

# Estimation of Reminant Gold Resources of Old Underground Workings by Indicator Approach – A Case Study\*

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## Abstract

The lack of geological control and old underground development at AngloGold Ashanti (Bibiani mine) in Ghana was a major setback for the conventional methods of resource estimation to produce accurate estimates of the deposit. Consequently, inverse distance weighting of indicator variables were used. This estimation approach, however, overestimated the boundaries of the old underground workings (voids) into inappropriate areas of the resource model and thereby caused significant underestimation of ore tonnage and overestimation of grade.

This paper highlights the study that re-evaluated the Bibiani deposit using indicator kriging. The results of re-evaluated reserves compared well with actual production figures in terms of tonnes, grade and stoping volume.

## 1 Introduction

AngloGold Ashanti (Bibiani mine) is located about 380 km by road, northeast of Accra (Fig. 1). The climate in the area is wet semi-equatorial characterised by annual double maximum rainfall pattern occurring in the months of March to July and from September to mid-November. The annual rainfall varies from year to year with a mean of about 1 473 mm.

The first recorded mining operation at the Bibiani mine was in 1902 (De Vente, 2002). However, the mine was closed down in 1968 due to lack of mineable reserves. After the change of ownership and further exploration, the mine was resuscitated in 1997. Open pit mining method was used without any detailed plans to indicate stopes, high grade, broken ore and pillars underground. This, in addition to little geological control, did not allow the conventional method of resource estimation to produce reliable estimates for the remnant gold resources. This called for a review of the resource estimation model. It was imperative to re-evaluate the Bibiani resources using an alternative approach to ascertain whether the consistent overestimation encountered by the conventional Inverse Distance Weighting (IDW) method could be significantly reduced.

This paper is the outcome of the research that re-evaluated the Bibiani resources using indicator kriging and an unconstrained estimation for lithology. The results of the research work compare well with the actual production figures from grade control in terms of stoping volume, tonnes of ore and grade.

