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An analysis of the practical and economic implications of systematic underground drilling in deep South African gold mines

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Using chip sample data and spatial structure parameters from a large mined-out section of a South African gold mine the advantages to be gained from a regular underground borehole drilling programme have been investigated for short- and medium- to long-term planning based on block valuations. The results have been compared with the current position, which relies invariably on the extrapolation of limited peripheral sampling data from raises, gullies or stope faces. Some preliminary work has also been done regarding the implications of such underground drilling on costs used for the present pay limit calculations.

The results of the study, though preliminary, show that the net advantage of advance regular underground drilling could be substantial and that a more intensive follow-up research is warranted.

Introduction

Mineral resource block valuation for short- and medium- to long-term production planning in most South African deep gold mines relies basically on the extrapolation of limited peripheral data into the interior of each ore block. The data available are invariably from the sampling of raises, gullies, and/or stope faces. Blocks on which selective mining decisions are based, i.e. selective mining units (SMUs) are large due to mining restrictions imposed by the depth. The estimation of these large SMUs for mine planning and the actual selection of the units mined in deep level mines are unreliable and smoothed due to the absence of data inside the blocks and the significantly high estimation variance. These inefficient estimates could be an increasingly critical problem especially for deep level gold mines, and could result in increasingly higher risks of achieving the implementation of efficient and profitable mining operations.

The wide limits of error with no boreholes as at present, demonstrate the reason why any planning to pinpoint payable reserve blocks based on extrapolation of the limited chip sample data is, and will be, inefficient. If, however, advanced drilling of additional underground boreholes within the block is implemented, with deflections if practical, the present wide confidence limits could improve significantly. For new deep level mines, or extensions of operating mines, with even larger SMUs, any significant improvement in these confidence limits could reduce the risk arising from the overall selective grade uncertainty to an acceptable level.

However, the advantages to be gained from the drilling have to be weighed against the additional costs and these, in turn, will depend on the optimum grid of drilling indicated for each case. The net advantage of advance underground drilling could be very substantial and the need for an analysis of the feasibility of doing such drilling for resource assessment and reliable mine planning seems obvious. The additional underground drilling information could also assist in avoiding disruptions from the stopping and restarting of stope faces due to limited information.

In the present system without systematic underground drilling, there is, in fact, some selectivity practiced within ore reserve blocks, the advancing stope faces within a block being resampled, e.g. after every 5 m advance; stoping is abandoned if extrapolation on the latest data over e.g. two to three sequential blast faces show likely unpay ore ahead. However, if the balance of the block is still extensive the presence of some payable ore in the balance of the block further ahead cannot be ignored and could lead to the substantial lock-up of potential ore. This position could change if some advance drilling is introduced.

The above implications are important for deep level mining as practiced at present in the South African gold industry, also for new deep level mines, and will become more important as mining proceeds to greater depths. The paper investigates the alternatives from a practical and financial point of view using typical data from a large mined-out area in an existing mine, as well as the preliminary implications of underground drilling costs at depth.

Database for the study

Chip sample data from a large mined-out section of a Witwatersrand gold mine on the Carbon Leader Reef provided gold cmg/t values for a total of 18,205 individual sampling sections for the study. The samples are on a 2 to 5 m grid. These values provided the spatial structure and the follow-up 'actual' mean grades for respective blocks as well as for the whole study area. The statistics of the 'actual' values and the semivariogram for the entire data are shown in Tables I and II.

Alternative scenarios

Block valuations for medium- and long-term planning in most Witwatersrand deep gold mines rely upon the extrapolation of limited peripheral sampling in raises, gullies and/or stope faces. For the present scenario, selection is accepted to be on 50 x 50 m selective mining units (SMU's), with original blocks developed on 200 x 200 m blocks with raises in the centre and gullies at the bottom. Short-term forward planning is then based on these SMU block valuations which are usually reflected as proved or at least probable reserves. Beyond these, the balance of the large 200 m x 200 m blocks are normally classified as indicated or inferred resources and probable reserves due to the much larger limits of error applicable. For these valuations to be conditionally unbiased, significant smoothing is involved and post-processing is called for to realistically estimate the required tonnage grade curves. These estimates will apply as and when more data become available following the advance of the stoping faces. However, these post-processed tonnage grade estimates are affected significantly by the extent of the uncertainty of the 200 x 200 m block estimates. To the extent that these relevant confidence limits can be reduced, the medium-to long-term planning will become more reliable and, in fact, show higher potential profits.

