Limitations in accepting localized conditioning recoverable resource estimates for medium-term, long-term, and feasibility-stage mining projects, particularly for sections of an ore deposit

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Synopsis

A localized nonlinear recoverable resource estimate technique has been applied using typical feasibility or new mining drilling data configurations drawn from a massive database from a mined-out area on a hydrothermal gold deposit. The results were then compared with the corresponding 8 m x 5 m grid grade-control data in order to determine the efficiency of the approach and the validity of the recoverable resource estimates for mine planning and financial forecasts.

Keywords

localized conditioning, post-processing, nonlinear recoverable estimates, direct and indirect recoverable estimates, kriging efficiency, slope of regression, relative profit, inefficient kriged estimate, conditional bias.

Introduction

The problem associated with the use of limited search routines and inefficient kriged estimates when estimating recoverable resources for new mining projects have been highlighted in several papers (Krige 1994, 1996; Krige and Assibey-Bonsu, 1999a, 1999b). The critical importance of using efficient and non-biased direct and indirect recoverable estimates in mine plans, and the corresponding financial forecasts for mining projects, has also been demonstrated in these papers.

The direct and indirect techniques are supposed to provide local adjusted grade-tonnage estimates for mine planning, but cannot identify the final individual blocks to be selected for mining above a specified cut-off. Techniques for estimating recoverable resources at the exploration or early stage of a mining project, or for extensions of existing mines, all suffer from the main problem of not being able to identify those specific blocks that are to be selected finally for mining above any cut-off. Thus any mine planning exercise based on these long-term recoverable estimates will, unavoidably, involve misclassification of blocks.

However, direct and indirect recoverable estimates based on inadequate data, as well as conditionally biased and inefficient estimates, can be badly misleading for the prediction of recoverable resource estimates for global life–of-mine estimates, as well as for sub-sections of the orebody. These will have obvious negative economic implications on the orebody to be mined in short-, medium-, and long-term periods, and hence also for the pattern of production and financial forecasts over the life of the mine, as well as for any grade control planning.

This paper analyses the effect of using inefficient localized conditioning recoverable resource estimates for project mine planning and financial forecasts.

Geology and the database used for the case study

The net effect of using inefficient direct recoverable estimates was analysed using historical production data from sections of a 3D hydrothermal gold deposit, which has been mined for several years from an open pit with grade control data on an 8 m x 5 m grid. The database for the case study also included resource drilling data. From this historic data, a set of resource drilling data, equivalent to exploration drill-hole values on an approximate grid of 40 m x 20 m, was selected to represent the data at the early stage of a new mining project.

Only resource drill-holes (RD) were selected for the initial resource modelling in this case study, and their orientations were predominantly steep as the drill-holes were oriented to intersect the main mineralization at better angles as far as practically possible (this has been continuously improved over time). The follow-up 8 m x 5 m grade control (GC) drill-holes, which were used as 'actuals' for the comparison with the direct recoverable estimates, were vertical.

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The set of 40 m x 20 m data was used to provide a geological wireframe model as well as ordinary kriged (OK) conditioning panel estimates. The panel size was 40 m x 20 m x 6 m.

In order to provide the recoverable resource estimates for the orebody, the localized conditioning (LUC) technique, as proposed by Abzalov (2006), was utilized. Abzalov proposed using the grade-tonnage functions from the large panel indirect estimates (derived from uniform conditioning (UC)) and then decomposing the panel-specific grade-tonnage data into a suite of individual SMU-sized units within respective panels. Abzalov suggested that the individual parcel grades of the SMUs derived from the decomposed UC approach be assigned, in this case, to the SMU-size blocks within the respective 40 m x 20 m x 6 m panels. In this case study the SMU used is 5 m x 5 m x 3 m.

The estimated localized recoverable conditioning SMU estimates (LUC) as derived from the 40 m x 20 m data were compared with the corresponding 'actual' SMU block values based on the available comprehensive 8 m x 5 m data grid from production grade control, in order to determine the efficiency of the localized recoverable estimates approach and the validity of the estimates for mine planning and financial forecasts.

The mine exploits oxidized and fresh ore in Tarkwaian sediments, which constitute a significant portion of the stratigraphy of the Ashanti Belt in southwest Ghana, West Africa. The hydrothermal mineralization occurs in two fault blocks of the Banket Sandstone. In each block, gold mineralization is concentrated in three to four structural zones with different orientations. The gold mineralization is associated with pyrite and pyrrhotite alteration and is usually located adjacent to en-echelon quartz veins. These alteration zones are often linked, and may result in significant volumes characterized by intense veining and gold mineralization. The model of the gold deposit is illustrated in Figure 1. A robust geological model/interpretation of the deposit was therefore available for the case study. In addition, there was further geological domaining aimed at providing practical homogeneous domains for the geostatistical assessment.

