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Improving Mineral Resource Reconciliation Using Ordinary Kriging with Improved Data – A Case Study

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Abstract

Reconciliation of mineral resource model with grade control model of the Teberebe orebody had some important variations. These were very significant where there were inadequate drill hole data and geological interpretation. Grade control drilling produced more geological data and allowed for improved interpretation of the geology. There was therefore the need to remodel the mineral resource with the additional data obtained from grade control drilling. Ordinary kriging was used to re-evaluate the mineral resource.

The study indicated that the new model reconciled practically better with the grade control model than the old one. It produced lower grade but higher tonnage than the old model using the same cut-off grade of 0.56 g/t. It also produced higher total gold recovered than the older one. The new resource model, unlike the old one, included the D zone of the orebody. It was recommended that grade control, sampling and modeling should include the D zone.

1. Introduction

Accurate prediction of the shape, location, size and properties of the solid rock materials to be extracted during mining is essential for reliable technical and financial planning. This is achieved through geological modeling of the three-dimensional (3D) shape and properties of the materials present in mineral deposits, and the presentation of results in a form which is accessible to mine planning engineers (Sides, 1997).

In recent years the application of interactive graphics software, offering 3D database handling, modeling and visualisation, has greatly enhanced the options available for predicting the subsurface limits and characteristics of mineral deposits. Despite the widespread introduction and acceptance of computers in mining applications, in recent years, there has been little fundamental change in the way in which geology is used in orebody modeling for predictive purposes. The estimation of mineral resources is concerned with geological data collection (drilling and mapping); sampling and assaying; geological interpretation and modeling; and grade/tonnage estimation (Dominy *et al*. 2002). Geological information such as drill hole logging, lithological and structural interpretation is the foundation of a high quality resource estimates (Snowden, 1993).

This paper is the outcome of research on improving upon resources of the Teberebe orebody with additional data. Teberebe is located some 70 km from Takoradi, the Western Regional capital in Ghana (shown in Fig. 1). The orebody is exploited by open pit mining and the gold recovered using carbon-in-pulp (CIP) plant.

Fig. 1 Map of Ghana showing the Location of AGA (Iduapriem) Ltd

Grade control drilling produced more geological data and allowed for improved interpretation of the geology. There was therefore the need to remodel the mineral resource with the additional data obtained from grade control drilling. Ordinary kriging was used to re-evaluate the mineral resource.

The study indicated that the new model reconciled practically better with the grade control model than the old one. It produced lower grade but higher tonnage than the old model using the same cut-off grade of 0.56 g/t. It also produced higher total gold recovered than the older one. The new resource model, unlike the old one, included the D zone of the orebody. It was recommended that grade control, sampling and modeling should include the D zone.

2. Physiography of Teberebe Area

The relief of the area is characterized by a series of undulating landscape with prominent ridges that are above 60 m to 80 m above sea level. The temperature in the area ranges between 24 °C and 35°C. Teberebe lies in the tropical rain forest zone. Torrential rains are the norm with bright sunshine and high humidity throughout the year (Gyimah, 2005). The relief of the area provides good drainage pattern, which serves as catchments for the streams that flow along adjacent lowlands.

3. Geology

The Iduapriem Mine is located within the Tarkwaian rocks and forms part of the West Africa Craton which is covered to a large extent, by the Birimian volcanics and metasediments (Fig. 2).

The Birimian underlying the Tarkwaian consists of metamorphosed lava and pyroclastic rocks with abundant greywackes, phylites, and intrusive rocks. As a result of deformation, some of the metamorphic rocks exhibit greenish colouration and constitute the greenstone belts notable for the presence of gold-quartz vein mineralisation within the Birimian (Kesse, 1985).

The Tarkwaian System consists of a thick sequence of clastic metasedimentary rocks which have suffered low grade regional metamorphism, contemporaneously or latter shearing and alteration by hydrothermal solution (Junner *et al*., 1942).