The present two scenarios of raise or raise plus gulley, thus need to be compared with the additional three scenarios which will arise when considering the additional information from underground grid drilling, i.e. boreholes only, raise plus boreholes, and raise plus gulley plus boreholes.

Based on the spatial structure parameters of the massive data in the study area, the effects of introducing a regular grid of underground boreholes have been analysed on a theoretical basis. At this stage, no deflections have been considered. To provide information on selective mining decisions, the indirect post-processing approach has been applied to the parent 200 m x 200 m block estimates to allow for a final selection on 50 m x 50 m SMU blocks (Assibey-Bonsu and Krige, 1999; Krige, 2003). As far as cost implications are concerned for the additional underground drilling, a preliminary analysis based on data available from the mine has been done.

The estimates for the different scenarios were analysed statistically and compared with the 'actual' values of the database with the main advantages measured relative to changes in error variances of these blocks based on the different data patterns as are summarized in Table III. Also the corresponding dispersion variances, confidence limits and relative profits have been analysed in this regard. All results reflect grade estimates as percentages of the mean grade, confidence limits as percentage deviations from the estimates, and relative profits as percentage of the theoretical maximum.

Implications for planning

Confidence limits for short-, medium- and long-term estimates

Table III provides the position of valuations of 200 m x

Table I
Statistics of data used for the study

Mean-cm.g/t	Variance (x 10^7)	Number of samples
2914	13.0	18205

Table II
Semi-variogram parameters used for the study

Structure	Sill relative to total variance (%)	Range (m)	Anisotropy		
			X	Y	Z
Nugget	44.4		1.0	1.0	1.0
Spherical	29.0	15	1.0	1.0	1.0
Spherical	14.0	60	1.0	1.0	1.0
Spherical	12.6	210	1.0	3.5	1.0

Table III
Showing error variances and confidence limits for block estimates for the five scenarios

Data type and scenario	Log error variance		Lower and upper 90% confidence limits*			
	50 m x 50 m Blocks	200 m x 200 m Blocks	50 m x 50 m Blocks		200 m x 200 m Blocks	
Raise only (1)	0.143	0.0343	-42.6%	+51.1%	-22.5%	+24.6%
Boreholes only (2)	0.155	0.0236	-44.1%	+53.3%	-18.8%	+20.3%
Raise and boreholes (3)	0.115	0.0224	-38.8%	+45.7%	-18.4%	+19.8%
Raise and gully (4)	0.122	0.0342	-39.9%	+47.2%	-22.4%	+24.6%
Borehole, raise and gully (5)	0.103	0.022	-37.0%	+43.3%	-18.36%	+19.8%

* Based on Lognormal error model

200 m blocks, which will form the critical base for medium- to long-term planning estimates. The results for the five data scenarios mentioned previously as applied to this size of block are shown. For short-term planning estimates the results for the same scenarios are based on 50 m × 50 m SMU blocks and are also shown. The log error estimates for ordinary kriging were significantly higher than that for simple kriging in all cases with significant conditional biases and have therefore not been reported in this study.

Short-term planning

From the confidence limits figures for the raise only and raise and gully, it is evident that the uncertainty attached to the 50 × 50 m SMU blocks is higher than when drilling boreholes are present. The Table shows that in the two scenarios where boreholes are introduced as an additional source of data (i.e. scenarios 3 and 5) the results are similar and are better than the two scenarios when we have raise only, or raise and gully (scenarios 1 and 4). Further implications are discussed later.

Medium- and long-term planning

The results for the 200 m × 200 m blocks cover this position (Table III). The results indicate that for medium- and long-term planning, advance underground drilling will provide a basis for planning significantly better than that based on raise or raise/gully, and this can be executed well in advance of developing the raises or gullies. This is evident from the significantly lower error variances and closer confidence limits for the large block valuations. The study also showed significant improved block efficiencies for the underground borehole scenarios.

