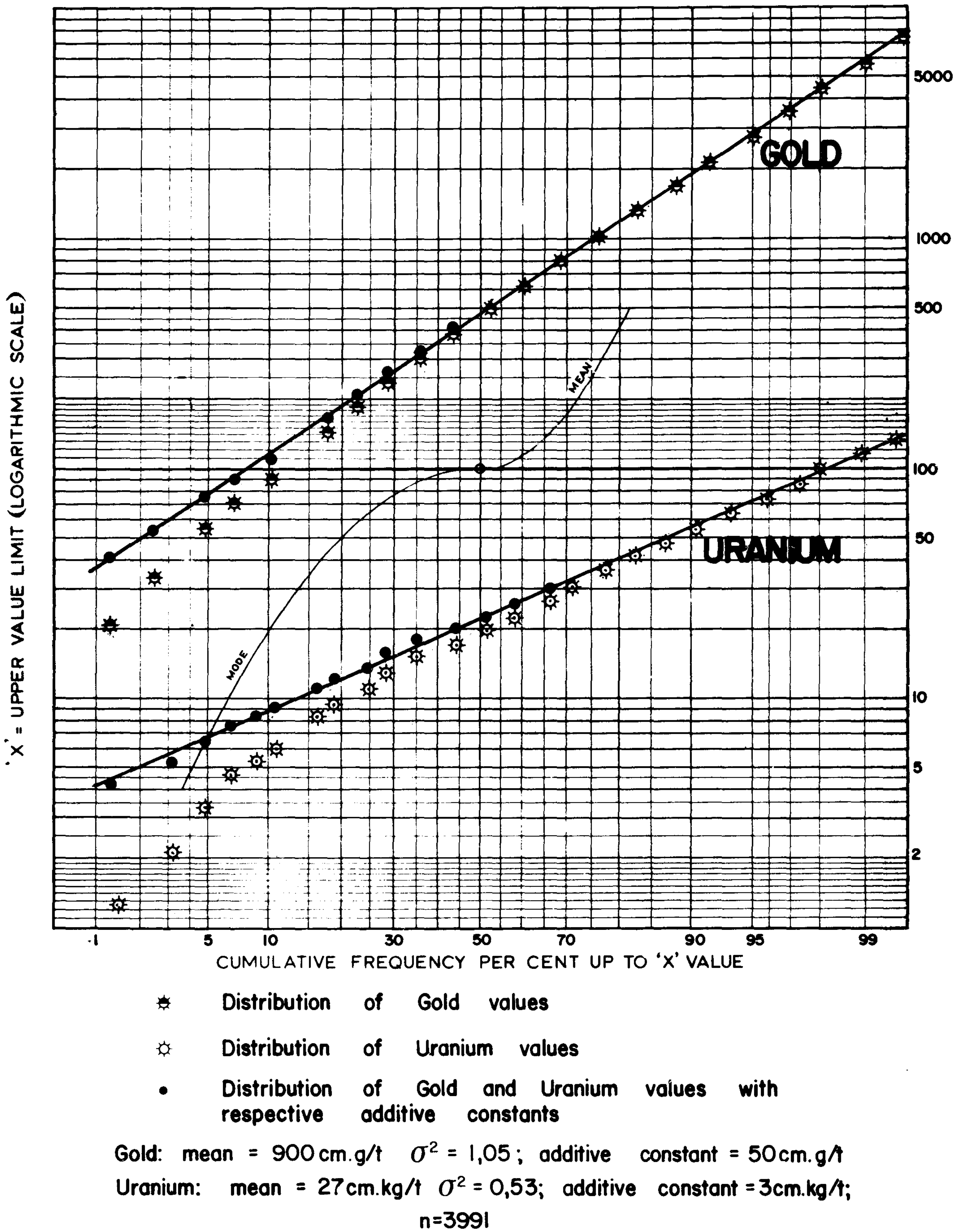
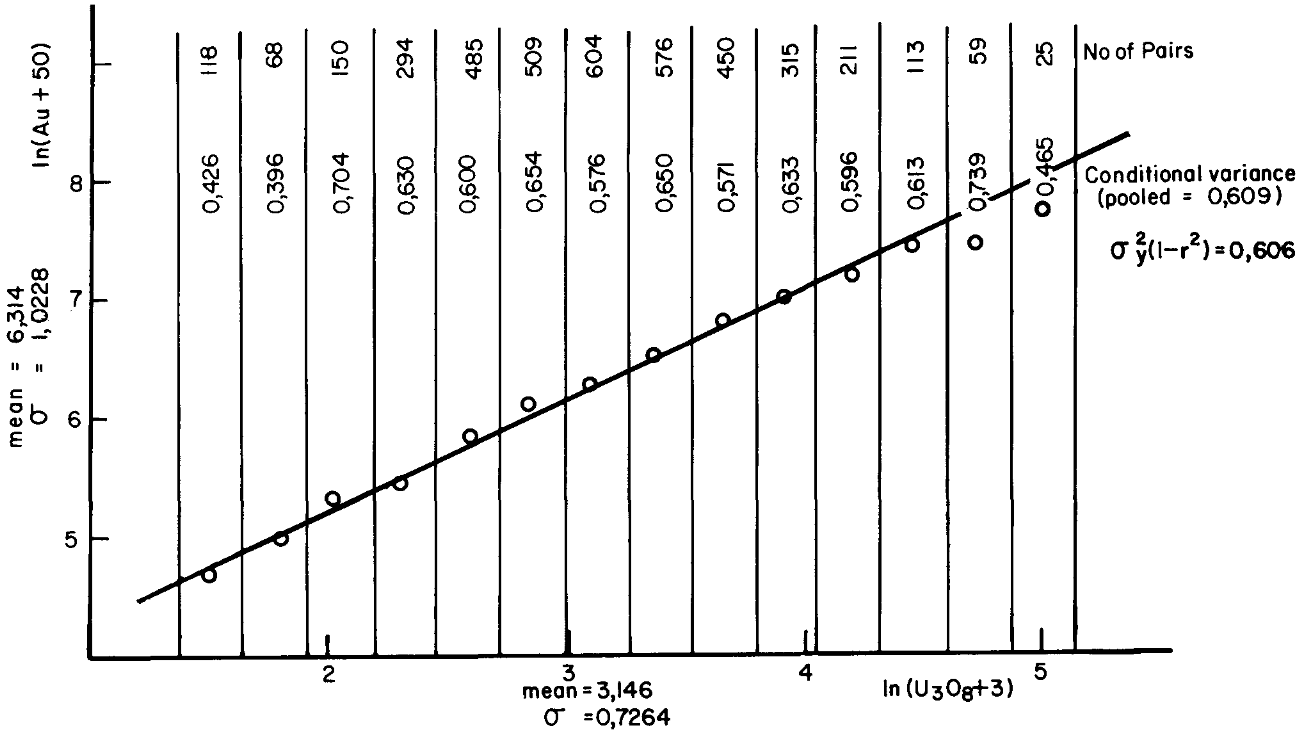


Fig. 2—Distribution of gold and uranium samples for a section of Hartebeestfontein Gold Mine



Regression line : $\ln(Au + 50) = 0,914 \ \ln(U_3O_8+3)+3,441$

$n = 3991 \qquad r = 0,649$

Bartlett's test : $\chi^2 = 20,5$; df = 13; critical value : $\chi^2_{.95} = 22,3$

Fig. 3—Bivariate normal test for samples

The joint distribution of gold and uranium values was split into a number of 'slices' (conditional distributions), and the conditional means and variances were calculated. This is shown in Fig. 3. It can be seen that the conditional means follow an approximately linear trend, and the result of Bartlett's test shows that the conditional variances can be considered homogeneous, thus supporting the use of the bivariate lognormal model. The application of Bartlett's test can be partially justified since most of the inter-correlation between samples is probably destroyed by the conditioning process.

15 m × 15 m Blocks

The chip-sampling data were condensed into 15 m × 15 m blocks, and only those blocks containing more than 4 samples were used for the bivariate test. (The average number of samples per block was 6,4.) Fig. 4 shows the lognormal fit to the marginal distributions, while Fig. 5 shows the procedure followed with the joint distribution.

30 m × 30 m Blocks

The basic data were also condensed into 30 m × 30 m blocks. Only those blocks with a reasonable number of samples were accepted, and 172 blocks were found. Data collected by the mine before 1978 in the form of averages of 7,5 m × 7,5 m blocks in the same mine section were also used by combining groups of 16 blocks. These were then used in conjunction with the 172 blocks based on the 3 991 sampling sections. The results can be seen in Figs. 6 and 7.

60 m × 60 m Blocks

The analyses carried out for the 60 m × 60 m blocks were similar to those for the 30 m × 30 m blocks. The results can be found in Figs. 8 and 9.

In all cases, Bartlett's test supported the use of the bivariate lognormal model.

Comparison between Sets of Data

The parameters obtained for three bivariate block distributions based on chip-sampling information and those observed from actual block values were compared by the following procedure.

Semi-variogram Analyses

Based on the available 3991 individual chip-sampling sections, the combined semi-variograms (average of all directions) for gold values after transformation and the cross semi-variogram, i.e. between transformed gold and uranium values, were obtained. Models were fitted to these experimental semi-variograms, and the average semi-variograms within 15 m × 15 m, 30 m × 30 m, 50 m × 50 m, and 100 m × 100 m blocks were obtained by numerical integration.

The results are shown in Fig. 10 for gold, and Fig. 11 for the cross products. The cost of each semi-variogram run in an IBM 370–158 computer was approximately R700.