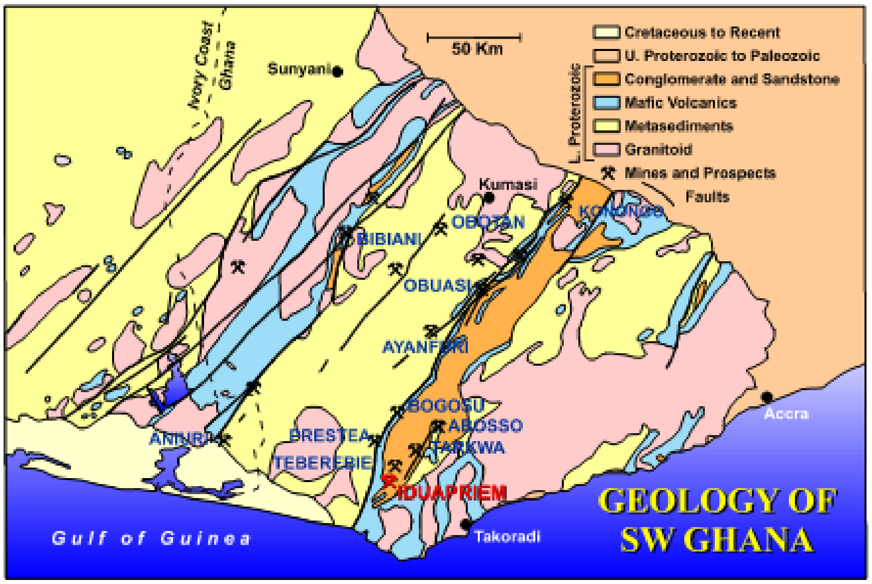

Fig. 2 Geology of Southern Ghana (After Berzinskaite, 1998)

The higher grades are uncommon and are often associated with intrusive rocks. The common minerals associated with Tarkwaian are: chlorite, sercite, zoisite, calcite, quartz, lominite and chloritoid. The Tarkwaian System is subdivided into four main groups in the order of stratigraphic younging. This is shown in Table 1.

All gold mineralisation occurs within the four specific zones or reefs and are unrelated to metamorphic and hydrothermal alteration events. The gold is fine-grained, particulate and free milling (i.e. not locked up with quartz or iron oxides). Mineralogical studies indicate that the grain size of native gold particles ranges between 2 and 500 microns and averages 130 microns. Sulphide mineralisation is present only at trace levels and is not associated with the gold (Whitelaw, 1929).

Ore grade mineralisation occurs within eight specific areas at GAG/Teberebie, known as Blocks 1 to 8. In Block 1, the deposit comprises single composite of C and D reefs.

Table 1 Stratigraphic Successive of the Tarkwaian Rocks

System/series	Thickness (m)	Composite Lithology
Huni Sandstone	1370	Sandstone, grits, quartzite, phyllite (Dompim type)
Tarkwa Phylite	120 – 400	Phylite, chlorites, sericite and schists
Banket Series	120 -160	Quartzite, grits, breccia and banket conglomerates
Kawere	250 – 700	Sandstone, quartzite, grits, and conglomerate

(Source: Whitelaw, 1929)

At the eastern end of Block 2, the single composite reef gives way to multiple zones (A, B, C and D) which extend further west into Block 3, where there are up to four specific zones of ore grade mineralisation. The A, B, C, and D reefs also occur at Block 4, 5, 7 and 8. Only the B and C Reefs are recognisable at Block 6 (Ajopa). The Banket Series Rocks are narrow and steep and adjoins Gold Fields Ghana Limited's Kotraverchy deposit (Fig. 3).