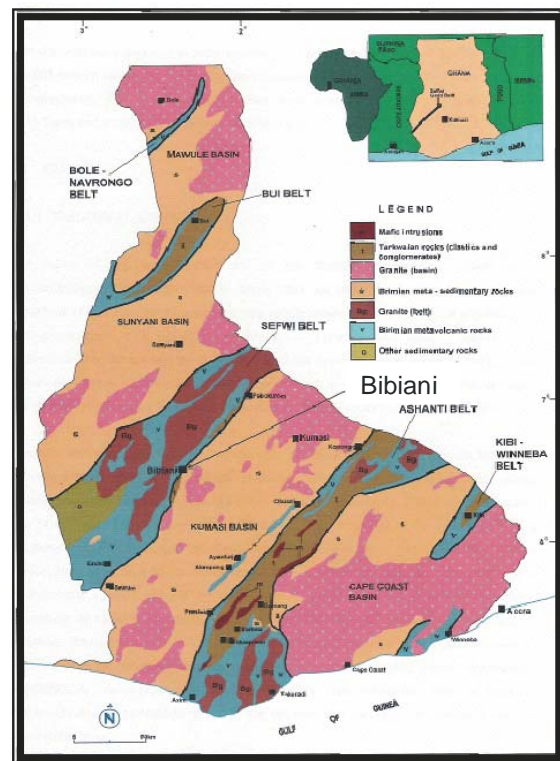


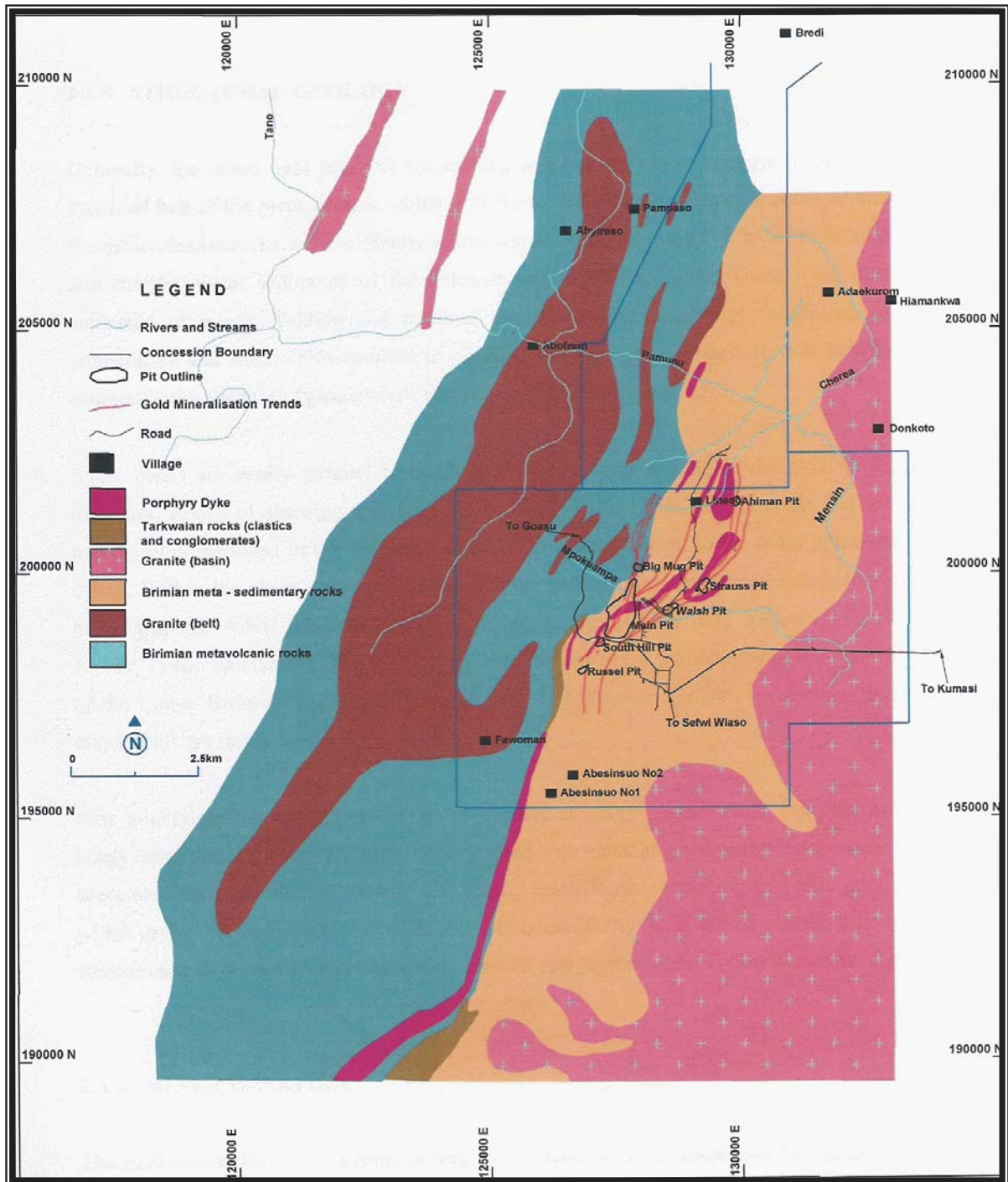
Fig. 1 Location of Bibiani

## 2 Local Geology

The local geology of the mine has features that are typical of Birimian gold deposits. The host rocks for the gold mineralization are quartz veins, metavolcanic, volcanoclastic and metasedimentary rocks (Fig. 2).

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**Fig. 2 Plan of Bibiani Geology Showing Trend of Gold Mineralisation.**

The quartz veins are developed on a shear zone which trends parallel to the belt but with dips slightly flatter than the host rocks and parallel to axial plane cleavage. Gold mineralization often shows close spatial relationship to zones of alteration such as carbonation, sericitisation and silicification (Leube *et al.*, 1990).

Two types of auriferous ore bodies may be identified as (Leube *et al.*, 1990):

1. Disseminated sulphide type (DST) that is

either lithofacies controlled, regional in extent and syngenetic in origin (DST1) is associated with the salvage of quartz veins and is epigenetic (DST2).

2. Quartz vein type (QVT) of local gold mineralisation that is structurally controlled and epigenetic in origin.

### 3 Data Collection and Analysis

Data from 357 holes involving reverse circulation

and diamond drilling holes totalling 5.86 km was collected. About half of the drilling and the bulk of the deeper holes were carried out by diamond coring in HQ, NQ and BQ sizes. Each diamond drill core was sampled by conventional splitting using a diamond saw. For low grade intersections, the sample interval was 3 m. However, this was reduced to 1.5 m or less in high grade areas. Geological control has been a more important factor in deciding on sampling intervals for the later holes with BQ cores.

The data was input into the spreadsheet and saved in four files namely: assay, lithology, downhole survey, and collar. The database was validated for irregularities in the form of missing information such as illogical data entries and overlaps of sample intervals.

Analysis of the data was aided by surface geological maps (including structural maps) at a scale of 1:2500 and mnemonic lithological codes which make the data tractable for resource modelling (Speijers and Macdonald, 1996).