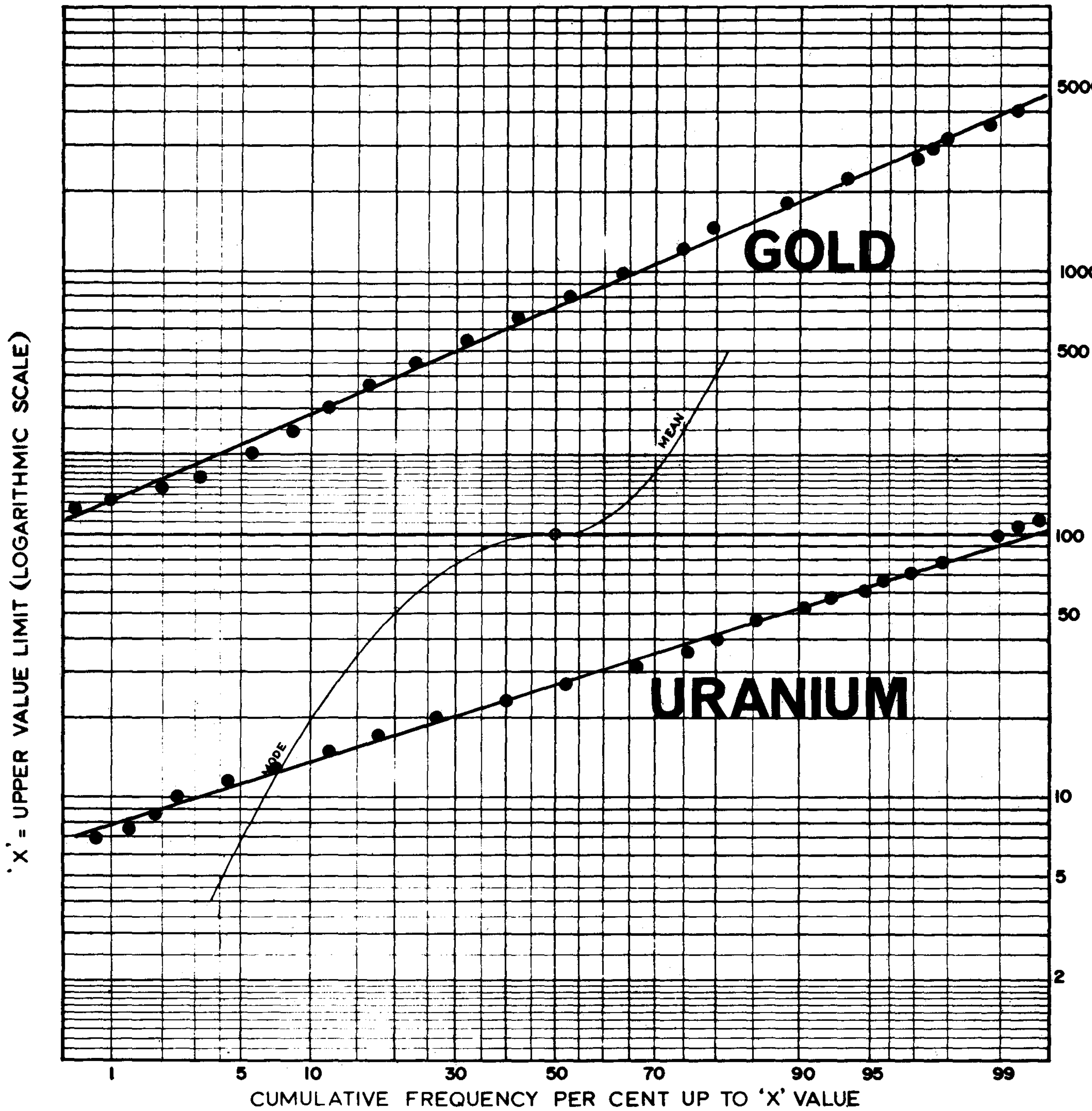
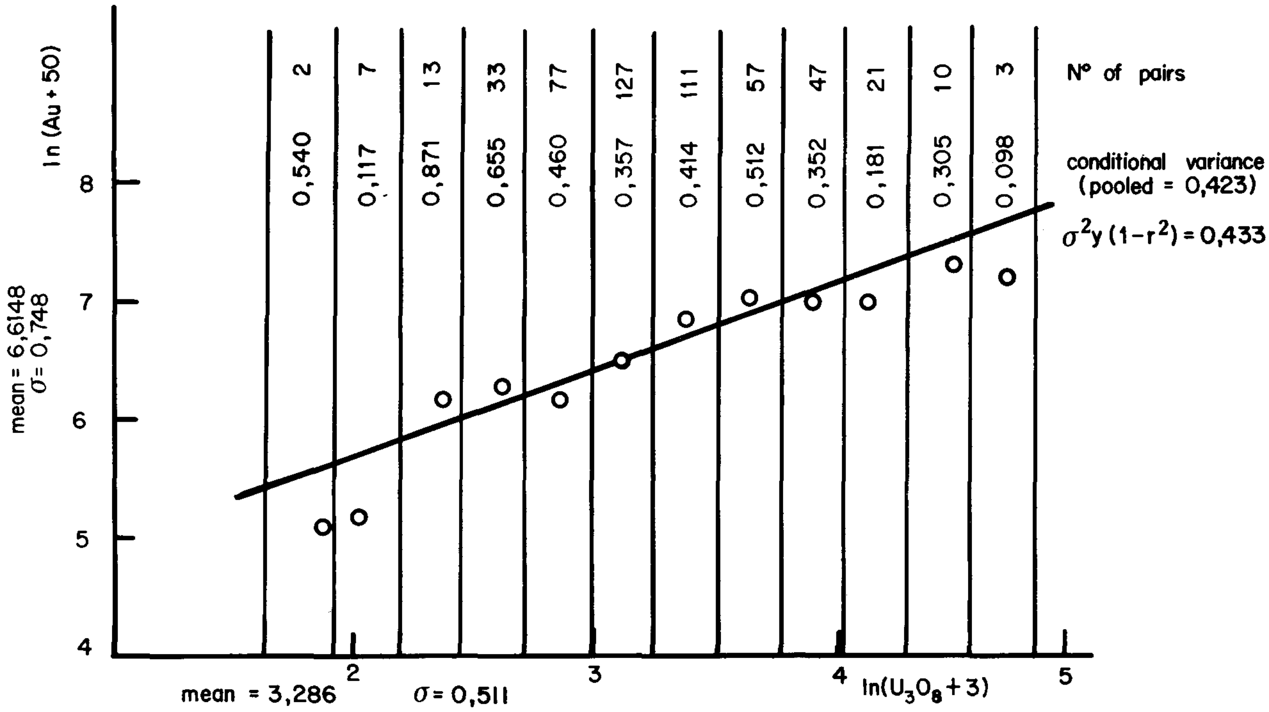


Fig. 4—Gold and uranium distributions of 15m × 15m blocks with more than 4 samples per block n=510, additive constants as in Fig. 2



Regression line : $\ln(Au + 50) = 0{,}695 \ln(U_3O_8 + 3) + 4{,}331$

$n = 508$ $\quad r = 0{,}475$

Bartlett's test : $\chi^2 = 19{,}4$; df = 11 ; critical value : $\chi^2_{.95} = 19{,}7$

Fig. 5—Bivariate normal test for 15m × 15m blocks

Relationships between Variance (Covariance) and Size of Area

The relationships between the variance (covariance) and size of area were calculated directly from the 3991 chip samples by successively subdividing the total area into different block sizes, calculating the logarithmic variance (covariance) for each block, and pooling these estimates to give the average variance (covariance) of samples within a particular block size (Krige[4]).

These average variances (covariances) were plotted against the logarithms of the linear equivalents (sum of two adjacent sides of a two-dimensional block) of the different blocks. These are shown in Figs. 12, 13, and 14 for gold, uranium, and cross products respectively (plots based on 3991 samples).

The cost of a calculation of the relationship between variance and size of area was approximately R7 in the computer mentioned earlier.

Since the results of the semi-variogram (cross semi-variogram) integration also provide estimates of the variances of point samples within the different block sizes, these results were also plotted in Figs. 12 and 14 for gold and cross products respectively. It can be seen that the variogram integration results match the variance/size of area procedures fairly well; therefore, in view of the costs and effort of computation involved, the latter approach is preferred in the case where the study of anisotropies is not required.

The theoretical gold and uranium block variances for hte different block sizes shown in Table I were obtained by use of the additivity of variances theorem (Krige)[4], which is illustrated in Fig. 12 and is defined by

Variance of 'true block values' within the population	=	Observed variance of samples within the population	−	Observed average variance of samples within a block.

It is important to note that, in the mining process, blocks are selected according to their estimated values and not their true values; therefore, the likely errors of estimation of the blocks should be deducted from these variances. However, for the purpose of this exercise, this effect was ignored.

Since a similar theorem is applicable to covariances, the covariances and thereby the correlation coefficients between gold and uranium block grades were obtained; these are also shown as theoretical results in Table I.

It is worth noting that the hypothesis underlying the 'variance/size of area' computation procedure for log-transformed data is that the logarithmic variance of the geometric mean grades of blocks is the same as that for the arithmetic means of blocks since the difference between these two is constant on a logarithmic scale, provided the variance of samples within the blocks of a particular size is constant throughout the given population.

Practical Observations

The basic chip-sampling data were gridded into 15 m × 15 m, 30 m × 30 m, and 60 m × 60 m blocks, and only blocks with more than a minimum number of