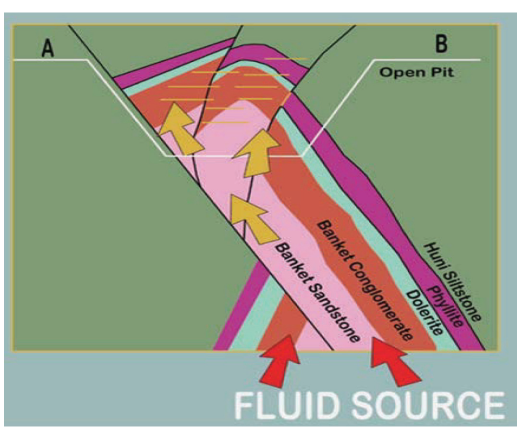

Figure 1—Schematic cross-section showing the main geological formations and structural controls

Basis for comparison of LUC estimates against actuals

The LUC recoverable estimates were compared with the corresponding 'actual' (GC) block values based on the available, comprehensive 8 m x 5 m grade control data grid in order to determine the efficiency of the approach (no resource drilling data was used for deriving the GC block values). Comparisons are provided for ore mined during 6 months, one year, and three years respectively in this paper. The efficiencies of the LUC estimates and the corresponding financial profiles are measured on the basis of the spreads of percentage errors defined as:

Percentage error = (Estimate/Actual - 1) 100%

Actual represents *in situ* grade control block estimates based on 8 m x 5 m data, and Estimate is the corresponding LUC resource estimates. Correlation and regression of LUC individual block estimates against Actuals were analysed. The financial profiles were estimated using the *relative profit* approach, which is discussed later.

Results

Table I shows the global *in situ* (zero cut-off) grades of the 40 m x 20 m x 6 m panels, and GC and LUC comparison for the main section of the study. The table does not reflect any *in situ* global grade distribution biases for the resource drilling panels, LUC, and the GC follow-up kriged outputs. The *in situ* panel resource and GC kriged block estimates in Table I further provide a declustered perspective of the input resource drilling and GC data grades. Table II shows typical variogram parameters observed in the study area for the Banket Sandstone and phyllite mineralization domains (similar variograms were used for the resource and the GC kriging).

Figure 2 shows a typical swath plot observed during the study. Although the figure shows slight deviation from data in one area, there are no obvious general biases.

However, in providing the ordinary kriged panel estimates, which were used for conditioning of the localized recoverable estimate, it was observed that a significant

Table I

***In situ* (zero cut-off) global grade comparison of OK 40 m x 20 m x 6 m resource panels, 5 m x 5 m x 3 m OK grade control blocks, and recoverable LUC 5 m x 5 m x 3 m estimates**

Cut-off (g/t)	5x5x3m grade control OK 'actual' values (g/t)	40x20x6m OK panel estimate used for LUC (g/t)	5x5x3m LUC estimates (g/t)
0.0	2.0	2.1	2.1

Table II

Typical variograms as observed in the Banket Sandstone and phylIite lithologies in the area of the case study (angle 1 = plunge, angle 2 = dip, range in z approx. 9 m)

Domain	Sill	Angle1	Angle2	Angle3	Nugget %	Range1 X	Range1 Y	Range2 X	Range2 Y
1	3.6	-15	-20	0	34	17	17	50	88
2	7.7	0	0	0	44	19	19	36	80
3	17.2	0	0	0	40	14	14	43	85

