J. S. Afr. Inst. Min. Metall., vol. 86, no. 8.
Aug. 1986. pp. 335-347.

A geostatistical study of diamond-saw sampling versus chip sampling

by E.J. MAGRI* and P. McKENNA†

SYNOPSIS

This paper describes a geostatistical study of the relative merits of diamond-saw sampling and conventional chip sampling, using results from experimental work carried out on Randfontein Estates Gold Mine and Western Areas Gold Mine.

The diamond-saw sampling procedure is described, and it is concluded that this is a very efficient operation and leads to good-quality sampling that is clearly an improvement over conventional chip sampling.

The study principally involved the computation of the errors of estimation of the mean gold value of mining panels for the two sampling methods, revealing that, in the normal production environment, the diamond-saw sampling method is a significant improvement over conventional chip sampling, as evidenced by the reduced estimation errors achieved.

The question of optimum sample spacing is discussed, and it is concluded that the required spacing for chip sampling needs to be smaller than for the diamond-saw method.

SAMEVATTING

Hierdie referaat beskryf 'n geostatistiese studie van die onderskeie verdienstes van diamantsaagmonsterneming en die konvensionele skerfmonsterneming met gebruik van die resultate van eksperimentele werk wat by die Randfontein Estates-goudmyn en die Western Areas-goudmyn gedoen is.

Die diamantsaagmonsternemingsprosedure word beskryf en daar word tot die gevolgtrekking gekom dat dit 'n baie doeltreffende bewerking is en lei tot monsterneming van 'n goeie gehalte wat klaarblyklik 'n verbetering op die konvensionele skerfmonsterneming is.

Die studie het hoofsaaklik die berekening behels van mynpanele se foute met die beraming van die gemiddelde goudwaarde vir die twee monsternemingsmetodes wat getoon het dat die diamantsaagmonsternemingsmetode 'n beduidende verbetering op die konvensionele skerfmonsterneming is soos blyk uit die kleiner beramingsfoute wat gemaak word.

Die kwessie van optimale monsterspasiëring word bespreek en daar word besluit dat die nodige spasiëring vir skerfmonsterneming kleiner moet wees as vir die diamantsaagmetode.

Introduction

The use of the diamond saw for underground face sampling was introduced into the platinum mines of Johannesburg Consolidated Investment Company (JCI) several years ago, with considerable success regarding the control of the sampling operation and the quality of the samples taken. Only in recent years has the method been introduced into the Group's gold mines. Its use was initially restricted to development, but the intention is eventually to use the diamond saw for both stope and development sampling.

As a part of other studies being carried out on Randfontein Estates Gold Mine (REGM) and Western Areas Gold Mine (WAGM) on such factors as optimum sample spacing, two raises of approximately 100 m in length (one at each Mine) were sampled at 1 m intervals using both diamond-saw and conventional chip sampling. It was felt that a geostatistical study of these detailed data would be beneficial. As the diamond-saw sampling method was of interest to both the JCI and Anglovaal Groups, it was decided to collaborate on this work to the mutual benefit of the two companies.

This study had two main aims: a quantitative assessment of the relative merits of the different sampling procedures, and the establishment of optimum sampling spacing.

Although data were collected on both gold and uranium sampling, this report is restricted to the more important metal—gold. The findings and conclusions for uranium sampling were similar to those obtained for gold.

Diamond-saw Sampling

Fig. 1 shows the start of the diamond-saw sampling procedure, which, as for conventional chip sampling, begins with the marking of the face. (The actual dimensions of the samples in the two experimental raises are indicated in Figs. 1 and 9 for REGM and WAGM respectively.)

Fig. 2 shows the cutting of vertical slots. The diamond saw illustrated here is the single-bladed type, which is generally favoured owing to its light weight and consequent easier use. A double-bladed saw is available with which two vertical slots can be cut at the same time, but this machine is more difficult to handle and is not necessarily faster than the single-bladed type. The cost of the single-bladed machine in October 1985 was about R1400. The blades cost around R230 each and can achieve approximately 20 m of complete channel sampling (i.e. 1 to 3 panels depending on sample size, spacing, and stope width). Considerably longer blade life has been achieved

* Valuation and Systems Manager, Anglovaal Limited, P.O. Box 62379, Marshalltown, 2107 Transvaal.
† Divisional Geologist, Johannesburg Consolidated Investment Company Limited, P.O. Box 590, Marshalltown, 2107 Transvaal.
© The South African Institute of Mining and Metallurgy, 1986. SA ISSN 0038-223X/$3.00 + 0.00. Paper received 7th October, 1985.

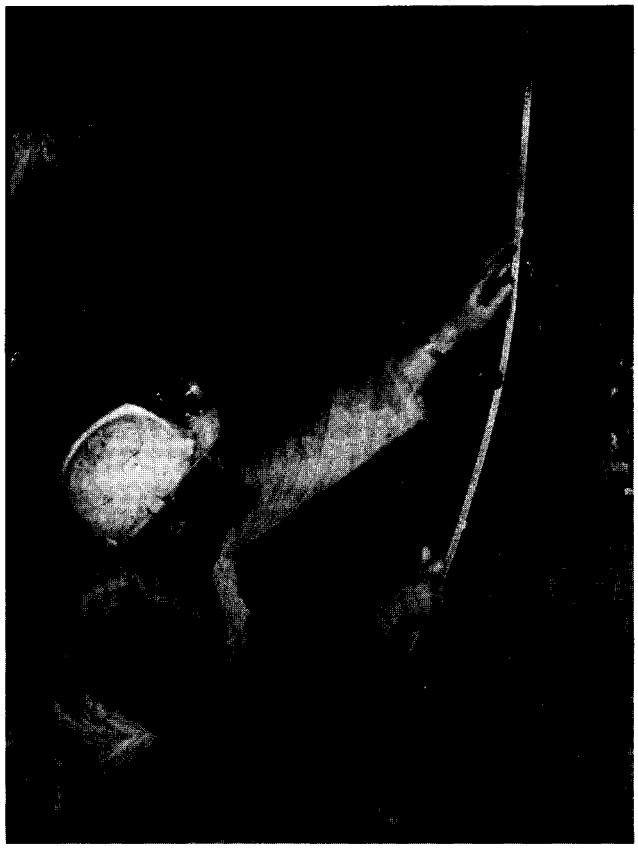


Fig. 1—A sampler marking a sampling section on a raise

Fig. 3—Cutting horizontal sample boundaries

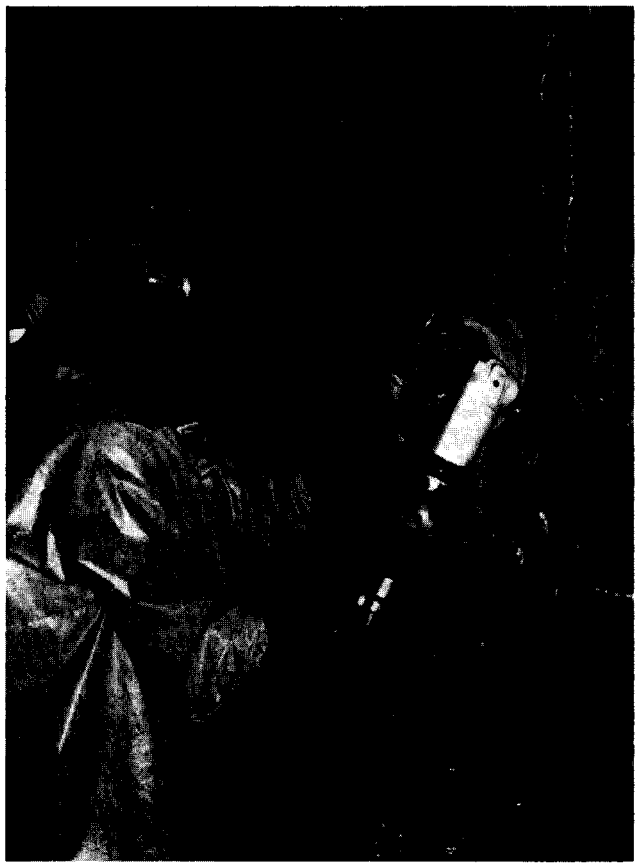


Fig. 2—Cutting vertical grooves along the sides of a sampling section

in the softer rocks found in some of the Barberton gold mines.

Fig. 3 shows the cutting of the horizontal sample boundaries. These cuts, of necessity, always extend by a few centimetres onto the rock face on either side of the sample section so that the positions of the cuts are visible after the sample has been taken. The sample section on completion of the sawing procedure is shown in Fig. 4.

Fig. 5 shows the chipping out of individual samples, which still has to be done with a chisel and hammer. However, the cuts made by the diamond saw make for a much 'cleaner' chipping operation with less chance of material being scattered.