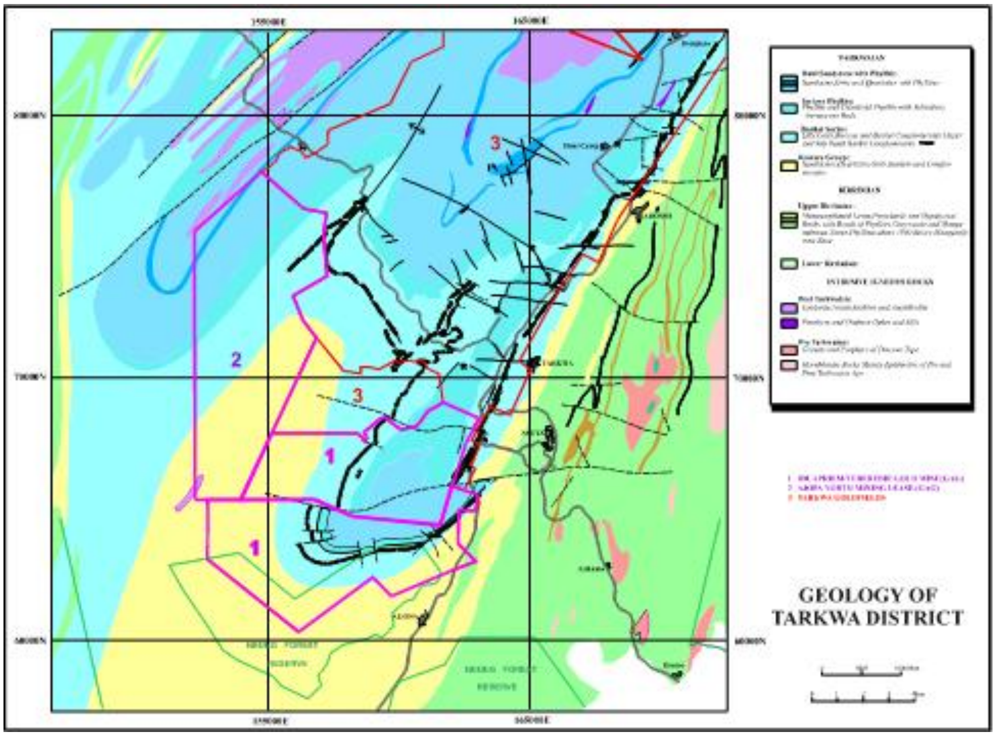

Fig. 3 Geology of Tarkwa District (After Berzinskaite, 1998)

4. Collection of Data

The data used was a combination of reverse circulation (RC) and diamond drill (DD) samples obtained from the exploration and the grade control campaigns carried out over several years. The drillhole data were compiled into four major files namely: Assay, Collar, Survey and Geology. Surface elevation data in the study area were obtained from the Survey Department of the company.

5. Modeling of Resource

5.1 Interpretation and Delineation of Ore Zones

Cross-sections were plotted on screen. Interpretation of the geology and delineation of the mineralization were also dine on the screen.

5.2 Wireframe Modeling

The strings used for digitising the ore zones for each section were linked together to generate a triangulated 3-dimensional wireframe model as seen in Fig. 4. The created wireframe was validated by verifying for crossovers in the triangulated 3D solid. Areas with errors on the triangulated surfaces were indicated by the wireframe verification process and were duly corrected. Some of these errors were due to string crossovers and the wireframes not closed. Once these errors were fixed the wireframe passed the validation test.