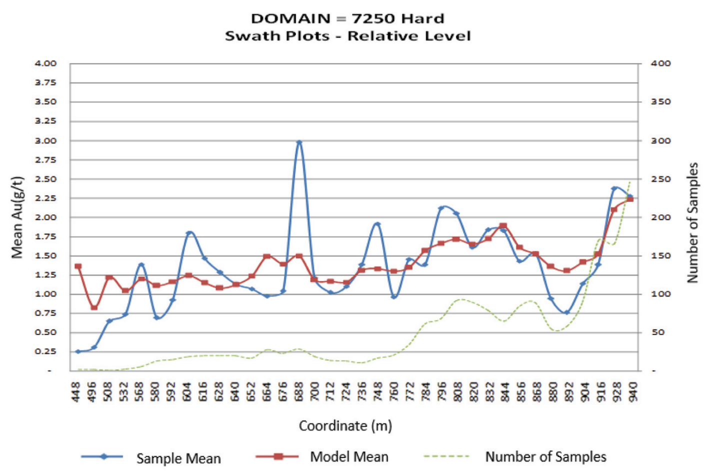

Figure 2—Swath plots of 40 m x 20 m x 6 m panel kriged estimates

number of the panel kriged estimates had poor kriging efficiencies (KEs) and low regression slopes (RSs), due mainly to limited available data during the resource modelling (See Krige 1996 for further details on KEs). This is typical of most exploration and new mining projects. An adequate search routine was used within the context of the resource drilling data available for the panel estimates. Figure 3 shows typical KE and RS correlation in this regard. It is important to stress that although the kriged panel estimates are globally unbiased, as demonstrated above (Table I), most of the individual panel estimates show poor/negative KEs and poor RSs (Figure 3) due to limited available data for local panel estimates. As highlighted previously, this (i.e. invariably limited resource data) is typical of most exploration and new mining projects. These negative KEs and poor RSs reflect significant conditional biases. The situation observed for the KEs and RSs worsened when smaller panel block sizes were used (which is to be expected).

As stressed by Krige and Assibey-Bonsu (1999), the *'efficient' application of any non-linear post-processing technique requires the need for all the block estimates (large or direct SMU) to be conditionally unbiased, which means the approach used by some practitioners in limiting search routines to increase the dispersion variance artificially cannot be justified. This implies the need for the use of an adequate search routine, and where this becomes impractical, the use of simple kriging (SK) with the global or a more local mean*. Deraisme *et al.* (2014) have demonstrated the presence of these biases in resource modelling even in a more continuous porphyry gold-copper orebody (these biases were also due to limited available data); the authors have demonstrated a practical solution to this problem by implementing SK with local means. From our perspective, adequate work is not readily found in the literature where practitioners effectively test the presence of these critical biases, including the use of KE and RS, when applying nonlinear post-processing techniques.

Analyses of 'actual' GC values used for comparison with LUC resource estimates

OK estimation technique was used for the follow-up GC block

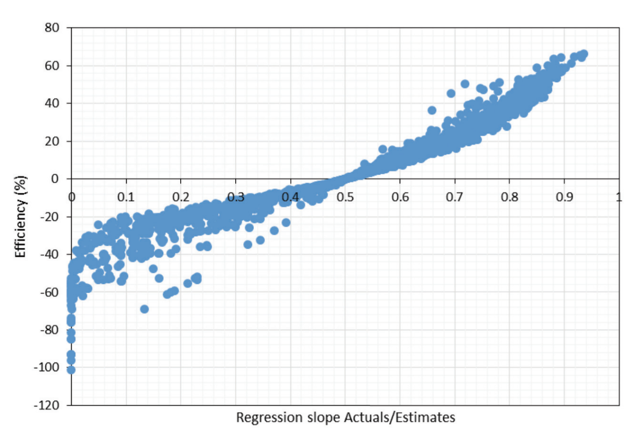

Figure 3—Correlation between OK kriging efficiencies (KE) and slopes of regression (RS) for resource panel kriged estimates

estimates. Simple kriging (SK) of the GC blocks gave similar results to those obtained for OK GCs, as both techniques were based on a comprehensive 8 m x 5 m grade control data grid. The efficiency of GC estimates is shown in Figure 4, as demonstrated by the high RS and very good KE values.

Correlation of 'actual' grade control values with the corresponding LUC estimates

Figure 5 shows the correlation of the localized conditioning SMU estimates (LUC) on the x-axis and the corresponding 'actual' block estimates (GC) based on the comprehensive 8 m x 5 m grade control production data in a typical section of the orebody. Figure 5 demonstrates the inherent systematic biases in the LUC recoverable estimate model, which constitutes a fundamental problem. The correlation coefficient and the slope of regression should be close to unity if the model is conditionally unbiased and robust, which would also mean a high level of correlation between the LUC resource estimates and the actual grade based on the grade control. The trend line between the LUC resource estimates and the grade control values shows a slope of 0.1, reflecting significant conditional biases (Figure 5). In effect, there is almost no correlation between the individual localized LUC feasibility estimates and the 'actual' block values.

In addition, all the LUC estimates to the right of the intersection of the trend line and the 45° line (in red) are all over-estimated in terms of grade, while all the LUC estimates to the left of the intersection lines have been under-estimated.