Fig. 6 shows a chip of rock extracted from between the vertical slots made by the diamond saw.

The labour required for this work is similar to that of conventional chip sampling. One sampler–supervisor can control one or two teams consisting of 1 diamond-saw operator and 3 helpers. The time taken is also similar to conventional sampling—complete sawing and chipping of a 1 m channel take 20 to 25 minutes. The samples weigh 500 to 1000 g each.

When the method is observed in operation, it appears as an efficient procedure that leads to sampling of a very high quality and is evidently an improvement over conventional chip sampling. Better control is achieved, even under limited supervision, since, after the sample has been taken, the remaining vertical slot and parts of the horizontal slots are clearly visible and will remain so until the

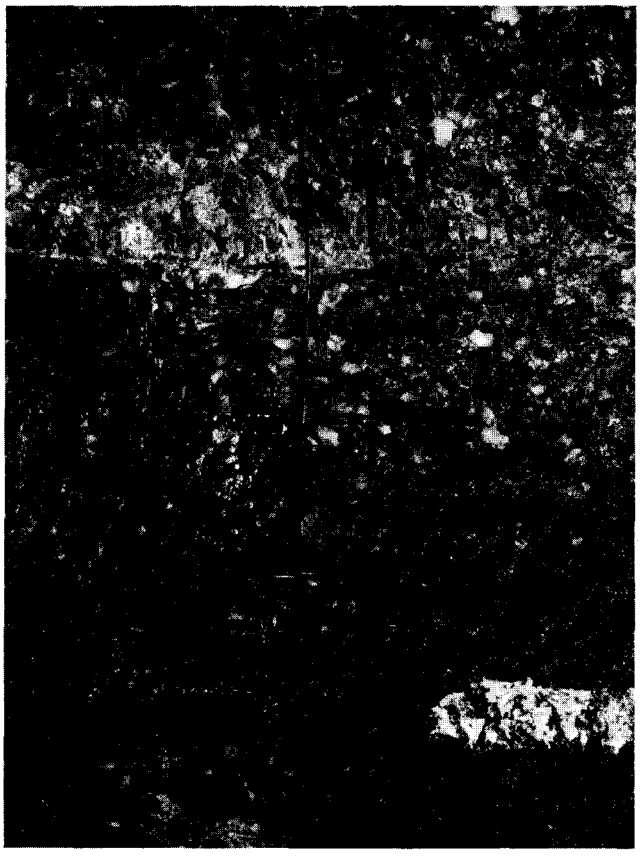


Fig. 4—A completely defined section: the samples are 7 cm wide, and between 10 cm and 20 cm long depending on the mineralization

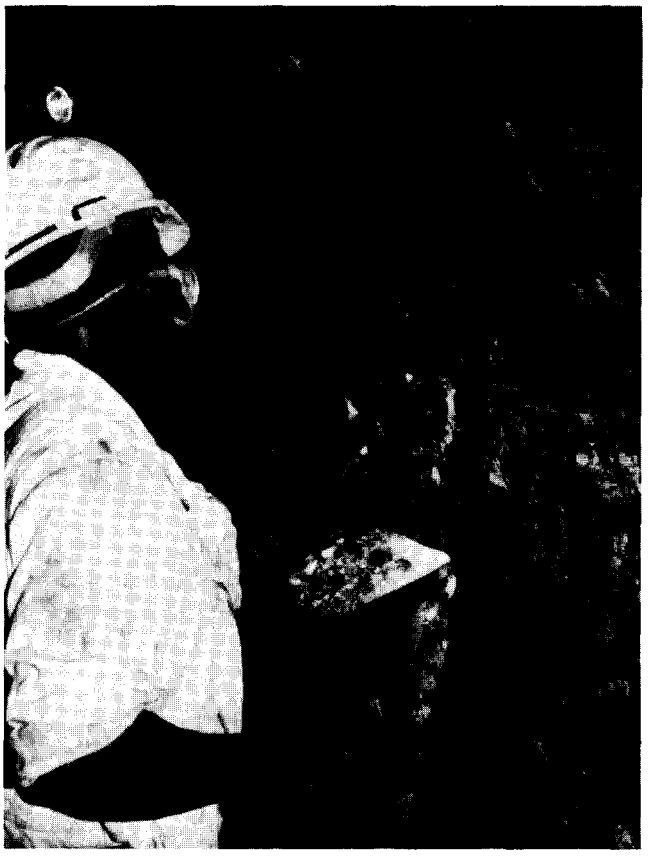


Fig. 5—Chipping of samples

face or raise is blasted.

Randfontein Estates Gold Mine

The experiment was conducted in a raise in the UE1A (Middle Elsburg Reef) on Cooke 2 shaft. A description of the sample sizes and arrangement is given in Fig. 7. Essentially, the method consisted of the following: the face was marked, chip samples were taken, and the much smaller diamond-saw samples were taken in exactly the same position. The whole sampling exercise (especially that of chip sampling) was done under the personal supervision of a senior mine surveyor.

Figs. 8 to 10 show histograms and probability plots for the gold values. While the samples are from a population known to be log-normal, the distribution of this particular data set is closer to a normal distribution and the data were treated as such in all subsequent exercises.

Fig. 11 shows the experimental semi-variograms of gold values from both the diamond-saw and chip sampling. Surprisingly, these are virtually identical. The same model was fitted to both, i.e. a linear model with a slope of 26 300 and a nugget effect of 210 000.

One would expect the diamond-saw results to show an appreciably lower nugget effect than the chip samples. However, the conclusion from this is that the chip sampling was conducted in a far-from-normal, highly supervised manner and as such achieved a quality equal to that of the diamond saw. It is probable that such high-quality chip sampling would not usually be achieved

Fig. 6—A chip of rock extracted from a sample (real width 7 cm)