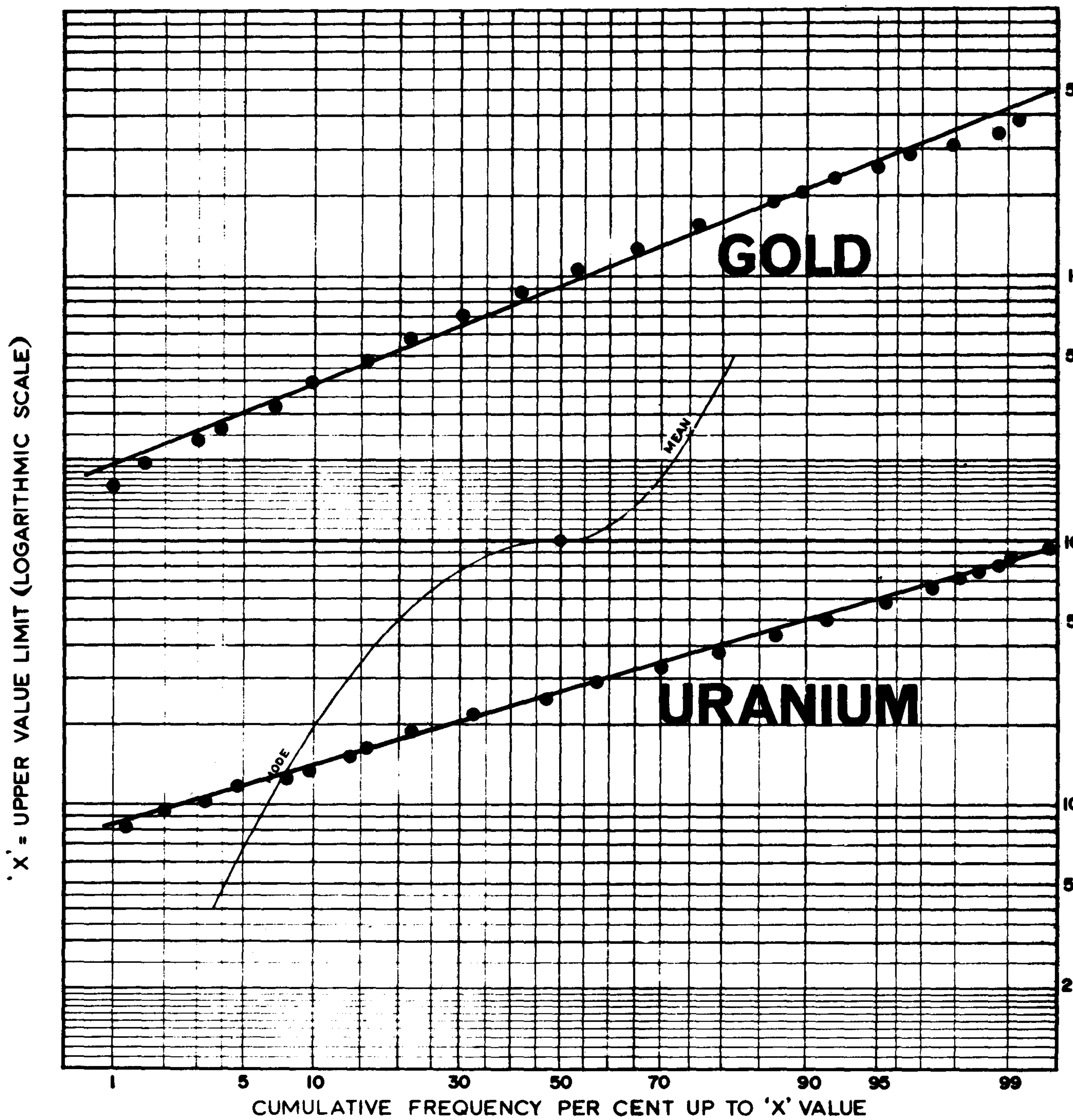
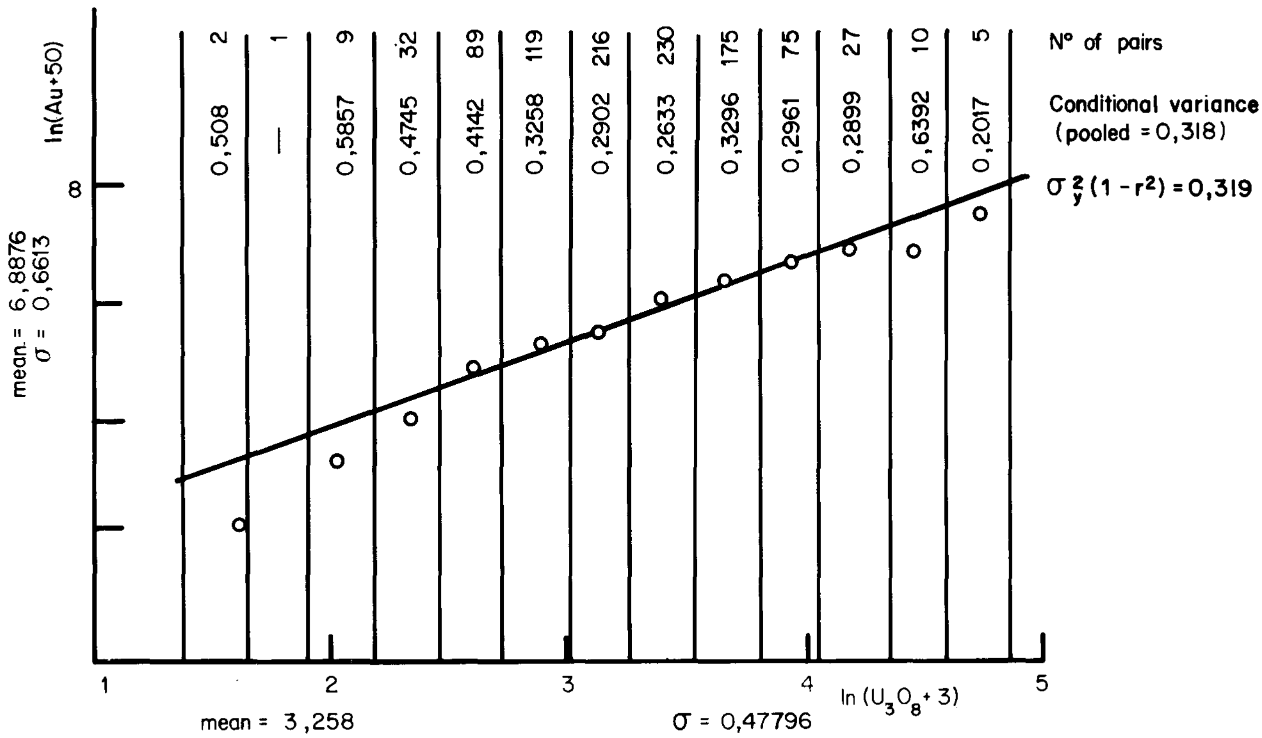


Fig. 6—Gold and uranium distributions of 30m × 30m blocks n = 990, additive constants as in Fig. 2



Regression: $\ln(Au+50) = 0,7205 \ \ln(U_3O_8+3) + 4,540$

$n = 990$ $r=0,521$

Bartlett's test: $\chi^2 = 15,7$; df = 11; critical value: $\chi^2_{.95} = 19,7$

Fig. 7—Bivariate normal test for 30m × 30m blocks

TABLE 1

COMPARISON OF GOLD AND URANIUM CORRELATION FOR DIFFERENT BLOCK SIZES

Item	Type of result	No. of samples	Mean Au (cm.g/t)	β Au (cm.kg/t)	Mean U (cm.kg/t)	β U (cm.kg/t)	σ^2 Au	σ^2 U	Cov (Au, U)	r
Point samples	Observed	3 991	916	50	27,4	3	1,048	0,534	0,488	0,65
15 m × 15 m blocks	Observed	510	936	50	27,5	3	0,559	0,261	0,181	0,47
	Error of estimation ..						0,240	0,070	0,070	—
	Observed – error ..						0,319	0,191	0,111	0,45
	Theoretical						0,308	0,194	0,122	0,50
30 m × 30 m blocks	Observed	172	944	50	26,9	3	0,425	0,196	0,125	0,43
	Error of estimation ..						0,150	0,030	0,020	—
	Observed – error ..						0,275	0,166	0,105	0,49
	Theoretical						0,263	0,164	0,102	0,49
60 m × 60 m blocks	Observed	94	987	50	26,5	3	0,286	0,159	0,0863	0,40
	Error of estimation ..						Difficult to estimate			
	Observed – error ..									
	Theoretical						0,223	0,136	0,082	0,47