Table III shows that all the LUC resource estimates with grades of 12 g/t ended up on average just above 3 g/t based on the grade control block values. Similarly, LUC block estimates of 6 g/t are on average about 2.3 g/t based on grade control data. Conversely, LUC estimates of 0.3 g/t (*i.e.* material classified as waste by LUC, *e.g.* based on a 0.6 g/t cut-off), ended up on average just below 2 g/t, indicating that they have been significantly underestimated and misclassified, since they are actually ore when compared to the grade control block values. These reflect serious conditional biases.

As the size of the unit volume is increased to that of ore mined over periods of 6 months, one year, and three years, the position shows certain improvements as shown in Table IV and Figure 6. However, the conditional biases for these macro sections' grade and tonnage estimates are still serious and show that these estimates provide a misleading pattern of mine production and financial forecasts for short-

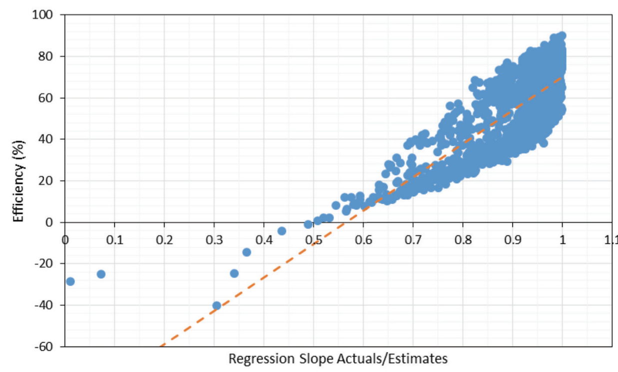

Figure 4—Correlation between OK kriging efficiencies (KE) and slopes of regression (RS) for grade control values based on 8 m x 5 m GC data

Table III

Recoverable LUC estimates and the corresponding 'actuals' based on grade control data

Recoverable LUC SMU estimates of blocks for grade categories	Corresponding average grade for actual blocks
12.0	3.0
6.0	2.3
0.3	1.7

Table IV

Percentage errors of ore mined over respective time periods

Cut-off (g/t)	6 Months tons (%)	6 Months grade (%)	1 Year tons (%)	1 Year grade (%)	3 Years tons (%)	3 Years grade (%)
0.6	-15%	31%	-15%	20%	-15%	16%
0.7	-14%	31%	-16%	22%	-16%	18%
1.0	-3%	27%	-16%	24%	-17%	19%

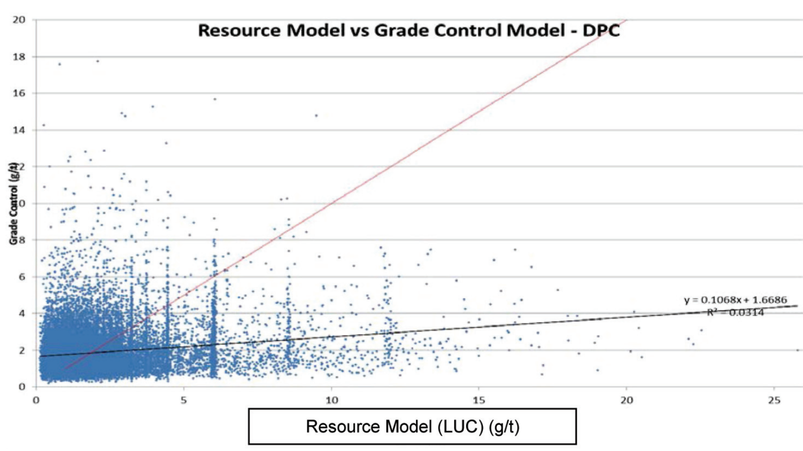

Figure 5—Regression of feasibility LUC SMU estimates against 'actuals' based on grade control data

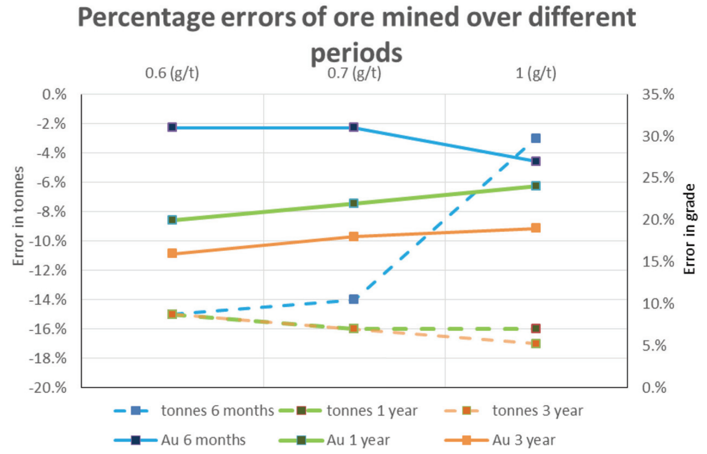

Figure 6—Systematic under-estimation of tonnage and over-estimation of grades demonstrated by percentage errors for ore mined over different time periods