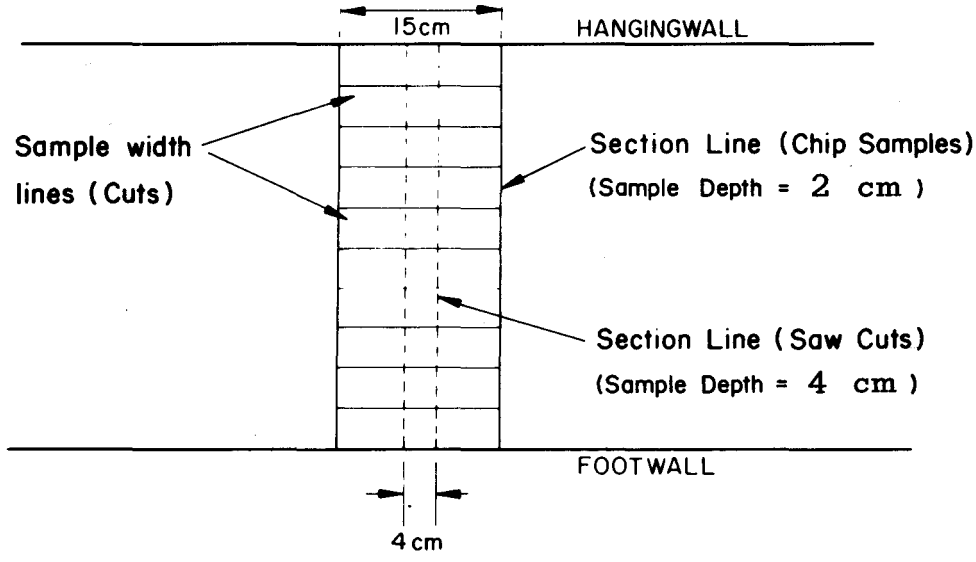


Fig. 7—Sampling method at Randfontein Estates Gold Mine

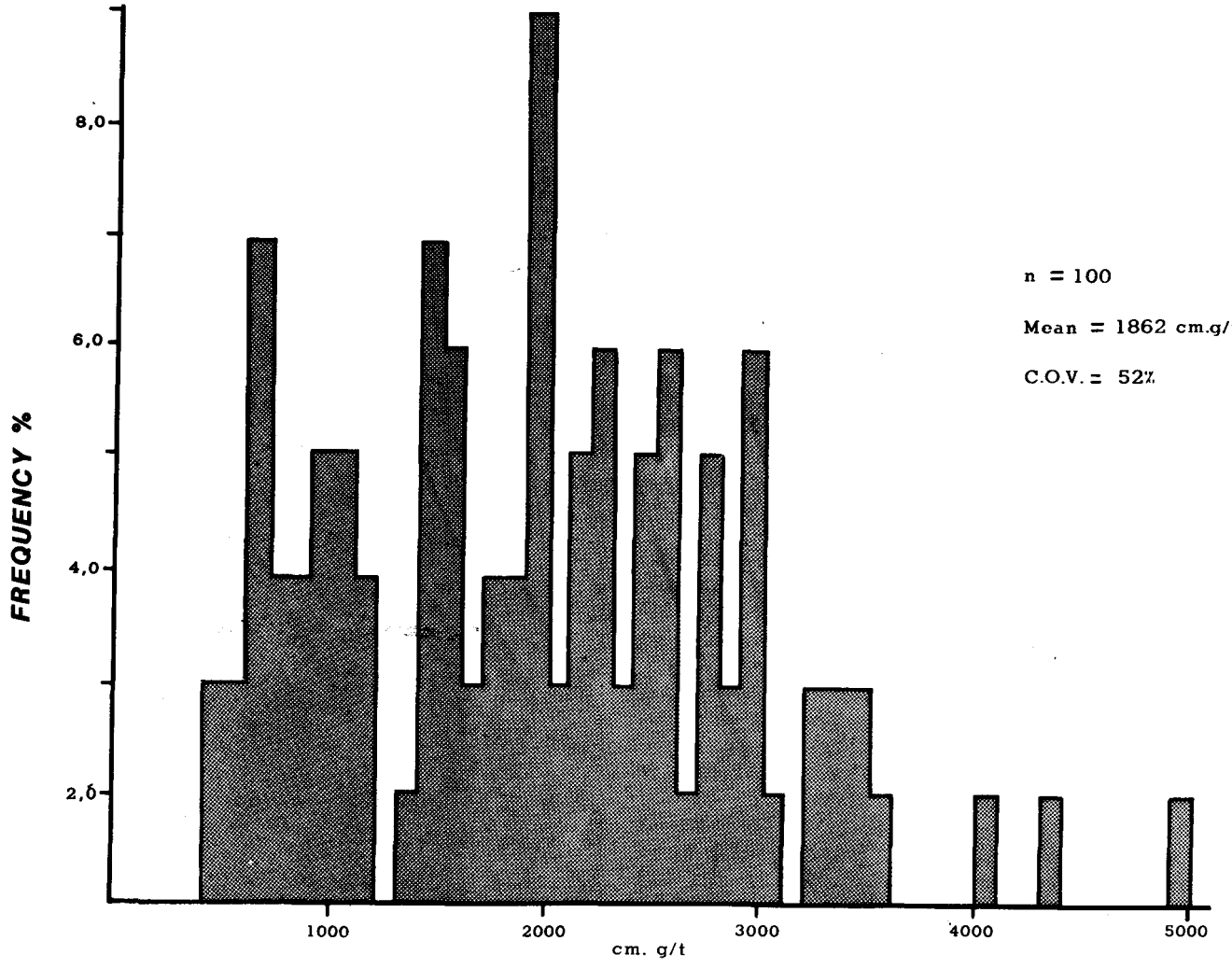


Fig. 8—Histogram of diamond-saw sampling gold values at Randfontein Estates Gold Mine