#### 4 Orebody Modelling

Sectional interpretations were digitised in cross-sectional views at appropriate intervals along

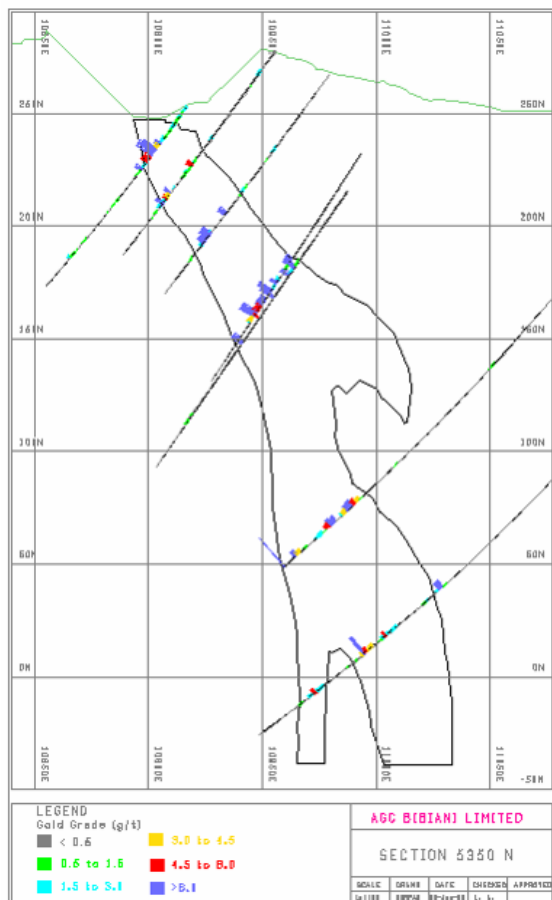


Fig. 3 Typical Section through the Orebody along 5350N

strike of the orebody. An example of such cross section along 5350N is shown in Fig. 3. The envelopes around the mineralised zone were drawn with a cut-off grade of 0.5 g/t for oxide and 0.7 g/t for primary material. However, some material with gold grades below these cut-offs were unavoidably included in some places to give a continuous smooth geometry.

The sections of each ore type were linked from one section to the next to form a three dimensional wireframe solid of the mineralisation covering the entire strike from 4650N to 1690N. Fig. 4 shows the isometric view of the wireframe model when looking above towards northwest.

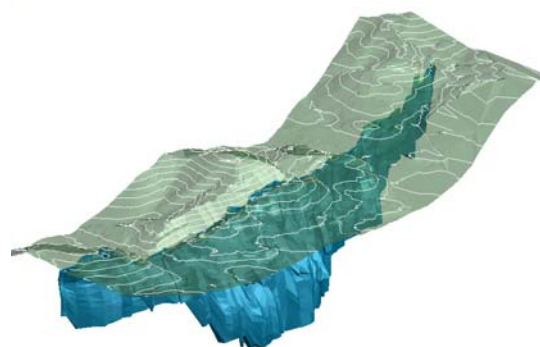


Fig. 4 Wireframe Model of the Orebody

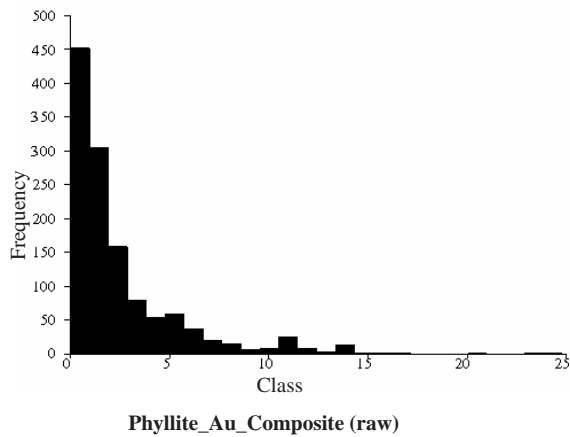
#### 5 Sample Compositing

Samples falling within each lithological unit and ore-type in the wireframe were selected and composited to 2 m length downhole for grade. A threshold length of acceptance was set to 75% (1.5 m). Any composite sample of length less than 1.5 m was discarded. For statistical analysis, it is required that the same support is used, otherwise any statistic, apart from the mean, will be statistically unrepresentative and meaningless (Marsal, 1987). Drill hole data for lithology estimates was not constrained to the limits of the wireframe models. Samples were composited to 2.0 m downhole intervals from top to bottom of holes.

#### 6 Statistical Analysis

The samples from the different drill types were tested statistically to verify if they come from identical populations using Analysis of Variance (ANOVA) method. The tests at 5% level of significance indicated that they come from identical populations and suggested that the samples from the different drill campaigns could be combined.

The sample statistics of the retrieved composites gold grade for each lithological unit within the wireframe were studied. An example of the histograms of their distributions is shown in Fig. 5



**Fig. 5 Histogram of Phyllite Composite Assays**

## 7 Geostatistical Analysis

### 7.1. Variography

Indicator flag fields were set for both lithology and gold composite groupings for variogram analysis. To reduce the effect of smoothing on estimates into inappropriate areas of the deposit due to strike change, the data was classified into two domains namely the south and north (along 5800N grid).