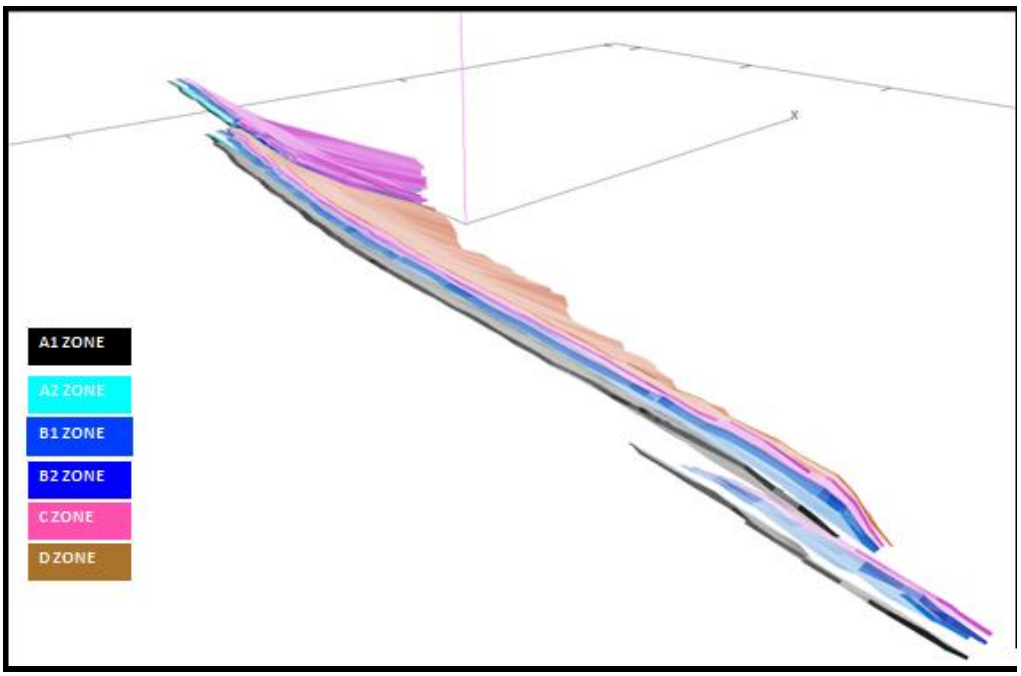

Fig. 4 D View of Ore Wireframe

6. Block Modeling

The purpose of the geological model was to accurately represent the grades of the deposit and also its boundaries and internal structures. The model was composed of 3-dimensional blocks each of which had attributes such as grades, rocktype, density and oxidation codes

The creation of a block model using Datamine started with the use of the PROTOM command to define the model prototype. This process created an empty file with standard model field names. Included in these standard fields were 6 fields (shown in

Tables 2) which were used to store the origin of the model and the number of cells in the 3 orthogonal directions.

Table 2 Prototype Field Names

Field Name	Description
XMORIG	Easting coordinate of the model origin
YMORIG	Northing coordinate of the model origin
ZMORIG	RL coordinate of the model origin
NX	Number of parent cells in the X direction
NY	Number of parent cells in the Y direction
NZ	Number of parent cells in the Z direction
XINC	X axis cell dimension
YINC	Y axis cell dimension
ZINC	Z axis cell dimension
IJK	Code generated and used by Datamine to uniquely identify each parent cell position within the model. Sub cells that lie within the same parent cell will have the same IJK value.

7. Statistical Analysis of Data

Using the wireframes for the various ore zones the Au values within the interpreted ore envelopes were extracted using a Datamine command called SELWF. The extracted assay values (from DD and RC holes) were composited at a sample length of 1 m and a minimum compositing length of 0.5 m. The composited holes were subjected to some statistical analysis using Microsoft excel and Datamine statistical tools. These included relative frequency histograms and cumulative frequency histograms. Being of different supports, they could only be combined if they were statistically established to come from identical populations.

Variography requires large data and therefore F- and t- tests were done at 5% level of significance to verify if the two samples could be combined. The results indicated in Tables 3 and 4 show that the DD and RC data probability come from identical populations. Hence, they were combined (Marsal, 1989).

Table 3 Summary Results of F-test on DD and RC Data

	A1 Zone		A2 Zone		B1 Zone		B2 Zone		C Zone		D Zone	
	AU(exp)	AU(gc)	AU(EXP)	AU(GC)	AU(EXP)	AU (GC)	AU(EXP)	AU(GC)	AU(EXP)	AU(GC)	AU(EXP)	AU(GC)
Mean	1.36	1.49	0.61	0.62	2.20	2.23	1.46	1.47	2.01	1.87	0.70	0.41
Variance	2.23	2.41	0.24	0.48	2.82	2.67	1.43	1.58	2.83	2.21	0.87	0.50
Observations	2782	1239	537	2771	3688	27422	2907	20368	2136	18779	450	252
df	2781	1238	536	2770	3687	27421	2906	20367	2135	18778	449	251
F	0.92		0.50		1.06		0.91		1.28		1.76	
P(F<=f) one-tail	0.05		0.00		0.01		0.00		0.00		0.00	
F Critical one-tail	0.92		0.89		1.04		0.95		1.05		1.20	