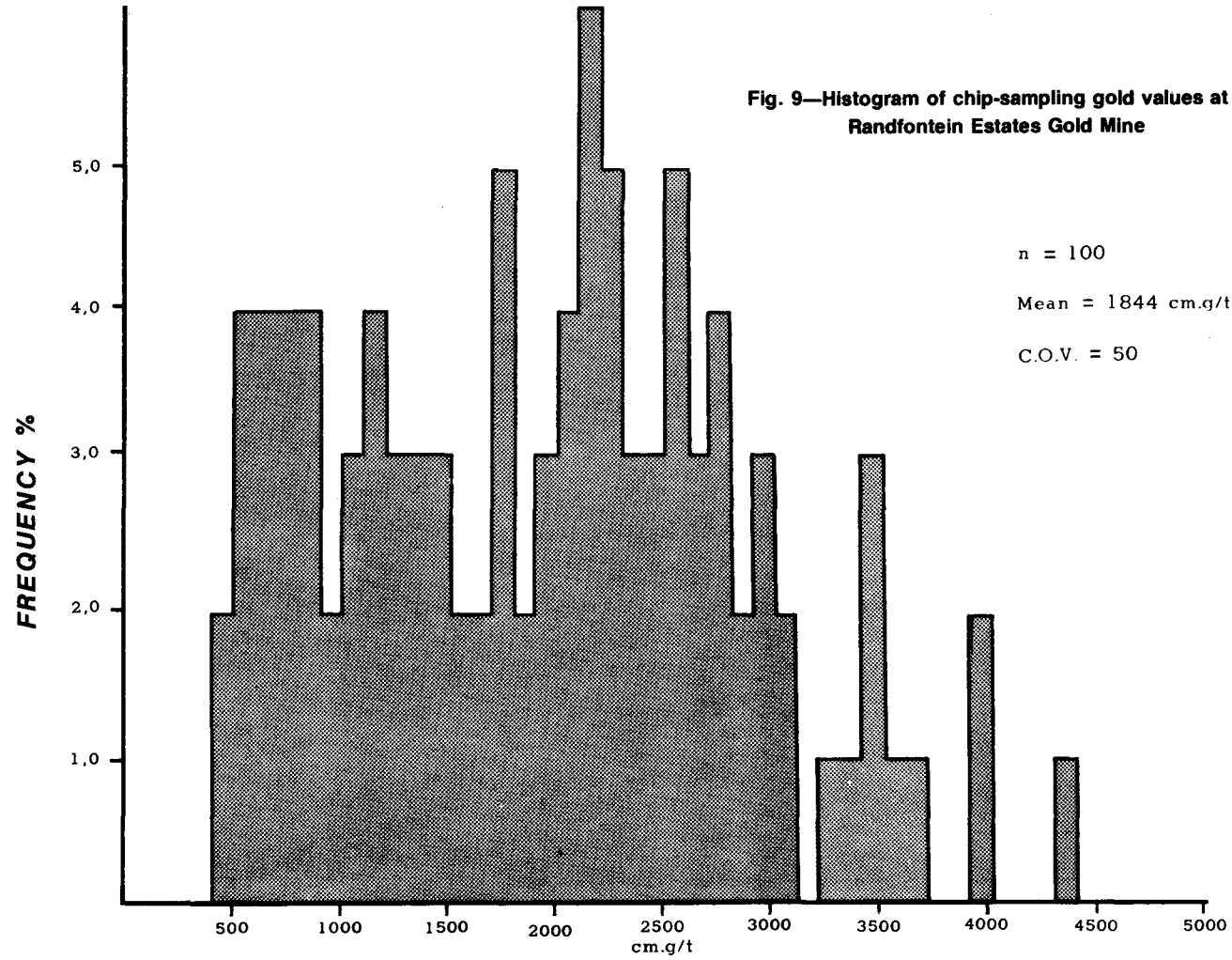


Fig. 9—Histogram of chip-sampling gold values at Randfontein Estates Gold Mine

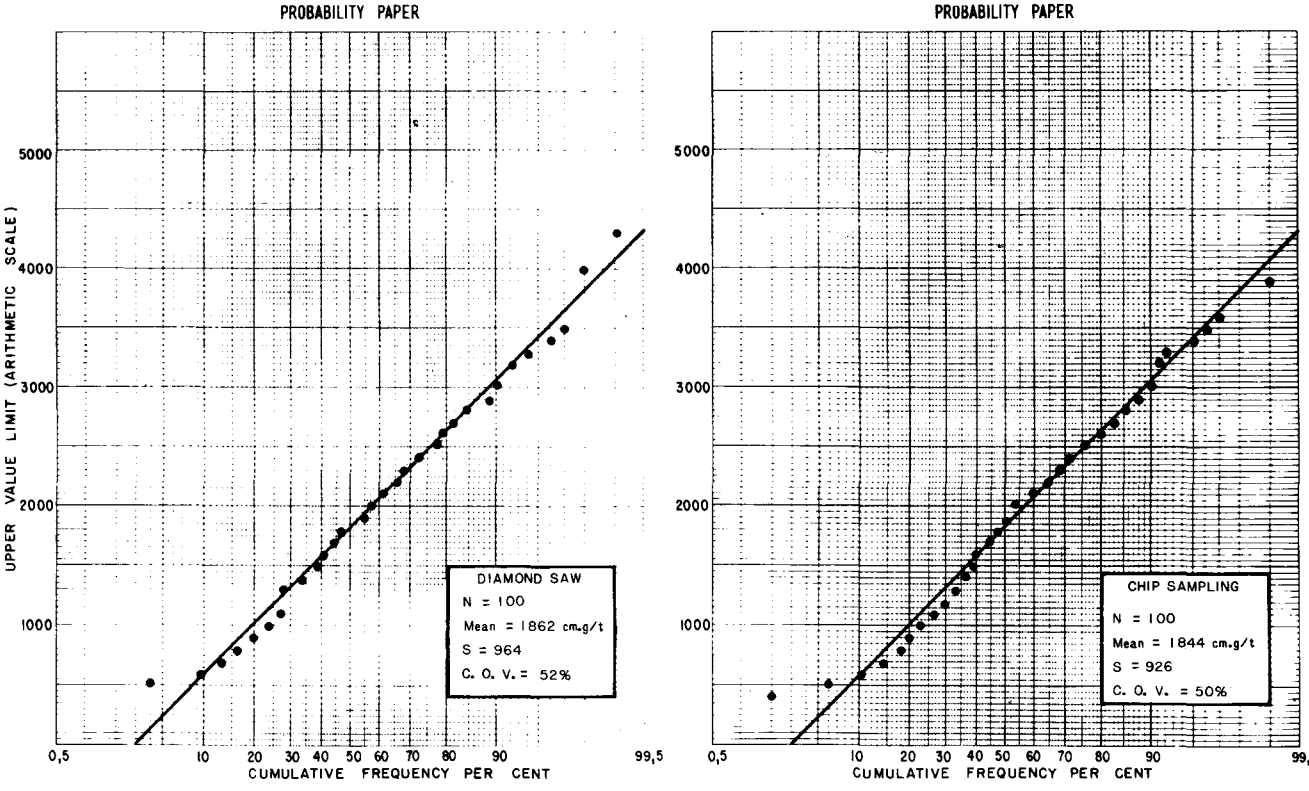


Fig. 10—Distribution of gold values obtained by diamond-saw and chip sampling at Randfontein Estates Gold Mine

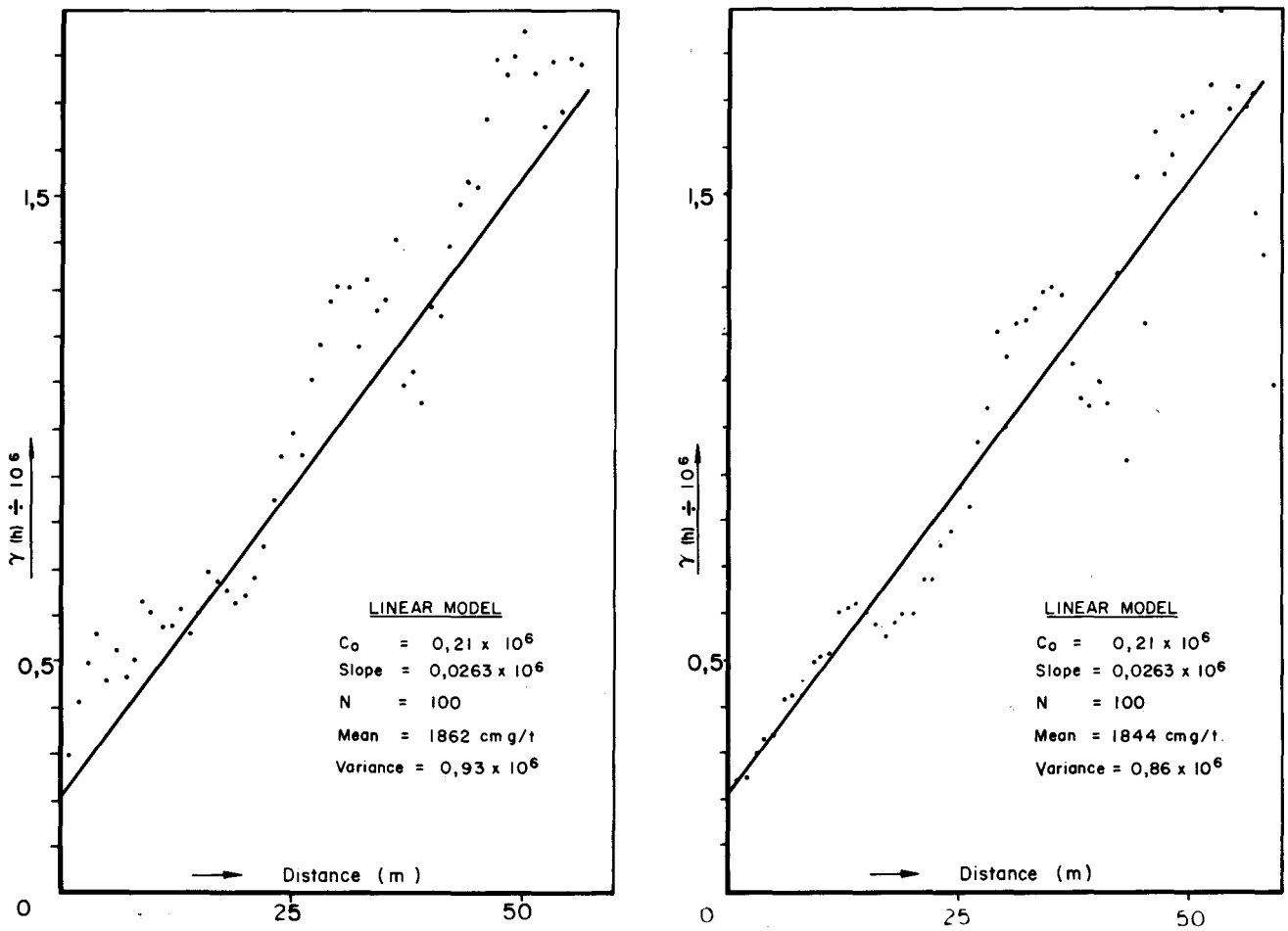


Fig. 11—Variograms for diamond-saw and chip sampling gold values at Randfontein Estates Gold Mine

under normal production conditions.

The nugget effect is inversely proportional to the volume of the sample, i.e. larger samples give a lower nugget effect. The diamond-saw samples were approximately one-third the volume of the chip samples. The diamond-saw method is therefore shown to be theoretically better by giving the same nugget effect (and consequently similar estimation error) for samples of one-third the volume.

Although the REGM data showed almost identical results for both methods, it was still possible to look at the question of optimum sample spacing.

Fig. 12 shows the two main sampling arrangements considered in this exercise—marked A and B. It should be noted that, when a face is sampled, the aim is not merely to achieve the most accurate value of that face but to evaluate a particular block of ore with certain dimensions. Both cases consist of a block of ore 30 m by 10 m. In case A, the block is sampled along the median of the length of the block. In case B, the block is sampled along the edge of one of the long sides of the block. These two cases could be thought to represent an idealized situation of a face 30 m in length that advances 10 m in a measuring period and is sampled once during that period. Case A would represent a situation where the block was valued by a face sampling done in the middle of the measuring period. Case B would represent a situation where the block was valued by a face sampling done either at the beginning or at the end of the measuring period.

For this exercise, 'optimum' sample spacing was considered only from the point of view of achieving acceptable errors of estimation (or limits of confidence) without the taking of too many unnecessary samples. It was not the aim of this work to consider such aspects as the costs and logistics of the sampling procedures.

Errors of estimation (σ_E^2) were computed by summing the 'line term' (σ_L^2) and 'section term' (σ_S^2) for different sampling arrangements, i.e.

$$\sigma_E^2 = \sigma_L^2 + \sigma_S^2.$$

The *line term* is the error variance made in the assumption that the mean value of the individual samples taken along a line (or face) extends over the whole of the line.

The *section term* is the error variance made in the assumption that the value of the line (or face) extends to the whole block.

The computation of these terms depends upon the parameters of the semi-variogram model that is used, as indicated in Fig. 12. The line term can usually be approximated fairly well by the use of simple formulae. The calculation of the section term requires more complex mathematics that utilizes the computation of certain 'aux-

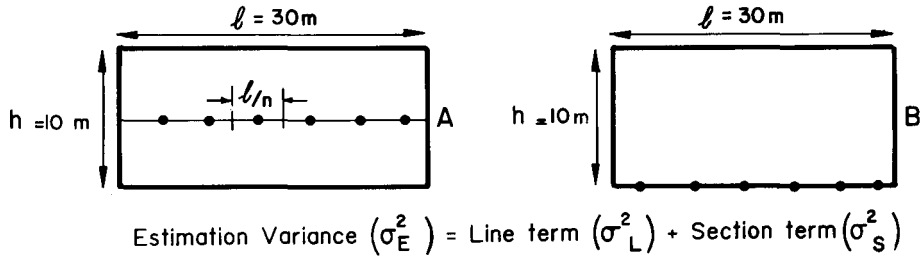


Fig. 12—Sampling patterns and the calculation of estimation variances

Line Term: $\sigma_L^2 = \frac{1}{n}\left[2\chi\left(\frac{\ell}{2n}\right) - F\left(\frac{\ell}{n}\right)\right]$

for the spherical and linear variogram models this expression becomes :

$$\sigma_L^2 = \frac{1}{n}\left[Co + \frac{C\ell}{4na}\right] \qquad \sigma_L^2 = \frac{1}{n}\left[Co + \frac{\ell P}{6n}\right]$$

Section Term:

I) for centred samples:

$$\sigma_S^2 = 2\chi\left(h/2, \ell\right) - F\left(h, \ell\right) - F\left(\ell\right)$$

2) for side samples :

$$\sigma_S^2 = 2\chi\left(h, \ell\right) - F\left(h, \ell\right) - F\left(\ell\right)$$

iliary functions' such as $F(h)$, $F(h,l)$, and $X(h,l)$.