Lag spaces of 25 m and 2 m were used for the horizontal and vertical semi-variograms respectively. Experimental semi-variograms were calculated on incremental angles of 25 degrees with angular tolerance set to 5 degrees to allow for adequate data capture to generate representative struc-

tures. A cylindrical radius of 2.5 m was used for all analysis.

The exponential model was found to give the most appropriate fit to the indicator experimental variograms for the Bibiani deposit. Subsequently, the exponential model was used to model both lithology and gold grade indicators. A typical semi-variogram is shown in Fig. 6.

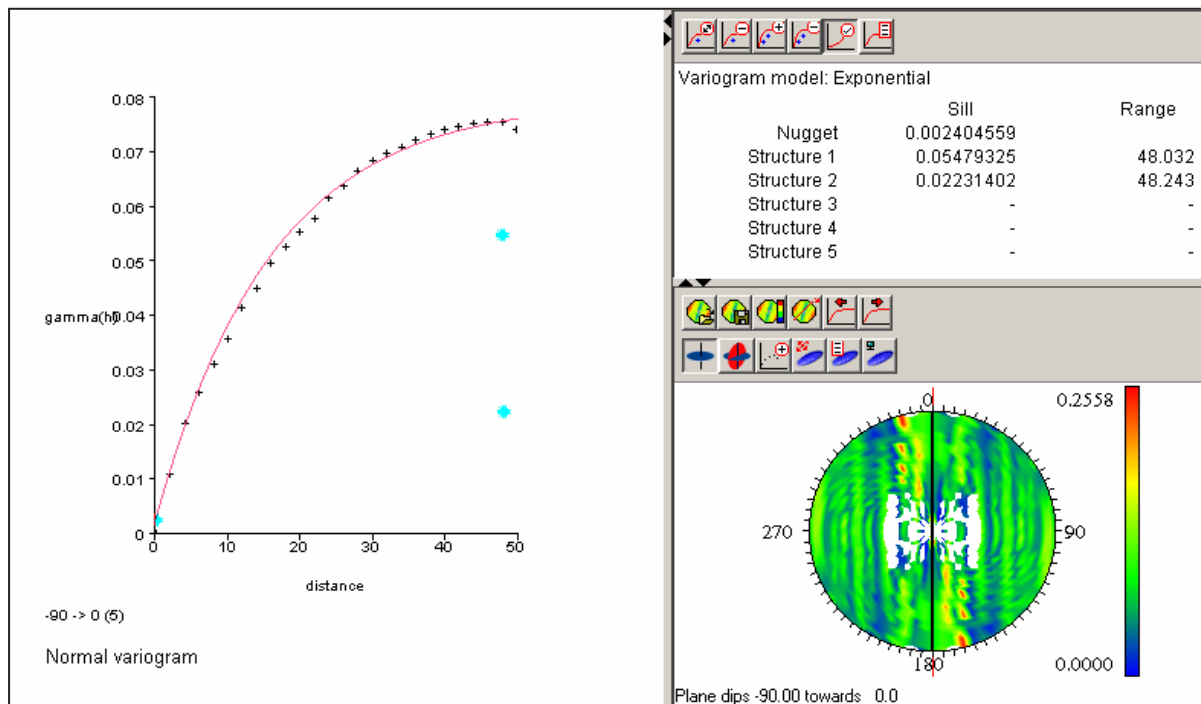
Considering the five lithology indicators and gold grade indicators for the 7 grade groupings within the south and north data domains, 61 individual variogram analyses were carried out.

### 7.2 Indicator Modelling

Indicator model was used to obtain the proportion of a particular lithology and grade category (bin) for a particular block of the deposit. The lithological codes in the drillhole database were grouped. Old underground workings were considered as a fifth lithology called stope (ST). The five groups are shown in Table 1. All drillhole intersections were then checked for missing lithological information. Intervals without any lithological code were assigned the code 'PH' for phyllite which is the most predominant rock.

To provide a geological constraint on the subsequent grade model, a probabilistic model was created using the following steps:

- i. A set of flag fields were created for the unconstrained drillhole data with one field for each lithology including stopes. These fields