Relative profits

The 'relative profits' criteria provides a preliminary indication of the likely financial implications of the respective data/drilling campaigns, where

Relative Profit = %tons above Pay Limit × (grade above Pay Limit–Pay Limit).

It assumes that the Pay Limit reflects the level of actual costs and that the grade above pay limit is directly proportional to revenue/ton; and that the percentage tonnage above pay limit multiplied by the average grade less pay limit (i.e. relative profit per ton) reflects the total relative measure of total profit to be gained.

Table IV shows the results of relative profits for the critical 200 m × 200 m parent blocks assuming the selection of blocks above the lower 90% limits of simple kriging estimates. To cater for the uncertainties attaching to the grade estimates of the large blocks, it has been assumed that allowance would be made for the mining of some probable 50 m × 50 m blocks in 200 m × 200 m large blocks, which are unpayable on their average estimates. This means that some large unpay blocks but with estimates above the lower 90% confidence limits, will also be selected. The results show higher relative profits when boreholes are involved, but do not cover the selection of ore on the basis of 50mx50m SMU's, dealt with in the (Post processing...) paragraph below.

Preliminary costs implications

Table V provides results of some preliminary cost analyses done regarding the implication of underground drilling on costs used for the present pay limit calculation. It indicates the cost/m² entering into the pay limit calculation is likely to be increased by about 0.3% for the 50 m × 50 m underground drilling spacing and would therefore not be critical. The additional cost of drilling was therefore ignored for this investigation. On balance it is expected that a more detailed analysis of cost/benefit implications will show further advantages for advance underground drilling such as resulting from possible avoidance of developing raises in likely unpayable areas. Additional advantages would include better geological/structure modelling, better planning of raise spacing relative to geological facies and for individual faulted blocks; also more reliable overall strategic life of mine and financial estimates and resource/reserve classifications. These should also result in reducing the risk/uncertainty inherent in planning.

Post-processing and final mining selection of 50 m × 50 m selective mining units

Selective mining decisions for 50 m × 50 m SMUs at the stage where more data will be available will provide

Table IV
Levels and certainty of Relative Profits based on different scenarios

	Relative Profit as a percentage of theoretical maximum*						
Pay Limit as a % of the Mean	20	30	40	50	60	70	80
Data type							
Only raise	71.9	67.9	62.5	55.0	44.0	26.3	2.4
Only boreholes	76.5	73.1	68.7	62.4	53.0	38.8	19.7
Borehole, raises and gully	77.1	73.8	69.4	63.3	54.9	41.7	22.8

* Incorporates lower 90% limits of error for respective scenarios using 200 m × 200 m block estimates

Table V
Preliminary cost implications of systematic underground borehole drilling

Type of data	Typical current cost/m² for Pay Limit calculation (Index = 100)	Total cost/m² including 50 m × 50 m borehole drilling	Per cent increase in cost/m² due to borehole drilling (%)
Including current raises and gullies	100	100.3	0.3

measured resource and proved reserves or at least some indicated resources and probable reserves. For this purpose valuations will be based on the raise values or raise plus gully values or alternatively on these plus underground drilling in advance and inside the block. Figures 1 to 4 show the post-processed grade-tonnage and relative profits results for 50 m x 50 m blocks based on the 200 m x 200 m blocks estimates. The Figures show that from raise only to raise plus boreholes or raise and gully (scenarios 1, 3 and 4), there is significant improvement; and that the best scenario is achieved when using all three (scenario 5). The Figures also show that the theoretical 'actual', based on the lognormal model agrees very well with the observed 'actual' based on kriging all of the closely spaced 'actual' data into 50 x 50 m SMU blocks. It should also be noted that the 'actual' position relates to the ideal position and is based on all available samples inside the block after mining, which is therefore a position, which is never available for selective mining decisions, but it is only known retrospectively and not in advance. The direct financial advantage of scenario 5 over scenario 4 as shown on Figure 4 appears small but the additional cost of drilling is negligible. However, the SMU size used of 50 m x 50 m are on the small side for deep level mining and if larger size is considered the advantage will be more obvious as indicated in Tables III and IV.