These functions describe the variance between points along the line, the variance of points within the block, and the variance between the line sampled and the block. The section term can be estimated by the use of the graphs that are available in several geostatistical texts including that of Journel and Huijbregts[1]); or, as in the present exercise, use can be made of Royle's geostatistical tables[2].

The total errors of estimation as derived from the tables were checked against results obtained from a computation involving discretization of the block and use of the formula

$$\sigma_E^2 = 2\,\bar{\gamma}\,(W_s, W) - \bar{\gamma}\,(W, W) - \bar{\gamma}\,(W_s W_s),$$

in which $\bar{\gamma}\,(W, W)$ is the average semi-variogram within the block

$\bar{\gamma}\,(W_s, W_s)$ is the average semi-variogram within the sample set

$\bar{\gamma}\,(W_s, W)$ is the average semi-variogram between the sample set and the block.

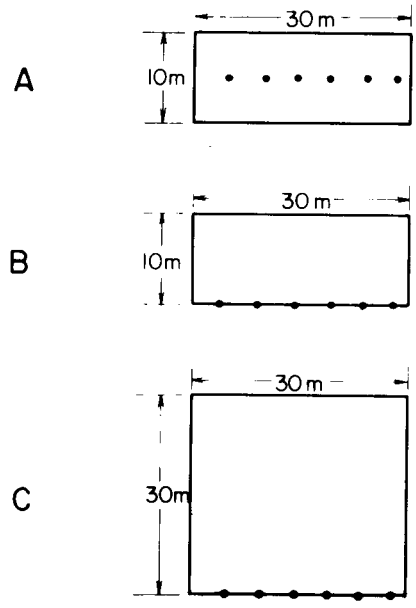
Table I gives a comparison of the estimation errors computed by the different methods for a block size of 30 m by 10 m and a sample spacing of 6 m. It is concluded that, with discretization of small enough units (in this case 1 m by 1 m), reasonably accurate results can be obtained by the numerical approximation method.

TABLE I
REGM: ESTIMATION ERRORS

Method	From tables	From discretization	Difference %
Saw and chips, centred samples	52 783	54 140	+2,6
Saw and chips, side samples	120 374	122 600	+1,8

Fig. 13 shows examples of line and section terms for different sampling arrangements using an arbitrary semi-variogram model. The line term is the same for all three arrangements and changes only with the sampling interval. The section term changes with the dimensions of the block and the position of the line of samples within the block, but does not change with the number of samples taken along the line.

It can be seen in the examples given that the centred sampling arrangement shown in A will have the least error of estimation owing to its small section term. It is shown that, when the samples are taken on the side of the block, as in case B, the section term is significantly increased, resulting in a much greater overall estimation error.



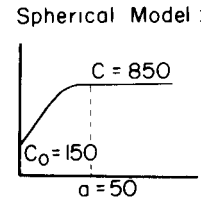


Fig. 13—Examples of line and section terms in the calculation of the error variance of estimation for the average grade of a mining panel

SAMPLE INTERVAL (m)	N° OF SAMPLES	LINE TERM (σ_L^2)	SECTION TERMS (σ_S^2) A	B	C
1	30	5			
2	15	11			
3	10	16	6	70	298
5	6	29			
6	5	35			
10	3	64			
15	2	106			

$$\sigma_E^2 = \sigma_L^2 + \sigma_S^2$$

Case C shows a situation where sampling is done along the edge of a block 30 m by 30 m. This could represent a face of exceptionally high advance during the measuring period, or a face value that is extended for a block to be mined over the following few months. It can be seen that, in this case, the section term is so high that there would be very little difference in the total error of estimation whether the face was sampled every 1 m or every 6 m.

Fig. 14 shows graphs of estimation error versus number of samples applicable to gold values at REGM. The estimation error is expressed as the coefficient of variation (C.O.V.), which is the standard deviation by the mean value × 100. It can be seen that, in cases A and B, the taking of 5 to 6 samples along the face, i.e. samples being 6 m or 5 m apart respectively, appears to be adequate. If the number of samples taken were decreased, the estimation error would increase drastically. By the taking of more samples along the face, little reduction in the error would be achieved, and this may not be worth the time and expense.

The 'flat' part of these two curves is due largely to the section term. This cannot be reduced by the taking of more samples along the face. If the error resulting from the section term is felt to be outside acceptable limits, the only way that this can be reduced is to sample the block more frequently. Curves C and D indicate the decreased estimation errors achieved when the block is sampled twice, instead of once.

Western Areas Gold Mine

The locality chosen for the experiment on Western Areas Gold Mine was in a E9EC (Middle Elsburg Reef) raise. Fig. 15 shows that the sampling method employed was quite different from that used in the experiment carried out at REGM. At WAGM, the chip sampling was deliberately carried out with less control and was done

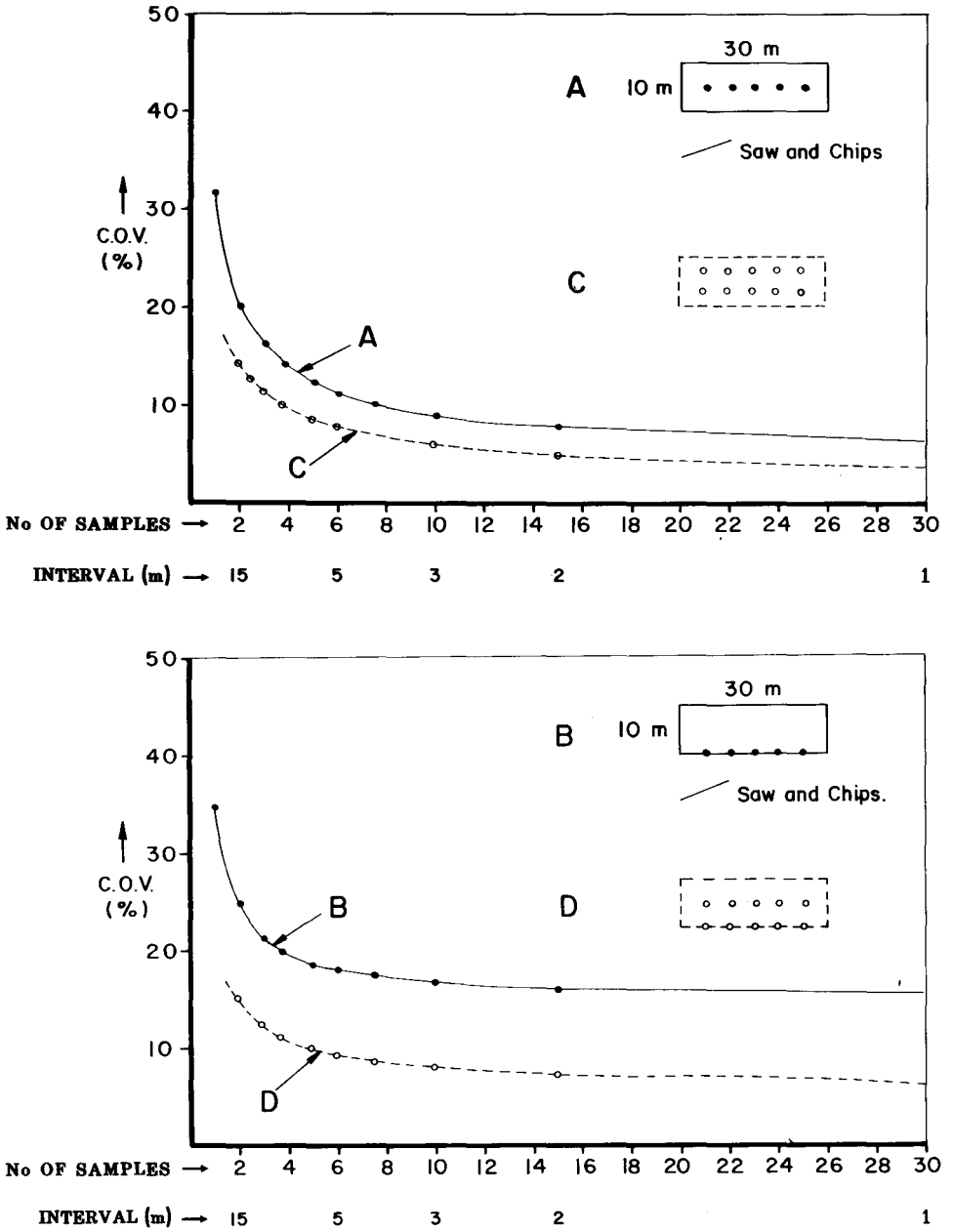


Fig. 14—Randfontein Estates Gold Mine: error variance of estimation of the mean gold value (cm.g/t) of a panel using sampling arrangements applicable to both diamond-saw and chip sampling

in the normal production manner. The diamond-saw sections were not made between the same channel lines but were off-set by 50 cm. It is felt that the WAGM data set is a much more realistic basis for a comparison of the two sampling methods.