**Fig. 6 An Exponential Model Fitted to Downhole Experimental Semi-variogram for Phyllite Stockwork in Bin 4.**

- ii. For each downhole interval the flag field corresponding to the actual lithology code for that interval was set to a value of 1; all other flag fields keep a value of zero.
- iii. The five flag fields were then composited into 2 meter long downhole intervals so that each two-metre interval contained a value between 0 and 1, representing the length proportion of the lithology in question.
- iv. Geostatistical analysis was carried out for the flag fields. Each of the five flag fields was analysed separately as presented in Appendix A.
- v. Using the indicator variables established in step iv, the flag fields were interpolated to give a value between 0 and 1 for each field in each block.
- vi. The five fields in the model were standardised so that they summed to 1. The grade was estimated for each of the lithologies in turn with the exception of stopes in a similar approach.
- vii. Seven grade intervals, called bins, were selected for each lithology, covering the range of assay values present. The grade ranges used were based on the 16, 30, 44, 58 and 72 and 86 percentiles of the frequency distribution estimated from the normal probability plots. The limits of the bins were carefully selected to give approximately equal data points within the various grade classes. The grade ranges are given in Table 2.
- viii. For each lithology a set of seven flag fields were created, one for each grade bin. All 28 flag fields were initialized to a value of zero.

### 7.3 Grade Model

The proportion of each lithology grade bin in each block was estimated as follows:

- i. Considering each uncomposited downhole interval in turn, the assay value and the lithology code were noted and a value of 1 was set in the bins with lithology and grade bin corresponding to those values.
- ii. The seven bins for each of the lithologies were then composited into 2 meter length downhole intervals so that each composite interval for each field contained a value between 0 and 1 that is the length proportion of the grade bin in question.
- iii. Geostatistical analysis was carried out for the seven bins in each lithology to establish model parameters for estimation. Each of the seven bins for the lithologies within each data domain was analysed separately. There was a total of fourteen variogram analysed for each of the four lithologies. Fig. 6 shows a typical case of such semi-variograms.
- iv. Considering each lithology in turn, each flag field value was estimated into the block model using the corresponding model parameters. Separate estimations were carried out for blocks lying within the south and north data domains. However, the data values were not constrained to their respective domains. A total of 56 interpolations were carried out for the four lithologies.
- v. The estimated flag field values in each block were normalized so that they summed to 1 for each lithology. The flag field values then correspond to the expected proportion of the associated grade bin at that location. The individual flag field values were then applied

**Table 1 Search Parameters**

Lithology	Search Strategy	Min Samples	Max Samples	Search Radius	Bearing	Plunge	Dip	Anisotropy Ratios	
								Major/Semi	Major/Minor
Quartz Vein	Ellipsoid	2	24	75	265	85	0	1	3
Phyllite Stockwork	" "	2	24	75	260	-85	0	1.4	2.5
Phyllite	" "	2	24	65	0	0	-90	1.2	2.3
Porphyry	" "	2	24	95	5	0	-90	3.3	5.2
Stope	" "	2	24	80	175	0	80	1.1	2.4

**Table 2 Indicator Grade Bins**

Lithology Code	Gold Grade Ranges (g/t)						
	Bin1	Bin2	Bin3	Bin4	Bin5	Bin6	Bin7
QV	<0.9	0.9-1.7	1.7-2.6	2.6-3.7	3.7-5.6	5.6-11.9	>11.9
PS	<0.9	0.9-1.4	1.4-2.1	2.1-2.8	2.8-4.2	4.2-6.1	>6.1
PH	<0.3	0.3-0.7	0.7-1.2	1.2-1.8	1.8-2.8	2.8-5.1	>5.1
PY	<0.4	0.4-0.8	0.8-1.1	1.1-1.4	1.4-2.2	2.2-4.2	>4.2

to the mean grade values of the associated bins and summed to give an expected grade of each block in a particular lithology. For the uppermost bin, the median grade values were used because no assay top-cuts were applied. Appendix A is a summary statistics of the bin grades for each of the lithologies.

- vi. On completion of the normalization for each of the lithologies, the expected average grade of a block as a whole was calculated by summing the products of the individual lithology proportions and their respective estimated grades. An example of the grade estimation procedure is provided in Appendix B.

## 8 Modelling Strategy

Block dimensions of 15 x 6 x 6 m were used. For boundary resolution a cell split into two was adopted. The model prototype is shown in Table 3. Search ellipsoids were used with appropriate radii corresponding with the anisotropies. Soft boundary conditions were allowed between the oxide, transition and primary material within each data domain.

## 9 Model Validation

The Bibiani deposit block model has been validated using visual examination of assay and estimated block grades in sections and plans. Block grades were compared spatially with input grades to ensure that grade trends were represented correctly in the block model. The trends seen in the block grades were consistent with those of the input data. Fig. 7 shows a typical cross-section through the blocks and the drill holes coloured on gold grade.

## 10 Discussion of Results

The results from IK are shown alongside those of IDW in Table 4 for comparison. For effective assessment of the propriety of IK and IDW methods in estimating the resources at Bibiani, their estimates were constrained with the wireframe of the mined out pit and topography where the data was obtained. Only materials, categorised as Indicated 1 and 2 were included in the reserves to conform to the Joint Ore Reserve Committee (JORC) Code. The global reserves within the pit perimeter are shown in Table 5.