Conclusions

The results of this research effort clearly indicate that there are advantages in implementing a regular underground drilling programme on a systematic grid. It must be seen as only the first stage of a more intensive effort to be executed as a follow-up; i.e., they are initial conclusions which justify further, more detailed, intensive research into all the detailed implications of such a programme.

The following are some of the advantages to be gained with the execution of a regular underground drilling campaign:

- Improved efficiencies of selection for short-, medium- and long-term strategic planning
- Flexibility and better definition in planning future financial patterns
- Improved efficiencies and conditional unbiasedness in block valuation and better reconciliations
- Better geological/structure modelling, better definition of multiple or thick reef profiles in hanging/footwalls, control of methane and water, and underground operational and environmental safety.

Aspects to be further investigated include:

- Effect of different spatial structures
- Effect of varying the underground borehole grids spacing and introducing borehole deflections
- Flexibility of ranking decisions on marginal areas where further information e.g., further drilling could lead to efficient selection of areas (e.g. the minimum 30% pay criteria for selecting areas for mining as practiced on some gold mines)
- Practical and realistic underground development rates and drilling campaigns/rates
- Implications of applying simulations to underground drill data for more detailed uncertainty modelling.

References

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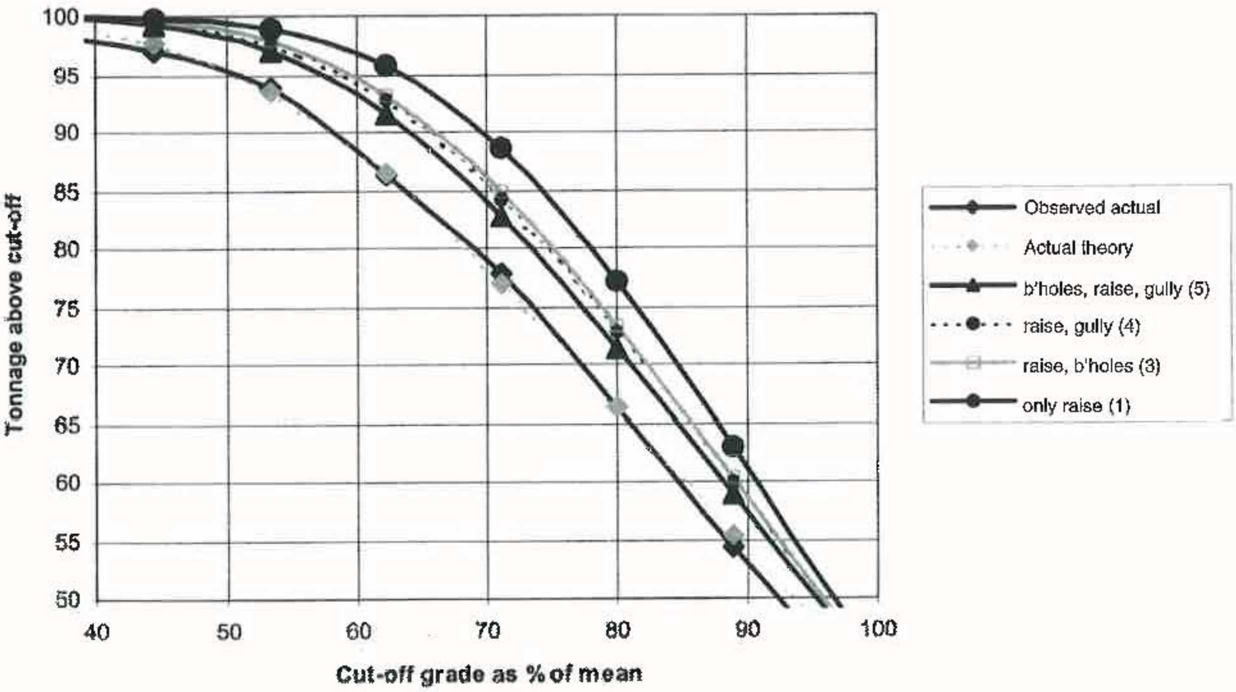