β: additive constant, i.e. third parameter of a lognormal distribution

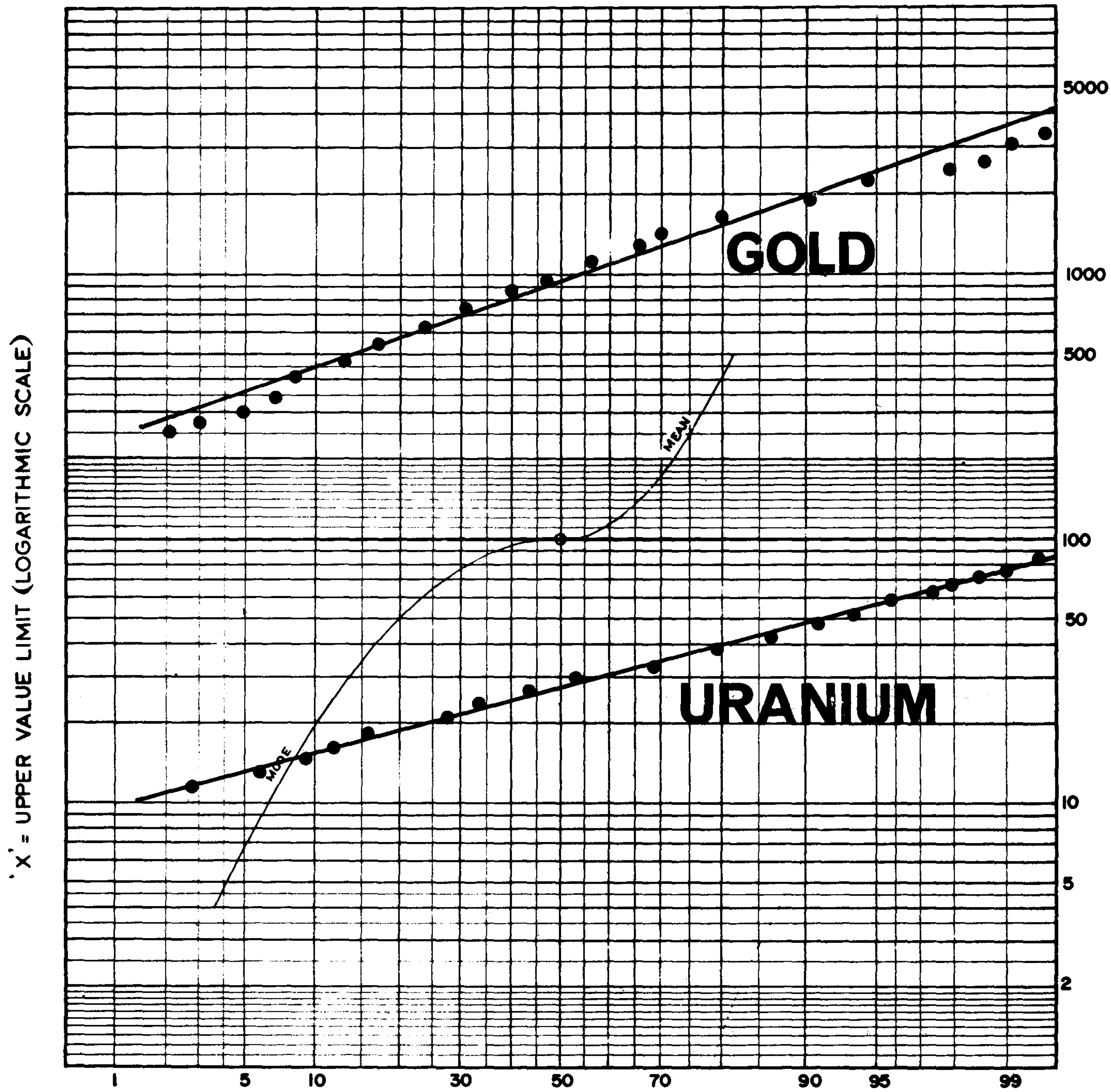
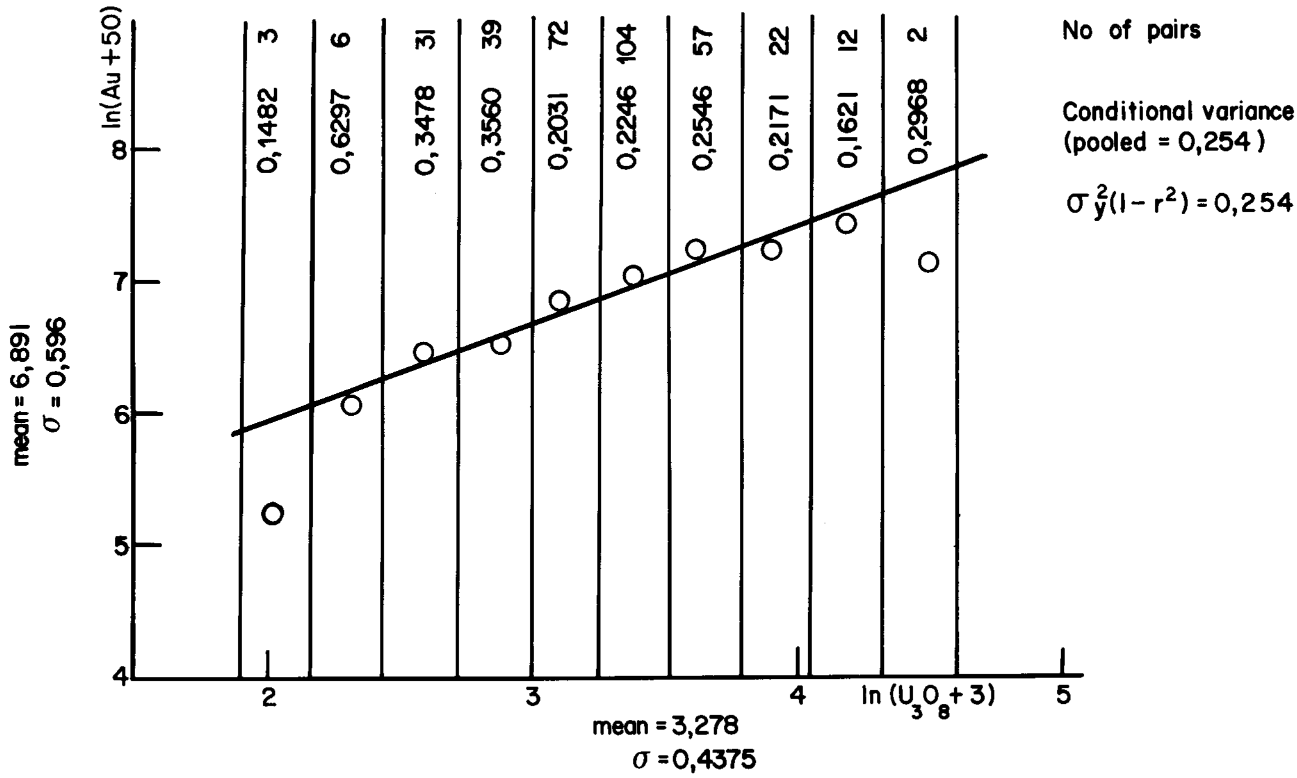


Fig. 8—Gold and uranium distributions for 60m×60m blocks
n=349, additive constants as in Fig. 2

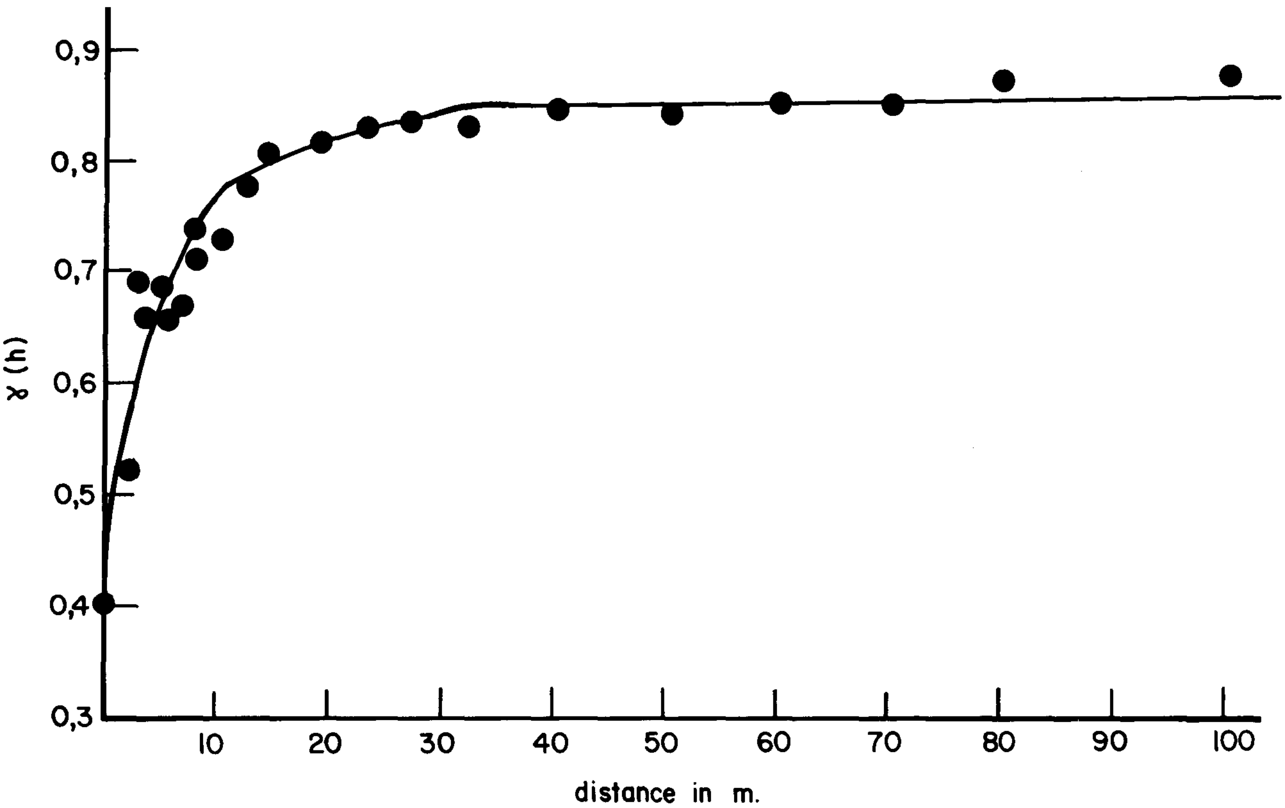


Regression line : $\ln(Au + 50) = 0{,}7254 \ln(U_3O_8 + 3) + 4{,}5136$

$n = 349$ $r = 0{,}533$

Bartlett's test : $\chi^2 = 10{,}1$; df = 9 ; critical value : $\chi^2_{.95} = 16{,}9$

Fig. 9—Bivariate normal test for 60m×60m blocks



n = 3991 $\sigma^2 = 1{,}048$

Semi - variogram model : nugget effect = 0,4 ; structure 1 : spherical (10 ; 0,33)

structure 2 : spherical (40; 0,125)

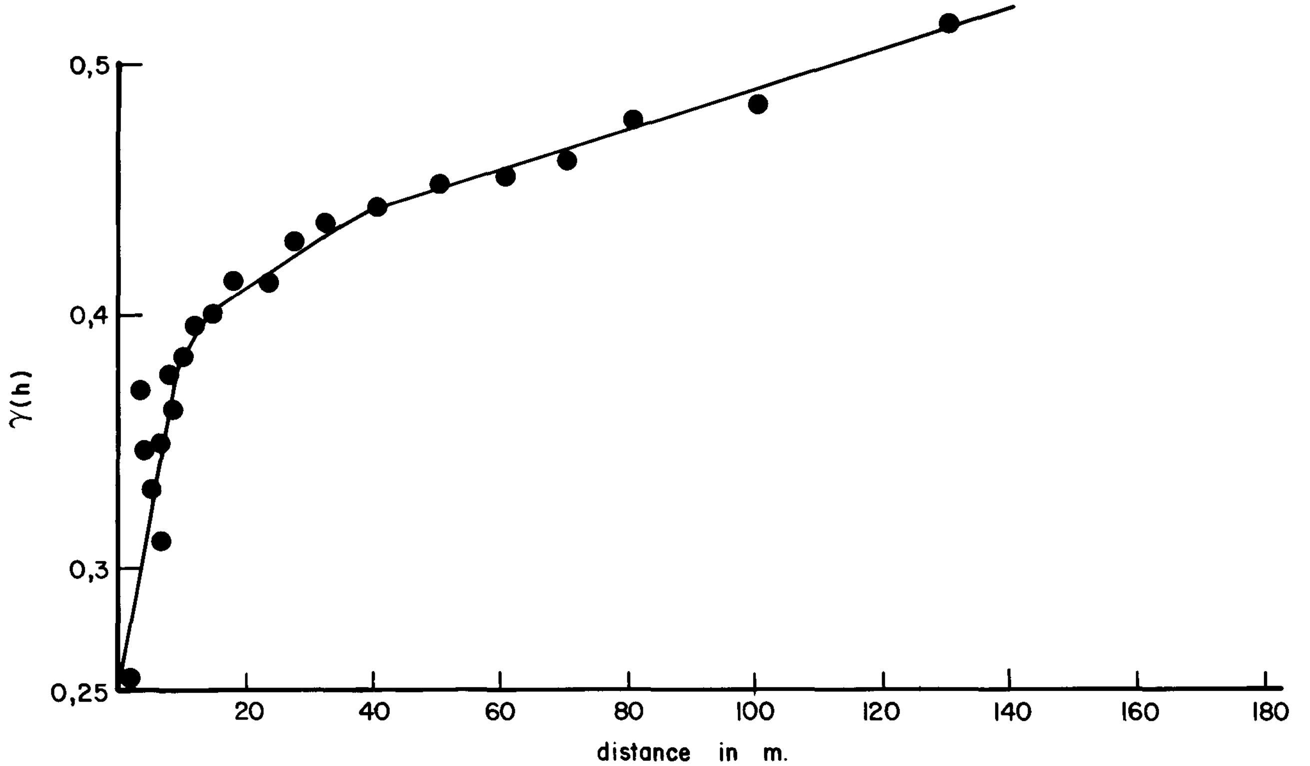
Average semi-variogram within a 15 m x 15 m block = 0,712