Table 4 Summary Results of t-Test on DD and RC Data

	A1 Zone		A2 Zone		B1 Zone		B2 Zone		C Zone		D Zone	
	AU(EXP)	AU(GC)	AU(EXP)	AU(GC)	AU(EXP)	AU (GC)	AU(EXP)	AU(GC)	AU(EXP)	AU(GC)	AU(EXP)	AU(GC)
Mean	1.36	1.49	0.61	0.62	2.20	2.23	1.46	1.47	2.01	1.87	0.70	0.41
Variance	2.23	2.41	0.24	0.48	2.82	2.67	1.43	1.58	2.83	2.21	0.87	0.50
Observations	2782	1239	537	2771	3688	27422	2907	20368	2136	18779	450	252
Hypothesized Mean Difference	0		0		0		0		0		0	
df	2294		999		4675		3878		2530		641	
t Stat	-2.48		-0.43		-0.98		-0.77		3.71		4.56	
P(T<=t) one-tail	0.01		0.33		0.16		0.22		0.00011		0.0000030	
t Critical one-tail	1.65		1.65		1.65		1.65		1.65		1.65	
P(T<=t) two-tail	0.01		0.67		0.33		0.44		0.00021		0.0000060	
t Critical two-tail	1.96		1.96		1.96		1.96		1.96		1.96	

7. Variogram Modeling

Separate semi-variograms were run for the various ore zones in three directions (down the dip, down the hole and along the strike of the orebody). This was done using the Datamine command called VGRAM. Table 6 is a summary of the semi-variogram model parameters obtained from the combined data for both exploration and grade control drill holes of the various ore zones.

From the variogram models (exemplified in Fig. 5) a double-structured spherical models can be inferred. They are nested spherical models. The down-the-hole variograms (e.g. Fig. 6) were used in fixing the nugget effect (Co) since the closest pairs for interpolation close to zero distance is down-the-hole.