Figure 1. Showing indirect post-processed 50 m x 50 m SMU tonnage estimates from 200 m x 200 m parent blocks, also the theoretical 'actual' and observed 'actual' distributions: scenarios are in brackets

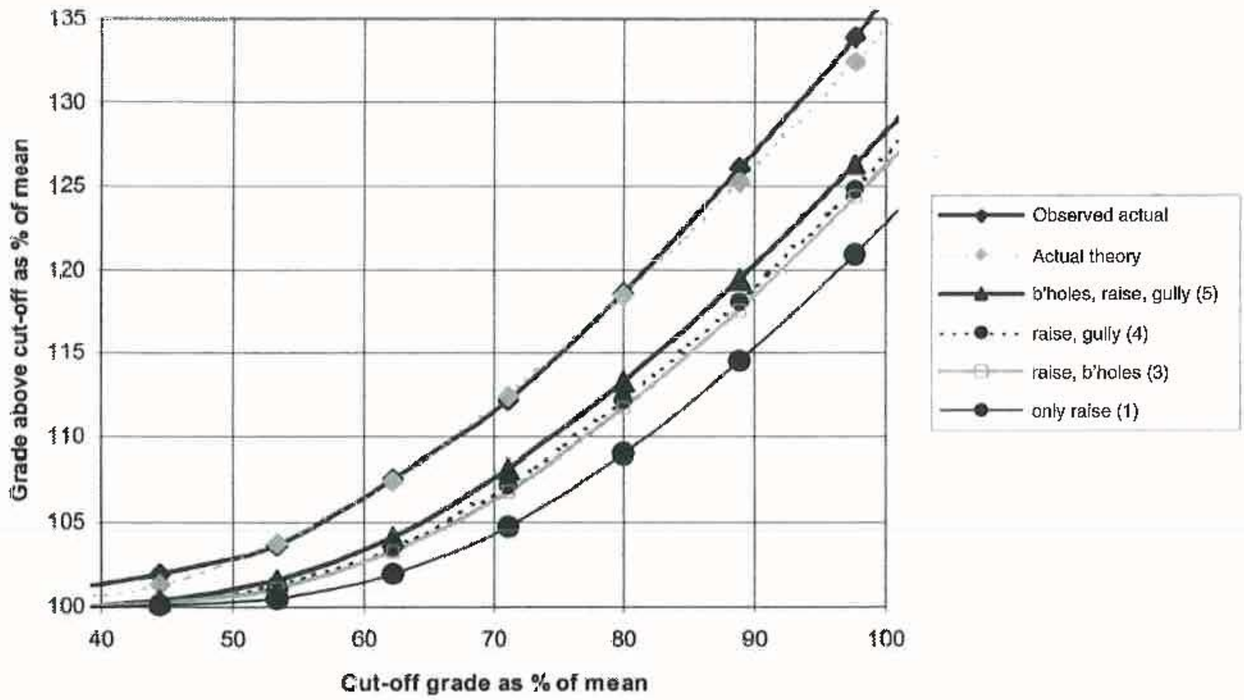

Figure 2. Showing indirect post-processed 50 m × 50 m SMU grade estimates from 200 m × 200 m parent blocks, also the theoretical 'actual' and observed 'actual' distributions: scenarios are in brackets