Figs. 16 to 18 show the histograms and probability plots of gold values. In this case, the data are clearly shown to be log-normally distributed. An additive constant of 150 cm.g/t was estimated.

Fig. 19 shows the experimental semi-variograms of the transformed gold values from both the diamond-saw and chip sampling. Both data sets were fitted to a spherical model having a similar sill and range. However, the nugget effect for the diamond-saw sampling is less than half that for the chip sampling. This clearly leads to much improved estimates for the diamond-saw samples, i.e. reduced estimation errors.

The logarithmic error variances of estimation of the mean gold value of mining panels were calculated for different sampling arrangements by use of the semi-variograms derived from each sampling method in the same way as for the REGM data.

The total logarithmic errors of estimation obtained by the addition of the line and section terms found on the tables were checked against the results obtained by numerical discretization of the block. The results obtained for a block of 30 m by 10 m and a sample spacing of 6 m are compared in Table II. It can be concluded that, with adequate discretization, accurate results can be obtained by the simpler numerical method.

Finally, the logarithmic error variances of estimation were expressed as coefficients of variation by use of the standard equation:

$$\text{C.O.V. } \% = \frac{\sqrt{(m + \beta)^2 \ (e^{\sigma^2} - 1)}}{m} \times 100,$$

where

m = population mean value (cm.g/t)
β = additive constant (cm.g/t)
σ^2 = logarithmic error variance.

TABLE II
WAGM: ESTIMATION ERRORS

Method	From tables	From discretization	Difference %
Saw, centred samples	0,0201	0,0203	+1,0
Saw, side samples	0,0435	0,0435	0
Chips, centred samples	0,0419	0,0423	+1,0
Chips, side samples	0,0641	0,0643	+0,3

Fig. 20 shows graphs of the error variances of estimation expressed as coefficients of variation against the number of samples used to value the mining panel using both diamond-saw and chip sampling techniques. It is clearly seen that the diamond-saw sampling method gives significantly lower errors of estimation. In the examples given in Fig. 20, it is shown that, to achieve the same error of estimation as that obtained with diamond-saw sampling at a sampling interval of 5 m, it would be necessary to have a spacing of 2 to 2,5 m with chip sampling.

As on REGM for the diamond-saw method, a sample spacing of 5 to 6 m appears to be close to the optimum, little reduction in estimation error being achieved by the taking of a larger number of samples. For chip sampling,