The results show that IK and IDW underestimated the tonnage but IK estimates were better. The IK estimates also showed closer grade estimates to actual than IDW. The comparison is better illustrated by the grade-tonnage curves in Fig. 8. The underestimation of the tonnage is due to overestimation of the stope volume (void). Irregularity of the orebody, due to local broadening of the orebody, may also contribute to it. For the ore grade,

IK underestimated by 0.6% whilst IDW overestimated it by 6%. The overall assessment indicates that the IK model compares better with the actual than the IDW estimates for both grade and tonnage.

**Table 3 Block Model Framework**

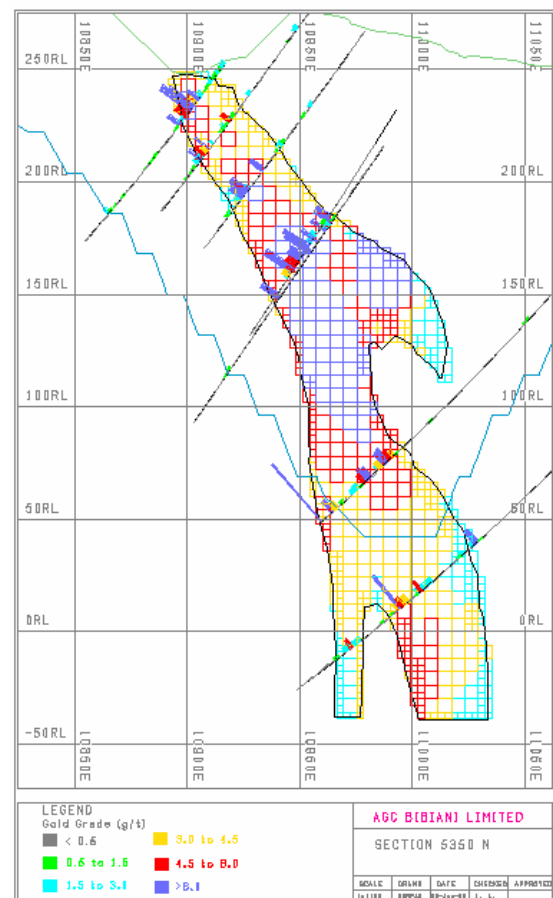
	Model Limit (m)	Cell Size (m)	No. of Cells	Sub-cell Size (m)
East - West	10501.5 - 11281.5	6	130	3
North - South	4720 - 6715	15	133	7.5
Vertical	-378	6	63	3

**Table 4 Resource Estimation Results**

Type	IK			IDW		
	Tonnage (10 <sup>6</sup> )	Grade (g/t)	Ounces (10 <sup>6</sup> )	Tonnage (10 <sup>6</sup> )	Grade (g/t)	Ounces (10 <sup>6</sup> )
Indicated 1	10.4	3.53	1.18	9.6	3.75	1.16
Indicated 2	6.8	2.54	0.55	6.1	2.49	0.49
Inferred	2.8	2.41	0.22	2.5	2.1	0.17

**Table 5 Reconciliation of Reserves**

Type	Model Estimates			% Difference (Actual versus Estimate)		
	Tonnes (t)	Grade (g/t)	Ounces (oz)	Tonnes	Grade	Ounces
IK	12,326,034	3.43	1,357,564	4	0.6	4
IDW	11,427,924	3.66	1,346,524	12	-6	5
Actual	12,766,813	3.45	1,417,988			