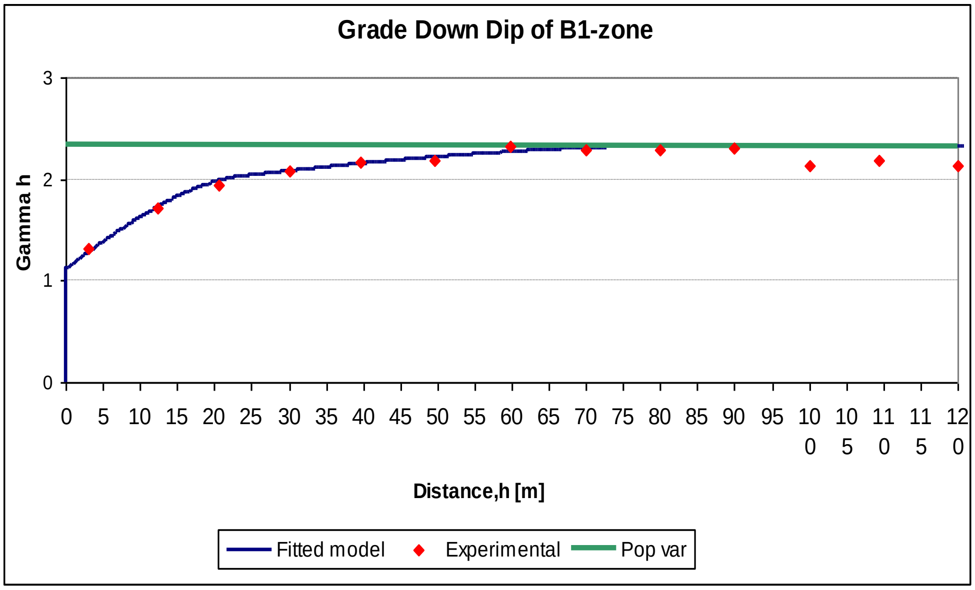

Fig. 5 Down Dip Semi-variogram of Au Grade for B1 Zone

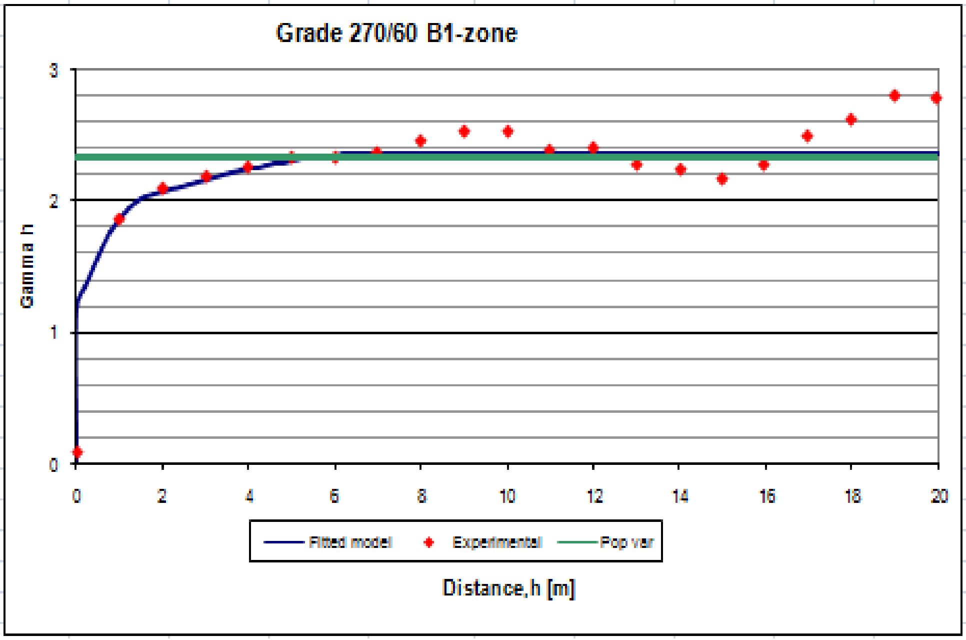

Fig. 6 Downhole Semi-variogram of Au Grade for B1 Zone

Table 5 Variogram Parameters obtained from the Combined GC and EXP Drill Data

Ore Zone	Structure		Range		
			Axis	1st(m)	2nd(m)
A1	*Co*	1.241	*X*	24	85
	C1	0.789	*Y*	16	120
	C2	0.568	*Z*	2	10
A2	*Co*	0.209	*X*	24	85
	C1	0.133	*Y*	16	120
	C2	0.096	*Z*	2	10
B1	*Co*	1.285	*X*	24	85
	C1	0.817	*Y*	16	120
	C2	0.588	*Z*	2	10
B2	*Co*	0.746	*X*	24	85
	C1	0.474	*Y*	16	120
	C2	0.341	*Z*	2	10
C	*Co*	1.089	*X*	12	85
	C1	0.692	*Y*	16	120
	C2	0.498	*Z*	1.6	4
D	*Co*	0.360	*X*	12	85
	C1	0.229	*Y*	16	120
	C2	0.165	*Z*	1.6	4

8. Search Strategy

Geometric anisotropy could be inferred from the results obtained from the semi-variography parameters shown in Table 5. This implies that an approximate zone of influence for a sample within the ore zones could be an ellipsoid with axes equal to the maximum ranges in x, y and z directions (Armstrong, 1998). The search strategy therefore is to create such an ellipsoid. The search ellipsoid for the grade interpolation was therefore constructed using these maximum ranges as dimensions and was also oriented by applying the left hand fingers to simulate the rotations and executed using Datamine command called ELLIPSE.

The maximum and minimum number of samples to be used in kriging were optimized using Quantitative Kriging Neighbourhood Analysis,QKNA,.(Van et al., 2003). The optimisation of the search parameters was done using a script software developed by Bloy Mineral Resources Evaluation (BMRE), a Resource Evaluation Consultant, which is interfaced with Datamine. Some of the graphs of the search parameters are shown in Figs. 7 to 10 for the B1 zone.