to medium-term mining plans. The general and significant underestimation of tonnage and the corresponding overestimation of grades for the respective sections of the orebody are clear, as demonstrated in Figure 6. These show how misleading any planning based on such tonnage and grades estimates could be.

Discussion

The analysis shows that the main reason for the systematic underestimation of tons and the corresponding overestimation of grades for the individual LUC block estimates, as well for the sections of the orebody, is the significant conditional biases, which, in turn, are a result of the invariably limited resource drilling data available for the LUC estimates. Krige *et al.* (2008) observed similar biases for localized block estimates. Also, as noted by Journel *et al.* (2000): *It appears that global accuracy (semivariogram reproduction [and non-smoothing]) cannot be obtained without sacrificing local accuracy. [Proper] kriging, notwithstanding its smoothing effect, remains the best local estimator*.

The limited resource data issue is typical of most feasibility studies, as well as new mining projects or extensions of existing mines. Where the data-set is larger, the grade-tonnage bias problem could be less serious. *However, the evidence sounds a valid warning not to rely on LUC conditioned by inefficient ordinary kriged panel estimates with significant conditional biases for feasibility mine planning and financial forecasts, unless such estimates can be shown to be effectively conditionally unbiased*. As demonstrated elsewhere (Assibey-Bonsu and Searra, 2014; Deriasme *et al.*, 2014), the corresponding simple kriging with local means provides better conditioning panel estimates for recoverable estimates.

Relative profits

Although the estimated grades to be mined above cut-off are of critical importance, the corresponding ore tons and metal content are also important. However, the final overall measure for a project's feasibility study, which incorporates all these variables, is the profile of the estimated profits to be earned relative to the capital investment. The analyses on the LUC grade estimates, as discussed above have, therefore, been extended to cover the corresponding estimates of *relative profits*, defined as:

Relative profit = % above cut-off (grade above cut-off - cut-off grade)* [2]

Figure 7 shows, for the different production periods, the percentage errors of the profiles of relative profits for different cut-offs based on the LUC recoverable estimates compared with the corresponding 'actual' block values based on the available comprehensive 8 m x 5 m grade control data grid.

Figure 7 also demonstrates that the percentage errors associated with the profit profiles for different production periods are very significant. In the short-term production period (*i.e.* 6 months), the percentage errors range from 36%-74% for cut-offs from 0.6 g/t to 1.0 g/t. Although the error percentages decrease as the production volumes increase, the percentage errors associated with these production periods are still substantial and any financial forecast based on these estimates can be misleading.

Conclusions

From the results of the study, the dangers of accepting localized direct conditioning estimates (LUC) of tonnage,

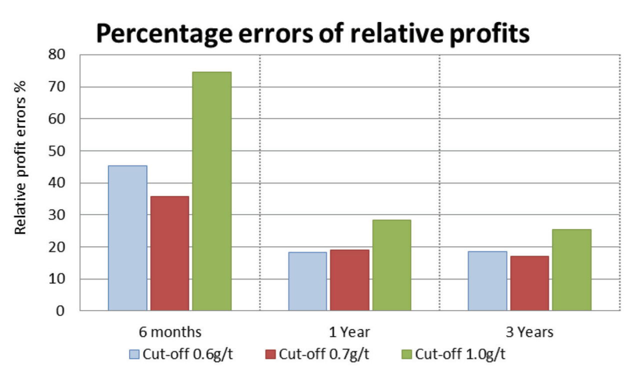

Figure 7—Percentage error profiles between LUC estimates and Actual Relative profits for different production periods (6 months, 1 year, and 3 years) at different cut-offs

grade, and profit figures for short- to medium- term production periods are obvious, particularly where the data-set is small. This is because the much smaller data-set effectively available for individual block and LUC estimates by ordinary kriging, as well as for the sections to be mined in these periods, could prevent efficient and reasonable estimates for planning purposes. In addition, these estimates could be subject to significant conditional biases and invalidate any estimates and patterns of financial forecasts for new projects or for extensions of existing mines.

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