**Fig. 7 Cross-section of the Bibiani Resource Model at 5650 Northing**

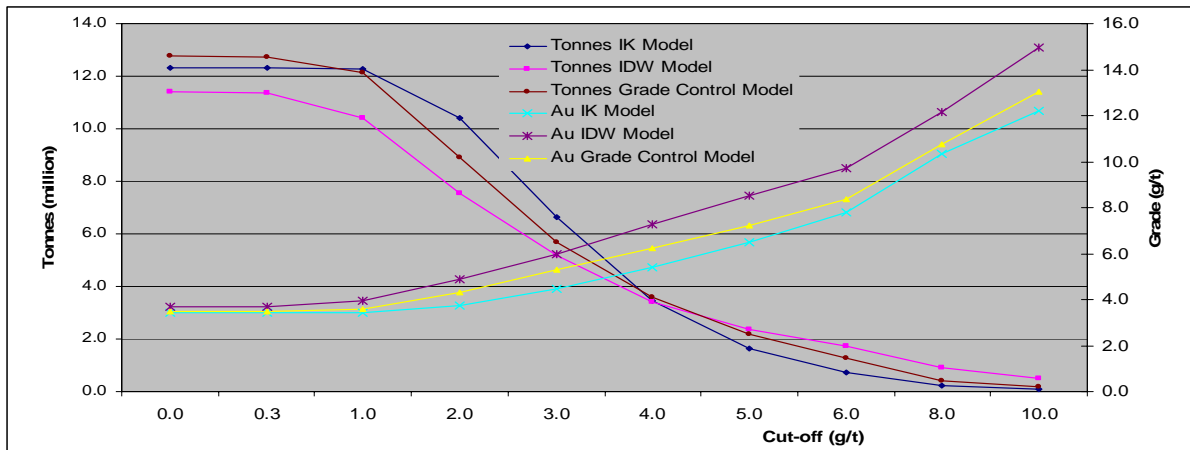


Fig. 8 Grade-Tonnage Curves for the IDW, IK and Actual Resources

## 11 Conclusions

The following conclusions are made from the analysis of the results:

- i. Indicator algorithm provides acceptable variable in estimating voids and lithology. The use of indicators also limits the undue influence of high grade values on grade estimates.
- ii. In the absence of comprehensive underground plans IK provides better estimates than IDW.
- iii. Comparison of IDW and IK against actual production values indicates that the IK model compares more favourably with the actual production figures than that of IDW for both grade and tonnage.
- iv. The IDW model overestimates the grade of the remnant gold resources. This is due to the inability of IDW to adequately deal with data clustering. The inappropriate estimation of stoping volume segments of the orebody caused an underestimation of low grade tonnage with the net effect of the average gold grade being overestimated.

## 12 Recommendations

From the results work, it is recommended that the company could consider using the IK estimation technique in the re-evaluation of the mineral resources to enhance the economics of either the proposed underground or cut-back projects.

## Acknowledgement

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## Appendix A Summary Statistics of Gold Grade Groupings

Lithology	Statistic	Gold Grade Range (g/t)						
		Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7
Quartz Vein (QV)	Number	100	84	78	85	84	84	84
	Mean	0.370	1.316	2.139	3.117	4.561	7.900	26.589
	Variance	0.077	0.058	0.078	0.108	0.325	2.953	676.171
	C.V	0.749	0.183	0.130	0.106	0.125	0.218	0.978
	Min.	0.000	0.900	1.710	2.609	3.700	5.620	11.900
	Median	0.331	1.345	2.106	3.106	4.470	7.758	20.169
	Max	0.888	1.692	2.596	3.684	5.583	11.790	218.000
	Phyllite Stockwork (PS)	Number	71	70	65	64	68	69
Mean		0.534	1.108	1.701	2.452	3.380	5.082	8.942
Variance		0.065	0.023	0.033	0.033	0.166	0.350	13.681
C.V		0.476	0.137	0.107	0.074	0.120	0.116	0.414
Min.		0.010	0.910	1.400	2.120	2.800	4.208	6.100
Median		0.560	1.100	1.703	2.503	3.325	4.948	7.980
Max		0.898	1.392	2.036	2.760	4.140	6.085	31.400
Phyllite (PH)		Number	182	186	184	183	173	176
	Mean	0.109	0.492	0.960	1.496	2.220	3.898	8.833
	Variance	0.008	0.013	0.021	0.031	0.078	0.577	11.541
	C.V	0.836	0.235	0.151	0.118	0.126	0.195	0.385
	Min.	0.000	0.300	0.700	1.200	1.808	2.800	5.140
	Median	0.088	0.500	0.968	1.510	2.138	3.842	7.673
	Max	0.286	0.697	1.195	1.798	2.798	5.096	23.840
	Porphyry (PY)	Number	41	43	34	33	34	37
Mean		0.173	0.625	0.951	1.246	1.751	2.929	6.887
Variance		0.009	0.014	0.008	0.008	0.050	0.331	11.807
C.V		0.548	0.187	0.091	0.073	0.128	0.196	0.499
Min.		0.020	0.422	0.805	1.119	1.412	2.200	4.215
Median		0.174	0.635	0.948	1.244	1.698	2.685	5.841
Max		0.350	0.793	1.096	1.380	2.172	4.020	23.110

## Appendix B

### Example of Indicator Estimate of Gold Grades

An example of an initial estimate of lithology proportions after kriging run is provided in the Table 1. where IJK number is the cell identification number of the model and qv\_prop, ps\_prop, ph\_prop, st\_prop are attribute fields for lithology estimates explained in Table 5.8.

The sum of the initial lithology estimate is not equal to 1.0. For an unbiased estimate of lithologies, the proportions must be normalized so that they sum equals 1.0.

The proportions are normalized by dividing each of the lithology proportions by the total to give a new set of values presented in the Table 2.