Average semi-variogram within a 30 m x 30 m block = 0,779

Average semi-variogram within a 50 m x 50 m block = 0,818

Average semi-variogram within a 100 m x 100 m block = 0,840

Fig. 10—Semi-variogram of gold values



n = 3991 cov. = 0,488

Cross semi-variogram model : nugget effect = 0,25; structure 1 : spherical (12 ; 0,17) } h < 40
structure 2 : exponential (80; 0,185) }
structure 3 : $\gamma(h) = 0{,}0008h + 0{,}408$; $h \geq 40$

Average Cross semi-variogram within a 15m. x 15m. block = 0,349
Average Cross semi-variogram within a 30m. x 30m. block = 0,386
Average Cross semi-variogram within a 50m. x 50m. block = 0,405
Average Cross semi-variogram within a 100m. x 100m. block = 0,435

Fig. 11—Cross semi-variogram between gold and uranium sample values

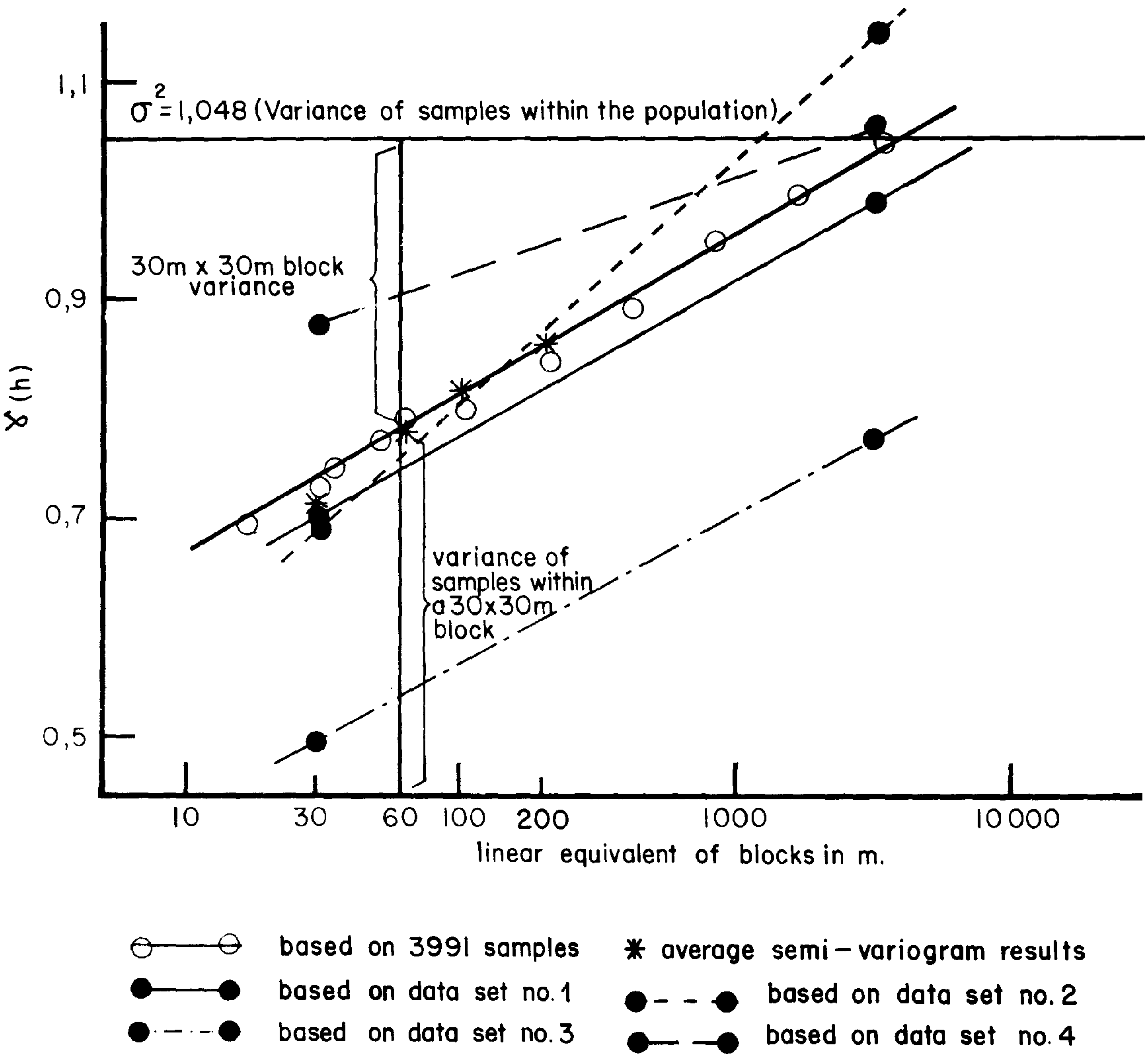


Fig. 12—Variance/area for gold sample values

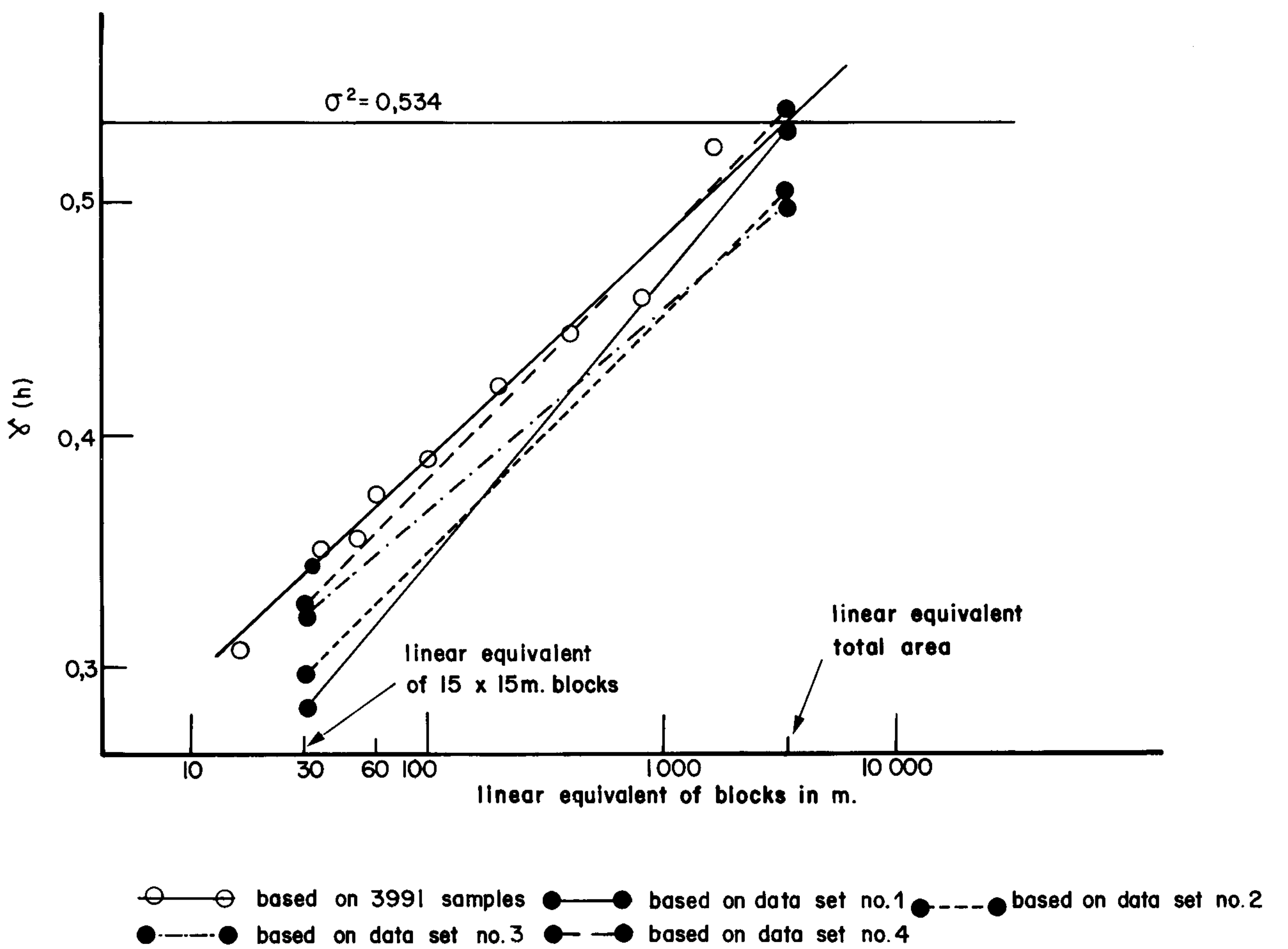


Fig. 13—Variance/area for uranium sample values

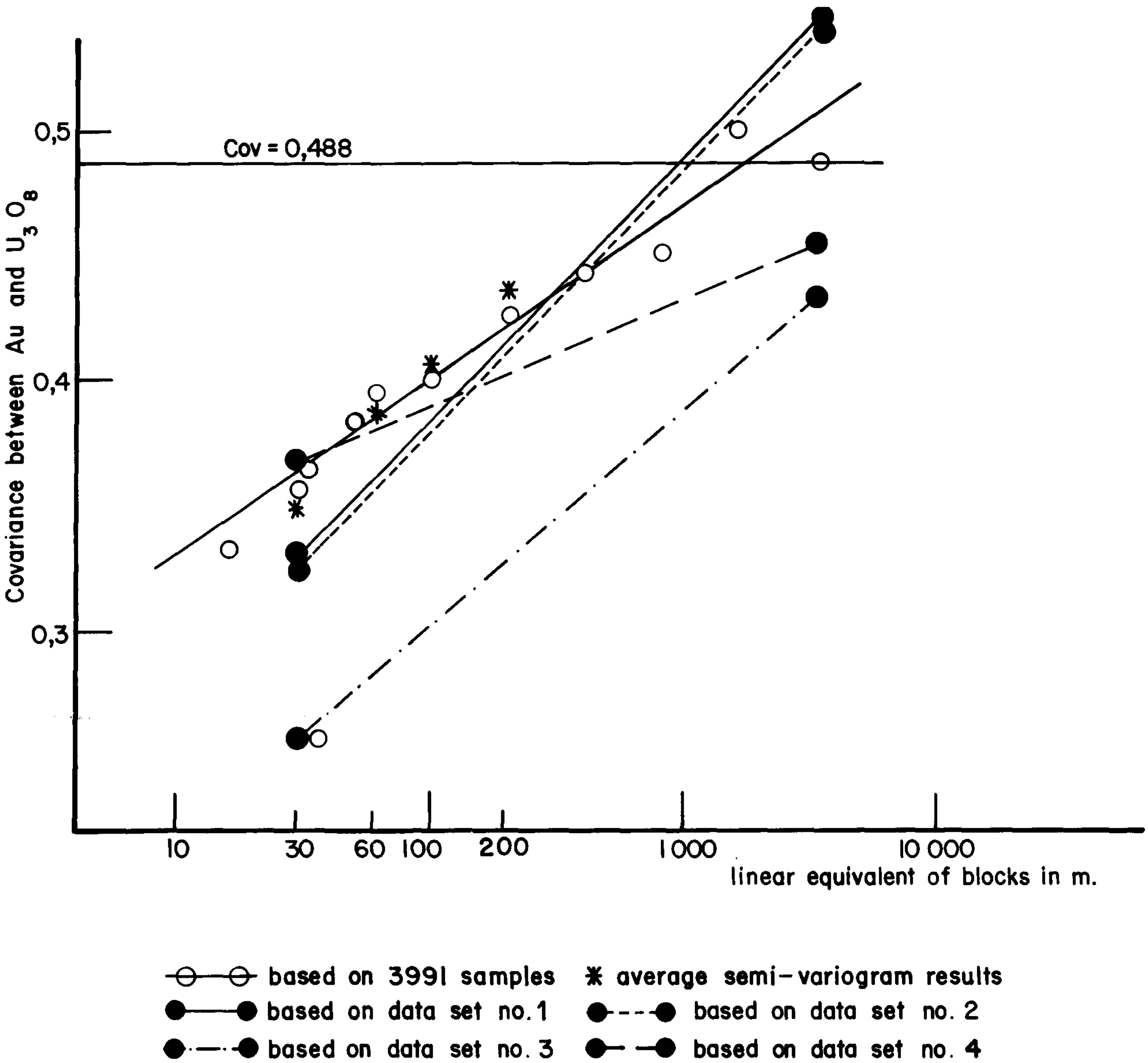


Fig. 14—Covariance/area for gold and uranium sample values

samples in them were used for the analysis. Table II shows the basic data for each block size.

Standard lognormal correlation analyses were applied to the observed block averages. The results are shown as 'observed' in Table I, and can be compared with the theoretical results in Table I. Example: For 30 m × 30 m blocks, the variance of observed block average gold values is 0,425, while the theoretical variance obtained from Fig. 12 is 0,263.

It can be seen that the 'observed' and 'theoretical' results are not in agreement. This is due to the fact that the observed results include the error of estimation of the block averages.