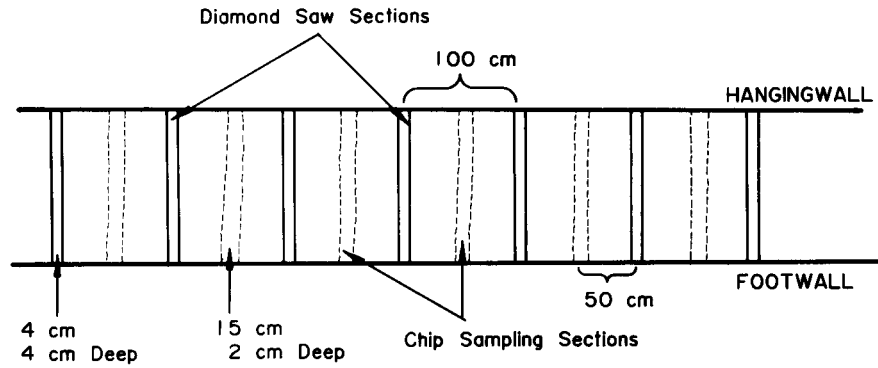


Fig. 15—Sampling method at Western Areas Gold Mine

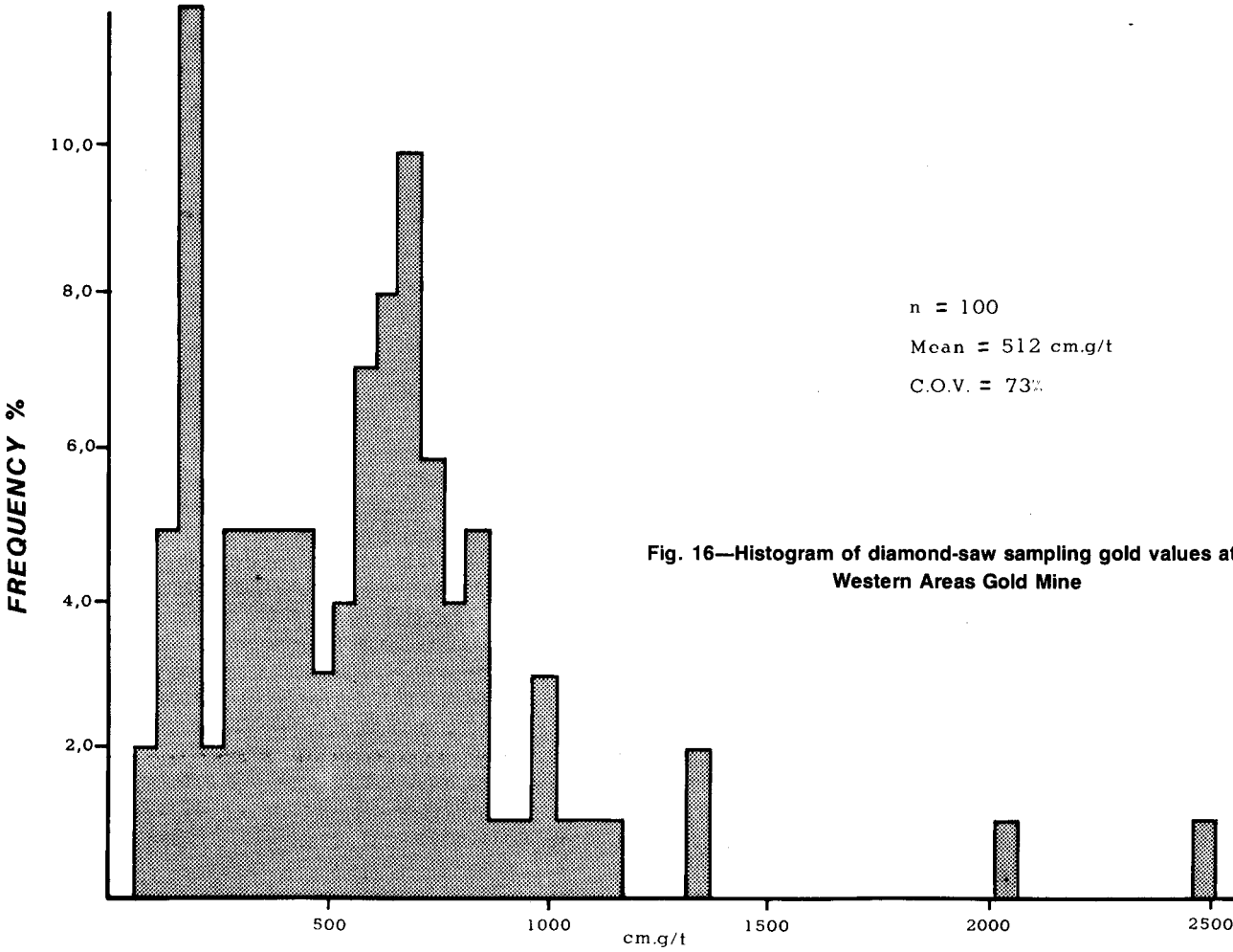


Fig. 16—Histogram of diamond-saw sampling gold values at Western Areas Gold Mine

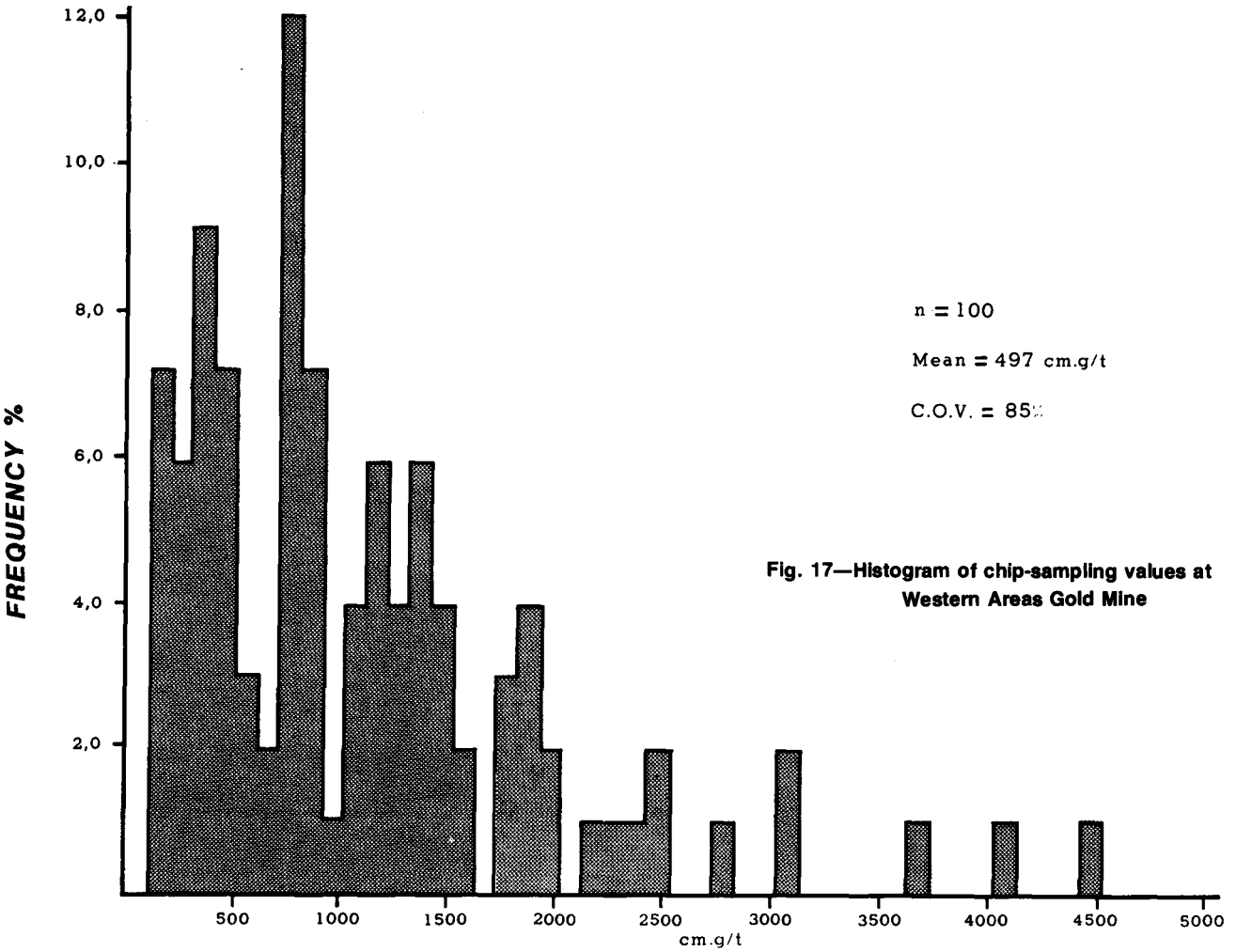


Fig. 17—Histogram of chip-sampling values at Western Areas Gold Mine

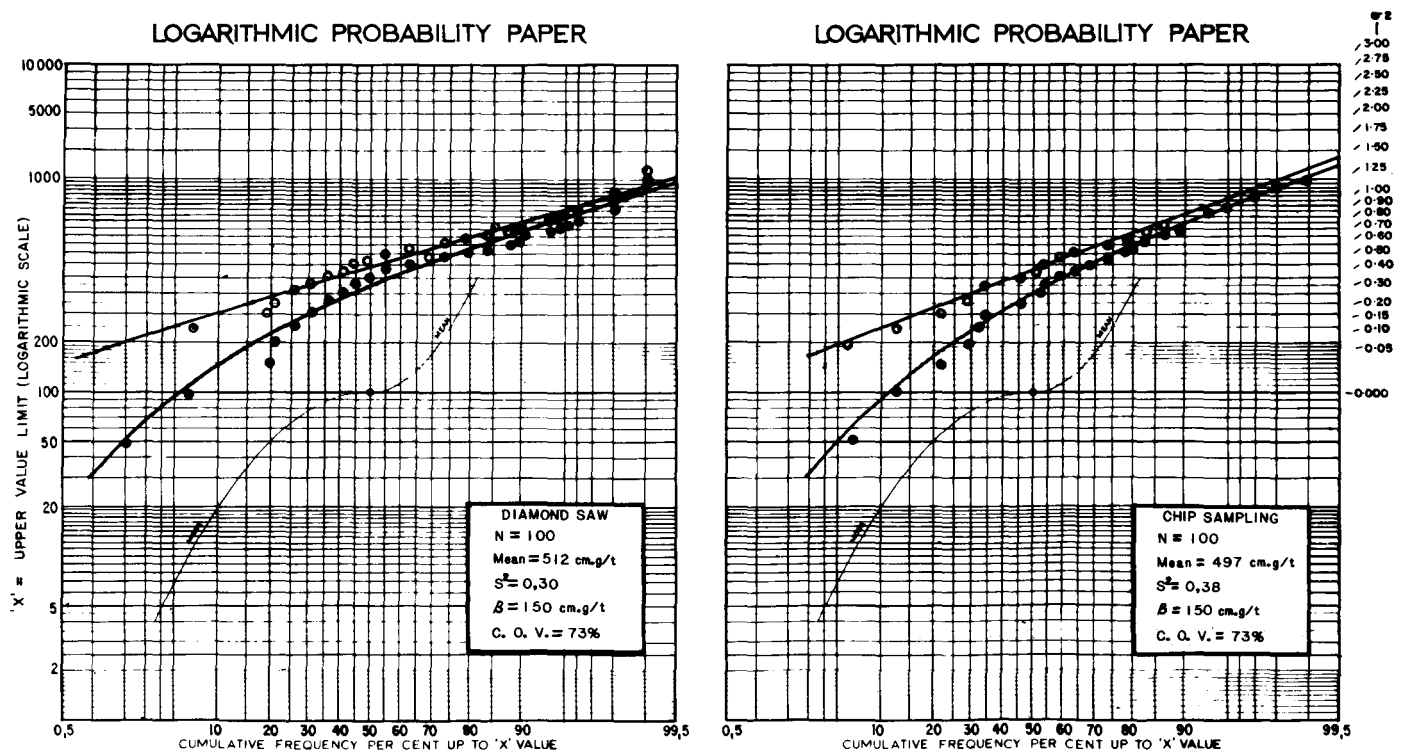


Fig. 18—Distribution of gold values obtained by diamond-saw and chip sampling at Western Areas Gold Mine