**Table 1 Initial Estimate of Lithology Proportions**

IJK Number	qv_prop	ps_prop	ph_prop	py_prop	st_prop
145678	0.156	0.275	0.536	0.023	0.047

**Table 2 Normalised Estimated Values of Lithology Proportions**

IJK Number	qv_prop	ps_prop	ph_prop	py_prop	st_prop
145678	0.1504	0.2652	0.5169	0.0222	0.0453

**Table 3 Initial Estimates of Lithology Grade Bin Proportions**

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7
qv	0.000	0.023	0.675	0.123	0.007	0.000	0.150
ps	0.568	0.111	0.045	0.000	0.000	0.277	0.000
ph	0.327	0.000	0.456	0.109	0.037	0.036	0.045
py	0.000	0.000	0.000	0.000	0.000	0.000	0.978

**Table 4 Normalised Estimated Values of Lithology Grade Bin Proportions**

	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7
qv	0.0000	0.0235	0.6902	0.1258	0.0072	0.000	0.1534
ps	0.5674	0.1109	0.0450	0.0000	0.0000	0.2767	0.0000
ph	0.3238	0.0000	0.4515	0.1079	0.0366	0.0356	0.0446
py	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	1.0000

An example of an initial lithology grade bin estimate for the cell after a kriging run is provided in the Table 3. The grade bin proportions are also normalized so that they sum up to 1.0 to give new figures provided in Table 4.

Using the grade bin means provided in Appendix B for Bins 1 to 6 and the median for Bin 7, the grade of the proportion of each of the lithology within the model cell is calculated as follows:

$$\begin{aligned} \text{Quartz vein grade (au\_qv)} &= qv_{bin1} * Au_{bin1} + qv_{bin2} * Au_{bin2} + \\ &\dots + qv_{bin7} * Au_{bin7} \\ &= 0.0 * 0.370 + 0.0235 * 1.316 + \\ &0.6902 * 2.139 + 0.1258 * 3.117 + \\ &0.0072 * 4.561 + 0.0 * 7.900 + \\ &0.1534 * 20.169 \end{aligned}$$

$$\begin{aligned} \text{Stockwork grade (au\_ps)} &= ps_{bin1} * Au_{bin1} + ps_{bin2} * Au_{bin2} + \\ &\dots + ps_{bin7} * Au_{bin7} \\ &= 0.5674 * 0.534 + 0.1109 * 1.108 + \\ &0.045 * 1.701 + 0.0 * 2.452 + \\ &0.0 * 3.380 + 0.2767 * 5.082 + \\ &0.0 * 7.980 \\ &= 1.9086 \text{g/t} \end{aligned}$$

$$\begin{aligned} \text{Phyllite grade (au\_ph)} &= ph_{bin1} * Au_{bin1} + ph_{bin2} * Au_{bin2} + \\ &\dots + ph_{bin7} * Au_{bin7} \\ &= 0.3238 * 0.109 + 0.0 * 0.492 + \\ &0.5415 * 0.960 + 0.1079 * 1.496 + \\ &0.0366 * 2.220 + 0.0356 * 3.898 + \\ &0.0446 * 7.673 \end{aligned}$$

$$\text{Porphyry grade (au\_py)} = py_{bin1} * Au_{bin1} + py_{bin2} * Au_{bin2} +$$

$$\begin{aligned} &\dots + py_{bin7} * Au_{bin7} \\ &= 0.0 * 0.173 + 0.0 * 0.625 + 0.0 * 0.951 \\ &+ 0.0 * 1.246 + 0.0 * 1.751 + 0.0 * 2.929 \\ &+ 1.0 * 5.841 \\ &= 5.841 \text{g/t} \end{aligned}$$

where Au represent the applicable gold grade for the bins. The average grade "au" of the cell in the block model is given by,

$$\begin{aligned} au &= \frac{qv\_prop * au\_qv}{qv\_prop + ps\_prop + ph\_prop + py\_prop} + \frac{ps\_prop * au\_ps}{qv\_prop + ps\_prop + ph\_prop + py\_prop} \\ &+ \frac{ph\_prop * au\_ph}{qv\_prop + ps\_prop + ph\_prop + py\_prop} + \frac{py\_prop * au\_py}{qv\_prop + ps\_prop + ph\_prop + py\_prop} \\ qv\_prop + ps\_prop + ph\_prop + py\_prop &= 0.1504 + 0.2652 + \\ &0.5169 + 0.0222 \\ &= 0.9547 \end{aligned}$$

Hence average grade "au" will be,

$$\begin{aligned} au &= \frac{0.1504 * 5.0261}{0.9547} + \frac{0.2652 * 1.9086}{0.9547} + \frac{0.5169 * 1.2788}{0.9547} + \frac{0.0222 * 5.8410}{0.9547} \\ &= 2.1502 \text{g/t} \end{aligned}$$

Therefore, the average gold grade of the cell is 2.15g/t.

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