Errors of Estimation of the Different Blocks

In order to obtain the errors of estimation for the different blocks, semi-variogram and cross semi-variogram analyses based on the different block averages were performed and the estimated nugget effects were accepted as the required errors.

The semi-variogram and cross semi-variogram results are shown in Figs. 15, 16, and 17 for 15 m × 15 m, 30 m × 30 m, and 60 m × 60 m block averages respectively. Theoretical semi-variogram models were not fitted to the experimental points, and the nugget effects were estimated by simple extrapolation. This was not possible for the 60 m × 60 m blocks. The nugget effects as estimated are shown as 'error of estimation' in Table I.

By deducting the errors of estimation from the observed results and recalculating the correlation coefficients, values that are comparable with the theoretical ones are obtained. These are also shown in Table I – under 'Observed – error'. Example: For 30 m × 30 m gold block averages, a nugget effect or error variance of estimation of such block averages of 0,150 was obtained from Fig. 16. By subtraction of this value from 0,425 (variance of observed block averages obtained above), a value of 0,275 (shown as 'Observed – error' in Table I) was obtained. This is comparable with 0,263 (theoretical variance of 30 m × 30 m blocks obtained earlier from Fig. 12).

TABLE II

BASIC DATA FOR EACH BLOCK SIZE

Block size	Minimum no. of samples per block	Average no. of samples per block	Number of blocks
15 m × 15 m	5	6,4	510
30 m × 30 m	10	19,0	172
60 m × 60 m	10	41,0	94

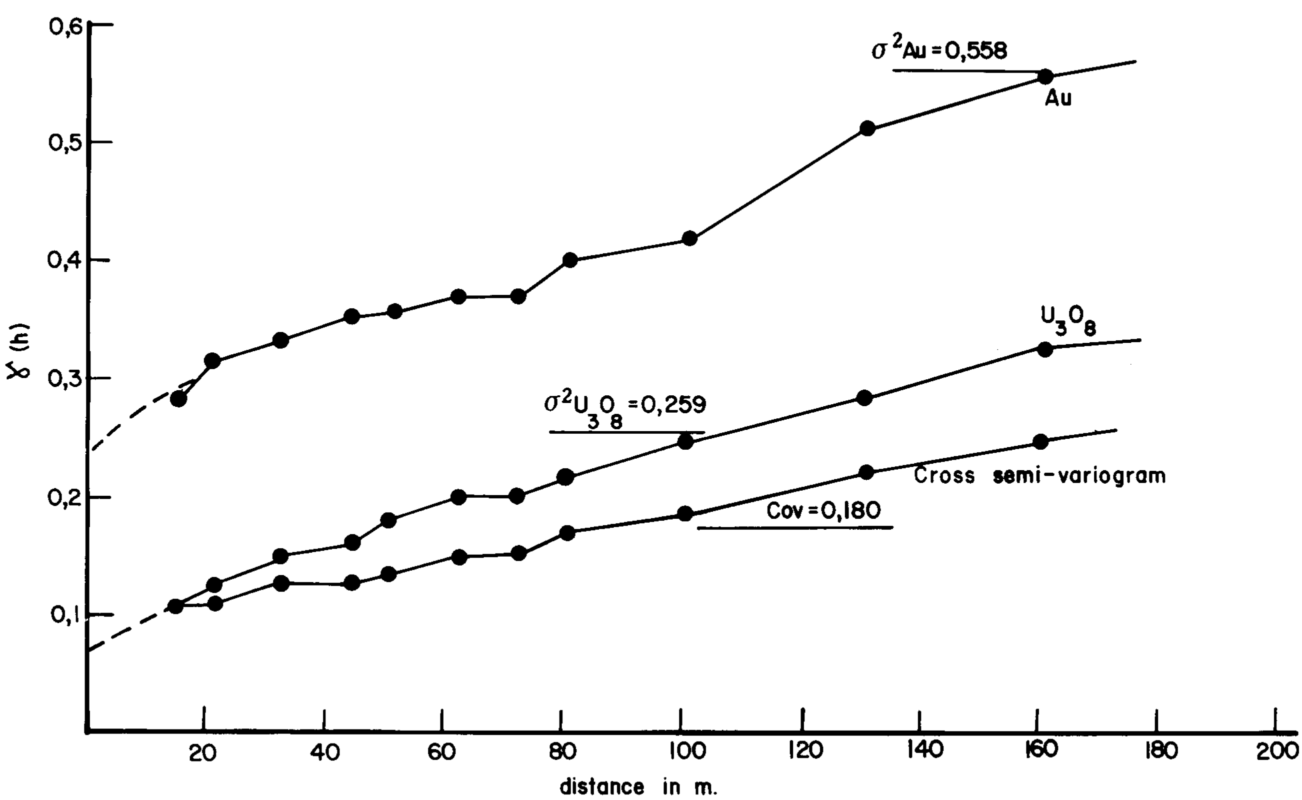


Fig. 15—Semi-variograms for 15m × 15m blocks with more than 4 samples per block
n = 510