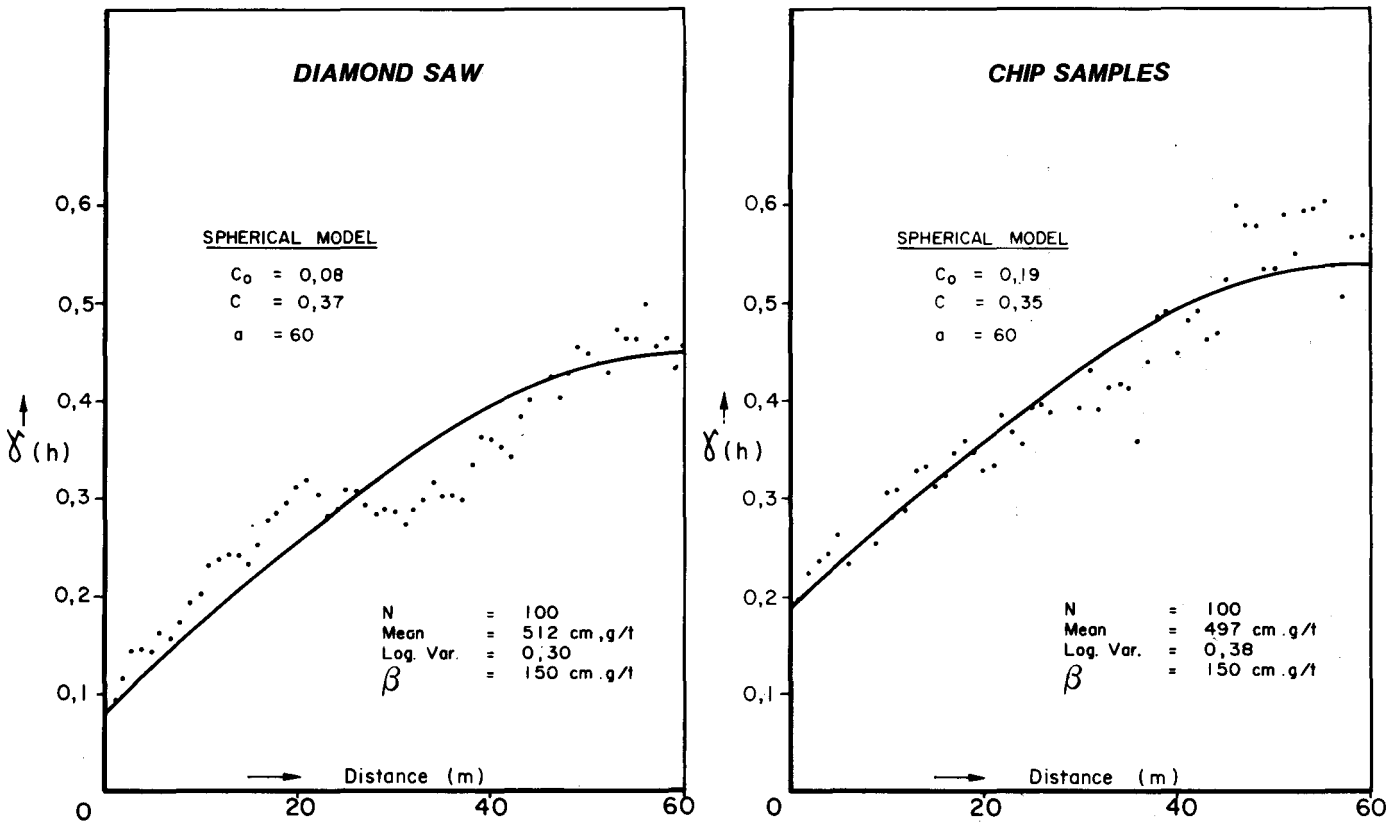


Fig. 19—Variograms for diamond-saw and chip sampling gold values at Western Areas Gold Mine

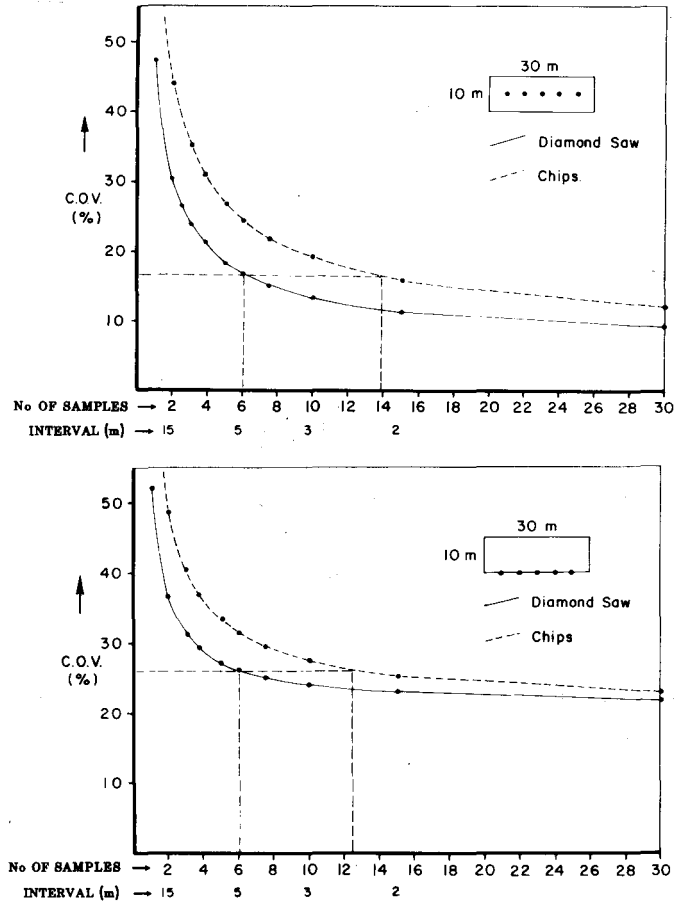


Fig. 20—Western Areas Gold Mine: error variance of estimation of the mean gold value (cm·g/t) of a panel using sampling arrangements applicable to both diamond-saw and chip sampling

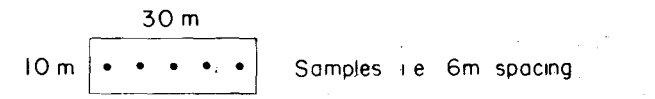
however, the optimum sample spacing would need to be about 3 m or closer.

The merit of the reduced estimation error achieved by use of the diamond saw depends upon the level of confidence required in grade estimates. This would obviously vary from mine to mine, and would depend on the main aims of the sampling. If the main aim of sampling is to achieve better mine accounting of such things as mine call factor and block factors, then narrow confidence limits are important for all values irrespective of payability. If the main aim of sampling is the selection of mining blocks, i.e. to decide if a block of ore is to be mined or not, then the levels of confidence in grade estimates become more critical when values are close to the pay limit.

Fig. 21 shows an example from WAGM where the estimation errors were translated into confidence limits based on the assumption of a log-normal error distribution as shown by Krige[3]. The mean value for diamond saw and chips is the same, being 5,0 g/t, but the 90 per cent central confidence limits are much narrower for the diamond-saw samples than for the chip samples. If the pay limit of the block was, for example, 3,5 g/t, then the diamond-saw valuation of the block would give better than 95 per cent confidence that the block was payable. In the case of chip sampling, this degree of confidence of payability would not be achieved.

Conclusions

This brief geostatistical study supports the view that the diamond-saw sampling method is a significant im-



	σ_E^2	LOW 95% (g/t.)	MEAN (g/t.)	UPPER 95% (g/t.)
DIAMOND SAW	0,0201	3,7	5,0	6,8
CHIPS	0,0419	3,2	5,0	7,8

Fig. 21—An example of log-normal confidence limits for the mean grade of a mining panel at Western Areas Gold Mine

90% Central Confidence Limits -

$$\text{Upper Limit} = \text{Exp}\left[\log_e(M+\beta) + \frac{\sigma_E^2}{2} + 1{\cdot}645\sqrt{\sigma_E^2}\right] - \beta$$

$$\text{Lower Limit} = \text{Exp}\left[\log_e(M+\beta) + \frac{\sigma_E^2}{2} - 1{\cdot}645\sqrt{\sigma_E^2}\right] - \beta$$

provement over normal production chip sampling.

As shown in studies such as those by Krige[4], Magri[5], and Magri and Finch[6], considerable economic advantages can be obtained from small reductions in the error of estimation of ore reserve blocks in the case of selective mining. The use of the diamond saw for stope and development sampling on gold mines should lead to such reductions in the error of estimation of ore reserve blocks, with a consequent reduction in the number of misclassified blocks, i.e. the mining of unpayable blocks and the leaving behind of payable blocks. This, in turn, could be translated into financial advantages that run into millions of rands per year.

Geostatistical studies, such as this, in which errors of estimation (or confidence limits) are computed for different sampling arrangements are of considerable benefit in the establishment of optimum sample spacings. As the data used in this exercise were fairly limited and obtained for a single direction, one must be careful not to read too much into the results in terms of sample spacing. But, if use is made of an extensive two-dimensional sampling data base, such work could be done in detail and factors such as anisotropy (existence of 'pay' shoots) could be taken into consideration. Such work might well show that, for the same level of confidence of grade estimates to be achieved throughout a mine, the optimum sample spacing would vary from reef to reef and from mine section to section.

Acknowledgements

The authors express their sincere appreciation to the Management of Anglovaal Limited and Johannesburg Consolidated Investment Company Limited for the opportunity to carry out this work and for permission to publish this paper. They also thank Messrs J.P. Wolhuter, P.D. du Preez, and N. Smit for their co-operation and assistance.

References

1. JOURNEL, A.G., and HUIJBREGHTS, H.J. *Mining geostatistics*. London, Academic Press, 1978. pp. 108–147.
2. ROYLE, A.G. A practical introduction to geostatistics. Leeds University, unpublished course notes, 1982.
3. KRIGE, D.G. Geostatistics and the definition of uncertainty. *Trans. Instn Min. Metall.*, Section A, vol. 93, Apr. 1984.
4. KRIGE, D.G. *Lognormal-de Wijsian geostatistics for ore evaluation*. Johannesburg, The South African Institute of Mining and Metallurgy, 1978.
5. MAGRI, E.J. Improved geostatistics for South African gold mines. Johannesburg, University of the Witwatersrand, Ph.D. thesis, 1983.
6. MAGRI, E.J., and FINCH, A. Increased profitability in South African gold mines by the application of geostatistics. Fifth General Meeting of the Geostatistical Association of South Africa, Johannesburg, Apr. 1985.