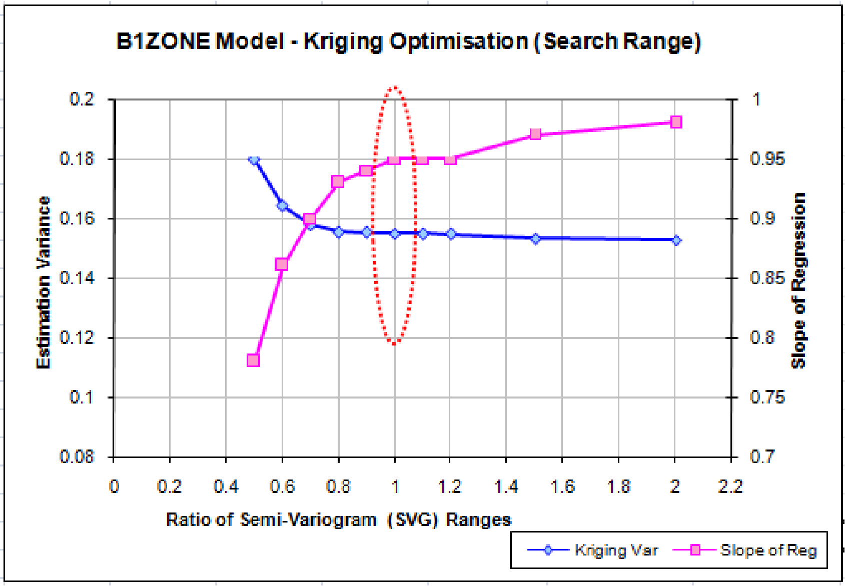

Fig. 7 Search Range Optimisation for B1 Zone considering Slope of Regression

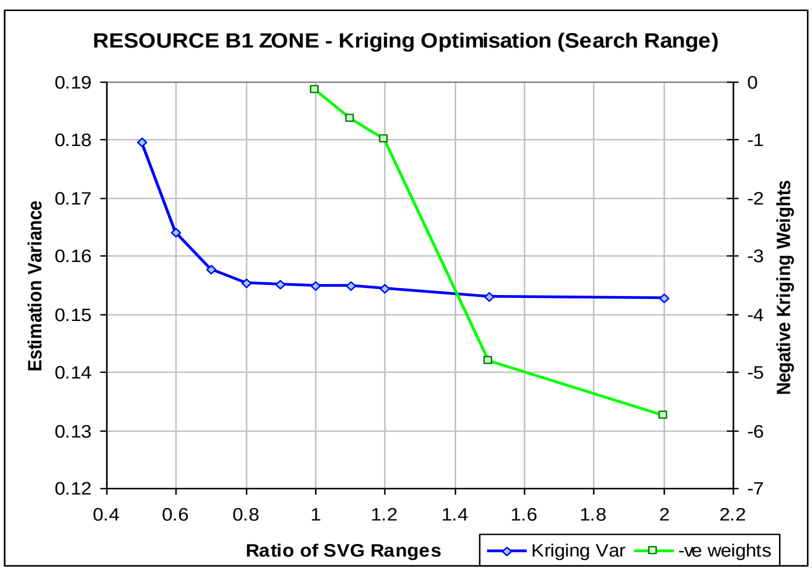

Fig. 8 Search Range Optimisation for B1 Zone Considering Negative Kriging Weight

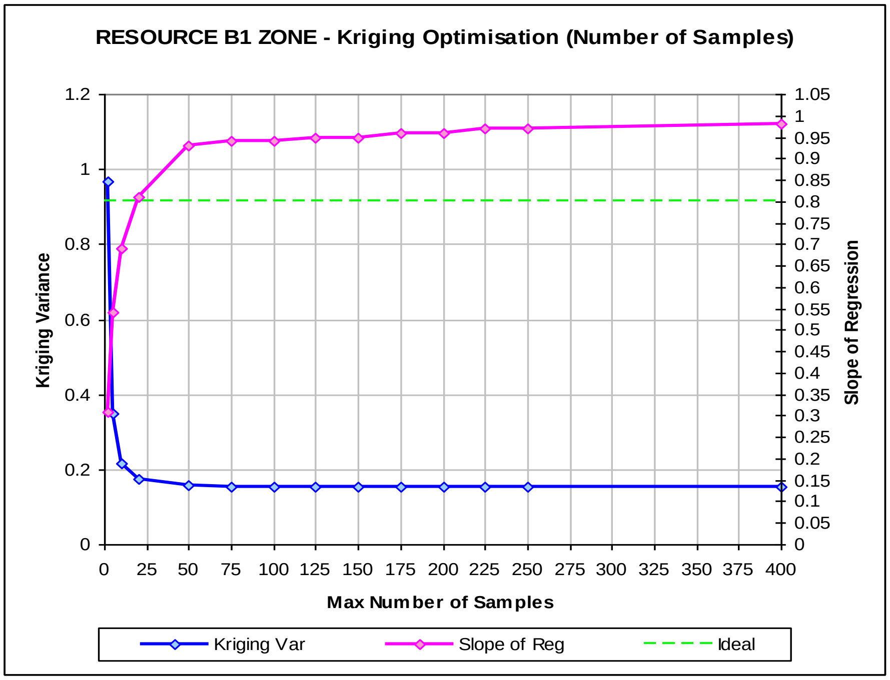

Fig. 9 Optimisation of Maximum Number of Samples for Zone B1 Zone Considering Kriging Variance