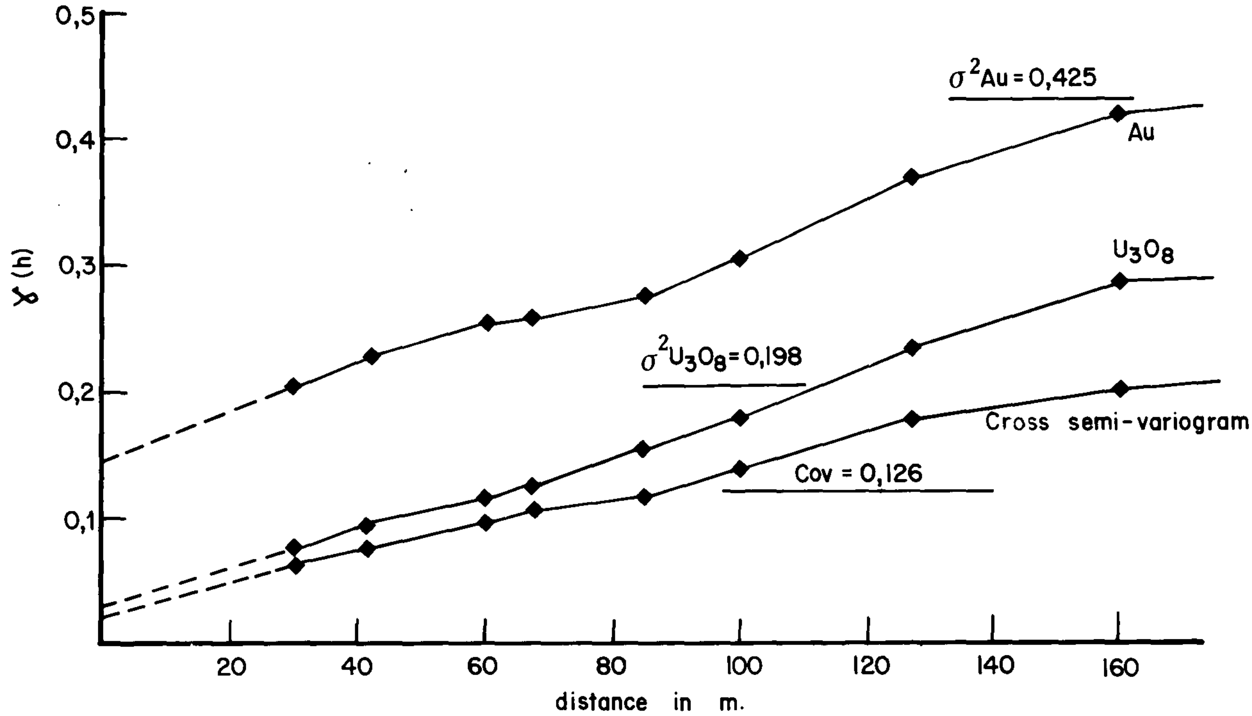


Fig. 16—Semi-variograms for 30m × 30m blocks with more than 9 samples per block
n = 172

TABLE III

SAMPLE CLUSTERS SIMULATING BOREHOLES WITH DEFLECTIONS (SET No. 4)

Region	BH	DEF 1	DEF 2	DEF 3	DEF 4	DEF 5	DEF 6	DEF 7	DEF 8
1	2 072* 20†	490 15	1 264 18	380 7	1 894 23	544 7	234 9	2 348 11	452 11
2	2 100 99	392 44	118 13	297 17	120 9	154 11	1 790 86	— —	— —
3	70 2	14 1	974 9	338 13	941 23	884 40	— —	— —	— —
4	543 6	1 764 11	70 2	79 6	1 661 18	— —	— —	— —	— —
5	966 22	737 25	1 112 19	372 29	4 912 25	2 760 17	362 14	2 025 20	2 426 7
6	281 18	2 196 69	106 13	350 15	222 11	1 001 38	220 15	614 13	— —
7	2 142 82	855 59	3 808 91	443 26	506 32	1 646 107	530 48	— —	— —
8	1 220 14	3 020 14	4 281 35	486 11	2 469 39	462 22	899 36	914 25	— —
9	714 5	144 11	56 4	232 13	556 11	— —	— —	— —	— —

*gold values in cm.g/t
†uranium values in cm.kg/t

Average within-cluster covariance = 0,367
Overall covariance = 0,453

Average within-cluster Au variance = 0,880
Overall Au variance = 1,052
Overall correlation coefficient = 0,60

Average within-cluster U_3O_8 variance = 0,326
Overall U_3O_8 variance = 0,535

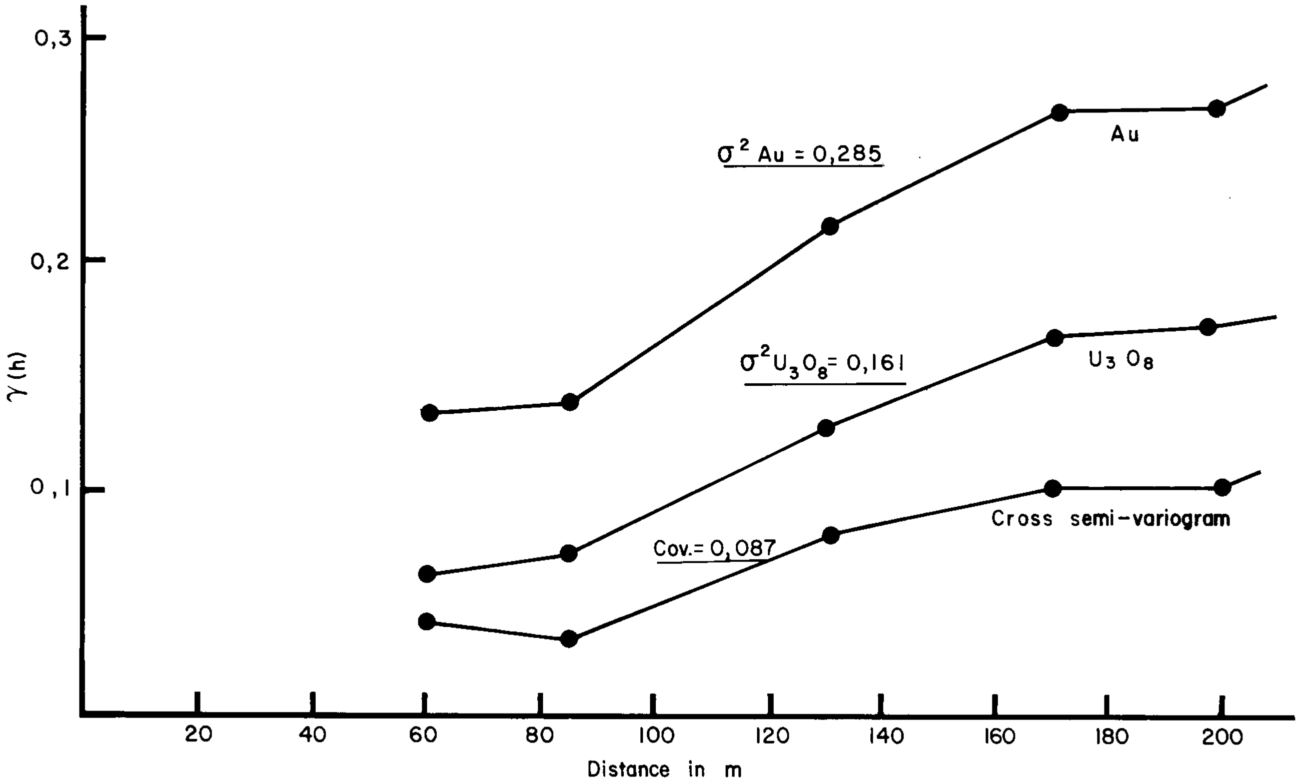


Fig. 17—Semi-variograms for 60m × 60m blocks with more than 9 samples per block n=94

TABLE IV

COMPARISON OF JOINT PAY LIMIT (J.P.L.) RESULTS FOR DIFFERENT DATA SETS

Item	Parameters								Estimates of payability and pay grades									Source of result
	Gold			Uranium			Combined		J.P.L. No. 1			J.P.L. No. 2			J.P.L. No. 3			
	Mean	σ^2	β	Mean	σ^2	β	Cov	r	%	Au	U_3O_8	%	Au	U_3O_8	%	Au	U_3O_8	
Samples	900	0,987	40	27	0,532	3	0,544	0,75	64	1 282	37	48	1 542	43	40	1 724	47	Data set 1
Samples	900	1,145	50	27	0,499	3	0,542	0,72	63	1 321	37	49	1 597	43	40	1 790	47	Data set 2
Samples	900	0,772	50	27	0,499	3	0,431	0,69	70	1 191	35	52	1 425	41	42	1 586	45	Data set 3
Samples	900	1,052	50	27	0,535	3	0,453	0,60	65	1 274	36	49	1 533	42	41	1 711	46	Data set 4
	900	0,276	50	27	0,248	3	0,215	0,82	86	988	30	64	1 140	34	50	1 256	38	Data set 1
	900	0,453	50	27	0,201	3	0,216	0,72	83	1 030	30	62	1 212	34	49	1 357	37	Data set 2
15 m × 15 m	900	0,275	50	27	0,176	3	0,174	0,79	89	973	29	67	1 118	33	52	1 238	36	Data set 3
blocks	900	0,172	50	27	0,209	3	0,086	0,45	95	929	28	73	1 032	32	55	1 119	35	Data set 4
	900	0,308	50	27	0,194	3	0,122	0,50	90	968	29	68	1 108	32	53	1 226	35	All the data
	900	0,237	50	27	0,212	3	0,184	0,82	89	969	29	67	1 107	33	52	1 219	37	Data set 1
	900	0,385	50	27	0,171	3	0,186	0,72	86	1 002	29	65	1 170	33	51	1 308	36	Data set 2
30 m × 30 m	900	0,232	50	27	0,151	3	0,148	0,79	91	953	28	70	1 085	32	54	1 200	35	Data set 3
blocks	900	0,147	50	27	0,177	3	0,073	0,45	96	920	28	76	1 011	31	57	1 095	34	Data set 4
	900	0,263	50	27	0,164	3	0,102	0,49	92	950	28	71	1 077	31	54	1 190	34	All the data
	900	0,197	50	27	0,177	3	0,152	0,81	92	948	29	70	1 073	32	54	1 179	36	Data set 1
	900	0,320	50	27	0,141	3	0,154	0,72	89	975	29	68	1 126	32	52	1 257	35	Data set 2
60 m × 60 m	900	0,190	50	27	0,125	3	0,122	0,79	94	936	28	73	1 052	31	56	1 160	34	Data set 3
blocks	900	0,122	50	27	0,146	3	0,060	0,45	98	912	27	79	990	30	59	1 069	33	Data set 4
	900	0,223	50	27	0,136	3	0,082	0,47	94	934	28	74	1 047	31	56	1 154	33	All the data