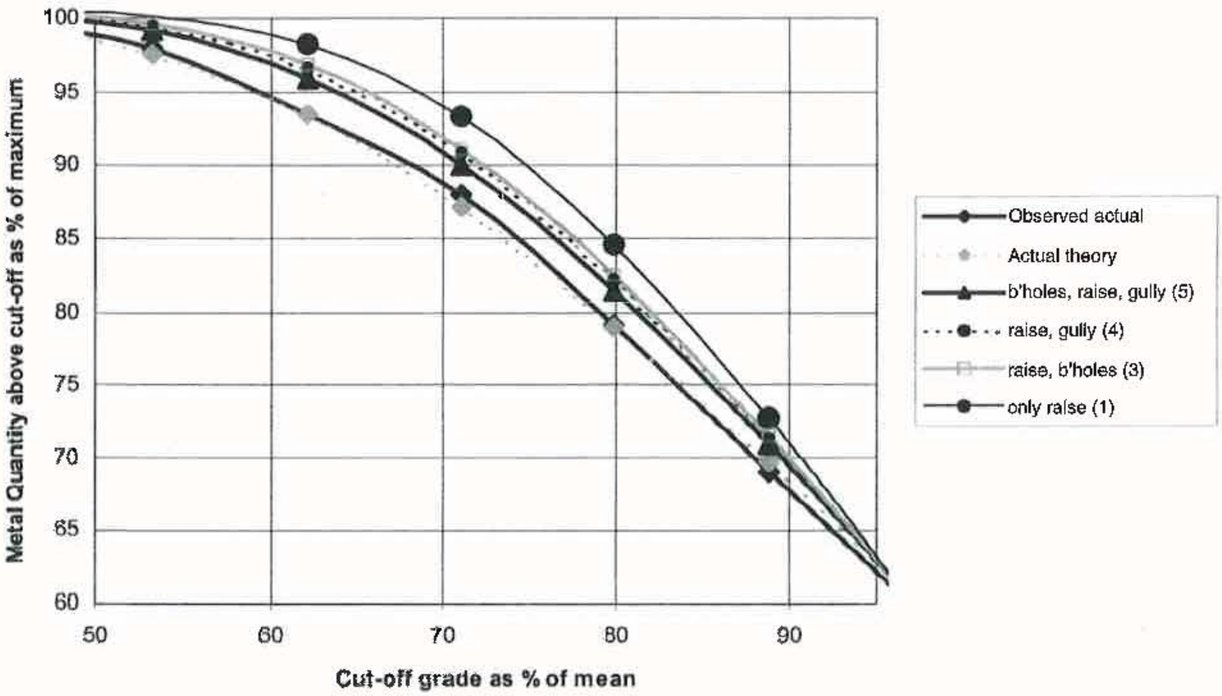

Figure 3. Showing indirect post-processed 50 m × 50 m SMU metal estimates from 200 m × 200 m parent blocks, also the theoretical 'actual' and observed 'actual' distributions: scenarios are in brackets

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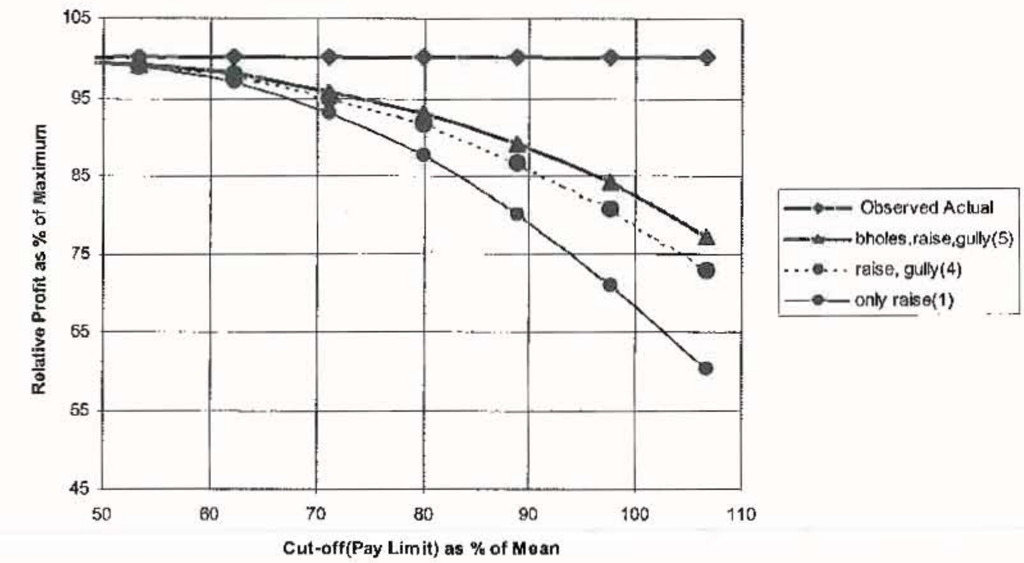

Figure 4. Showing indirect post-processed 50 m× 50 m SMU relative profits estimates from 200 m × 200 m parent blocks, also observed 'actual' distributions: scenarios are in brackets