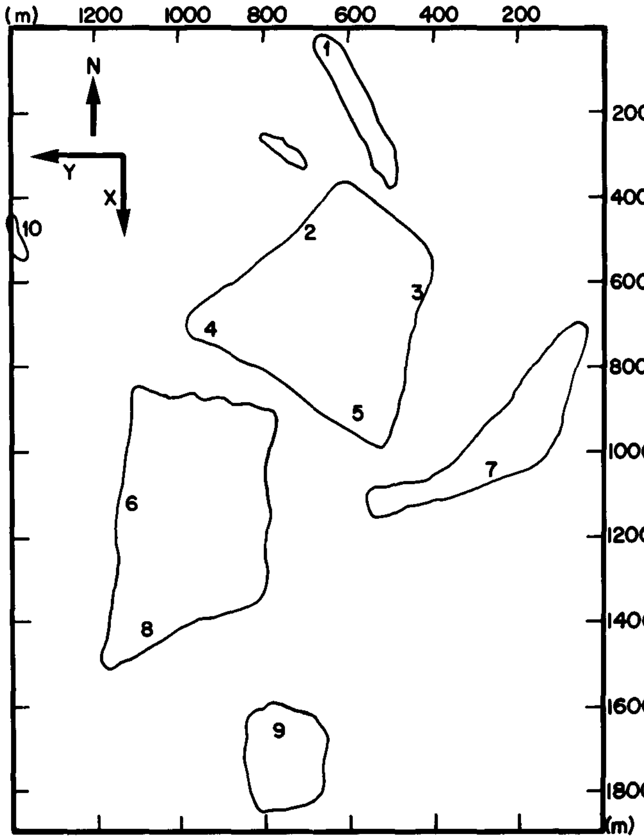


Fig. 18—Approximate location of available chip-sampling data and clusters used to simulate boreholes with deflections

Applications

In South African gold mines, global ore-reserve estimates for a new mine or a large undeveloped area of an existing mine must generally be carried out with very limited information, i.e. a dozen or so boreholes with, say, between four and seven deflections each. These boreholes are normally separated from one another by distances of a kilometre or more.

As can be seen from Figs. 12 to 14, the relationships between variance (covariance) and size of area for gold and uranium values generally follow a straight line on a logarithmic scale; therefore, the following procedure was tried out.

Clusters of Chip Samples Simulating Isolated Boreholes with Deflections

Four data sets, each containing nine or ten clusters of chip-sampling sections, were selected at random from the areas designated by the numbers 1 to 10 in Fig. 18. A data cluster is made up of all the chip-sampling sections falling within a 15 m $\times$ 15 m block.

These data clusters serve to simulate four sets of isolated boreholes with their deflections that are likely to be obtained as a result of an exploration programme. Actual boreholes, being almost perfect samples, will show a smaller nugget effect than the chip samples, but it is thought that this can only improve the analysis. The fourth set of clusters with the gold and uranium values in cm.g/t and cm.kg/t respectively is shown in Table III.

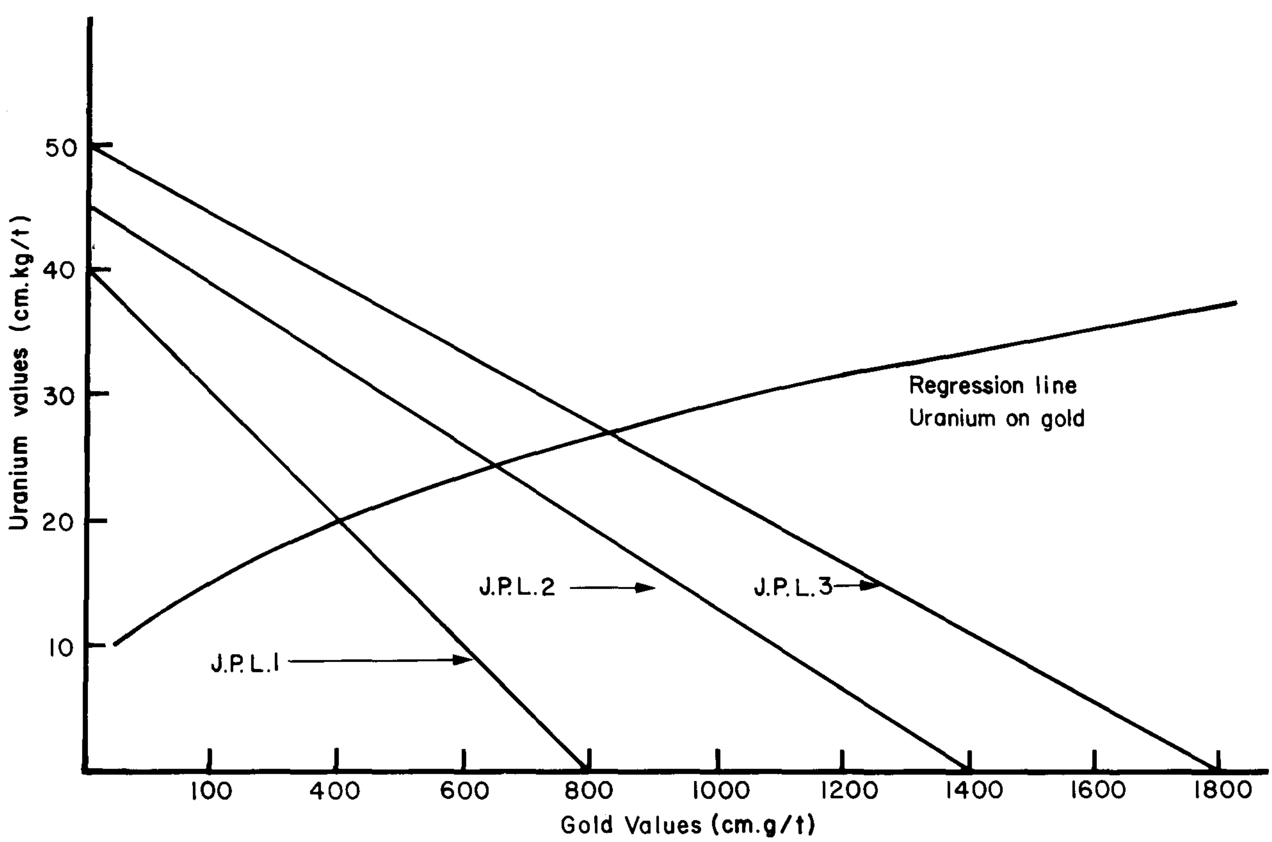


Fig. 19—Joint pay limits (J.P.L.) used for grade-tonnage calculations

Estimation of Parameters for Clusters of Chip Samples

For each set of clusters, the following two sets of estimates were obtained:

pooled within-cluster logarithmic gold variance, uranium variance, gold-uranium covariance; and

overall logarithmic: gold variance, uranium variance, gold-uranium covariance;

also, the overall correlation coefficient between gold and uranium values.

These results were plotted in Figs. 12 to 14 as graphs of variance (covariance) versus size of area fitted in each case by straight lines to the two relevant observations. It can be seen that the spread around the 'population' variance (covariance)/size of area line (based on 3991 values) is fairly large. However, if the lines are roughly parallel to the 'population' line, the results obtained from them are likely to be reasonably close to the 'population' results.

Using the abovementioned four sets of graphs, the necessary parameters for grade–tonnage estimates based on a joint pay limit were obtained for three different block sizes as shown in Table IV. The gold and uranium means have been taken as 900 cm.g/t and 27 cm.kg/t respectively rather than the observed means of the four data sets since it is well known that grade–tonnage estimates are highly sensitive to the observed means and the intention of this paper is to highlight the estimation of second order parameters for blocks from borehole results.

Results

Sets of grade–tonnage estimates were obtained for each block size corresponding to the three graphs of joint pay limit shown in Fig. 19.

Table IV shows a comparison of the grade–tonnage results obtained from the use of the 'population' parameters and the 'simulated borehole' parameters. For example, if the payability of 30 m $\times$ 30 m blocks relative to joint pay limit no. 1 is required, the estimates based on the 'population' parameters ('all the data' in Table IV) yield 92 per cent payability associated with gold and uranium grades of 950 cm.g/t and 28 cm.kg/t respectively. Similar estimates based on the '9 boreholes with deflections' shown as data set no. 4 in Table III give values of 96 per cent payability associated with gold and uranium values of 920 cm.g/t and 28 cm.kg/t respectively. If these estimates are based on parameters derived directly from the borehole values rather than on parameters applicable to block estimates, the following results (see top section of Table IV) are obtained for data set no. 4: payability 65 per cent, gold grade 1274 cm.g/t, and uranium grade 36 cm.kg/t. It can be seen that the results based on block estimates are quite acceptable, whereas the results obtained from the direct application of the borehole parameters as distinct from the estimated block parameters show serious over-estimations of grade and under-estimations of percentages of ore above the pay limits.

Conclusions

Based on analyses of a large number of gold–uranium sampling data from a South African gold mine, the permanence of the bivariate lognormal distribution for different support sizes can be accepted for practical applications.

'Block' parameters necessary for grade–tonnage estimates relative to a joint pay limit were estimated from abundant 'point' sampling data; these compare favourably with those obtained from observed block values.

A simple method applicable to South African gold and uranium mines for obtaining acceptable global grade–tonnage estimates from very limited borehole information is given.

Acknowledgements

Grateful acknowledgement is made to the following: Drs D. M. Hawkins, D. G. Krige, and A. Maréchal for their helpful comments, Mrs G. Knox and Mrs M. van Aswegen for their help with the computer work involved, and the management of Anglovaal Limited for the opportunity to do the research and for permission to publish this work.

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Occupational accidents and diseases

The Third International Colloquium on the Prevention of Occupational Accidents and Diseases in the Iron and Metal Manufacturing Industry is to be held in Palma de Mallorca (Spain) on 15th and 16th June, 1982.

The three themes of the Colloquium are as follows:

- Safety management in the iron and metal manufacturing industry.
- Working with dangerous substances.
- Measures of protection against heat in the workplace in the iron and metal manufacturing industry.

The main objective of the Colloquium is to provide an opportunity for the exchange of experience and knowledge among experts from different countries in the fields of Industrial Safety, Hygiene, and Occupational Medicine.

The official languages of the Colloquium will be the following: German, French, English, and Spanish. All the working papers of the conference will be edited in these four languages. Simultaneous translation will be available in the four official languages for both reports and debates.

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