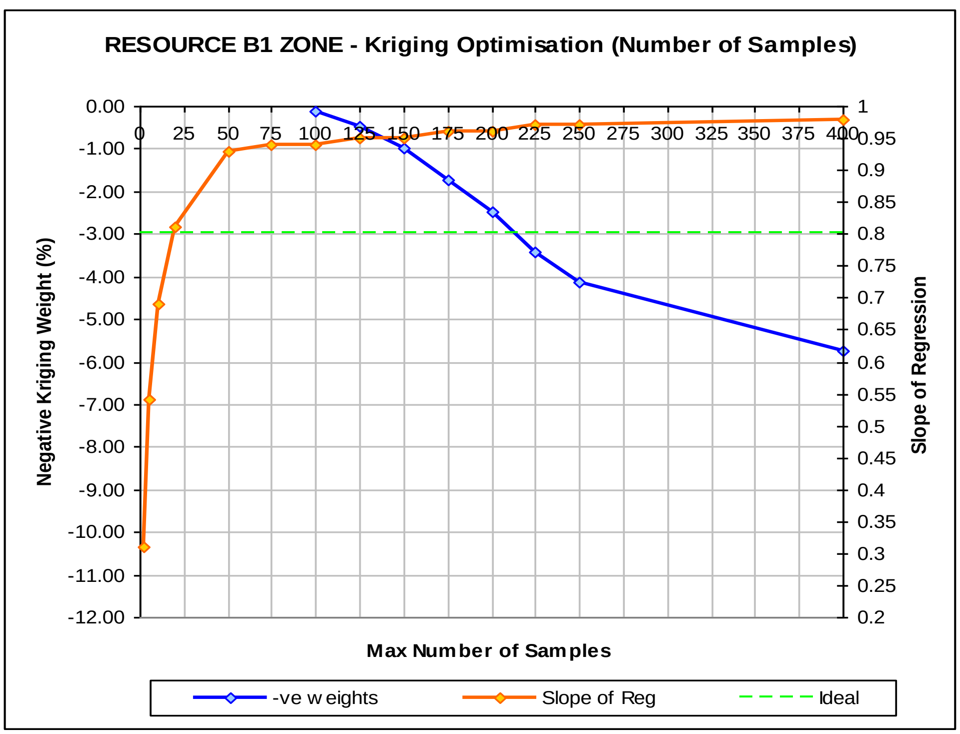

Fig. 10 Optimisation of Maximum Number of Samples for B1 Zone Considering Negative Kriging Weights

Those descriptions are indicators of an appropriate search neighbourhood most likely to yield minimal conditional biasedness (Van et al., 2003).

9. Grade Interpolations (Ordinary Kriging)

Using ESTIMA, a Datamine grade interpolation program, grades were krigged into the block model. In ESTIMA the variogram parameters were set up by inputting the optimised values as recorded in Table 7. The search parameter are also shown in Table 8.

Table 7 Resource Variogram Parameters for Kriging

Variogram Parameter for kriging into Exploration Block Size *(5x25x6)*	Parameter value for the ore zones					
	A1	A2	B1	B2	C	D
First rotation angle (^{o})	6	6	6	6	6	6
Second rotation angle (^{o})	-32	-32	-32	-32	-32	-32
Third rotation angle (^{o})	0	0	0	0	0	0
Axis for first rotation	3	3	3	3	3	3
Axis for second rotation	2	2	2	2	2	2
Axis for third rotation	3	3	3	3	3	3
Nugget variance	1.241	0.209	1.285	0.746	1.089	0.360
Variogram model type	Spherical (1)	1	1	1	1	1
Range along x for structure 1 (m)	24	24	24	24	12	12
Range along y for structure 1 (m)	16	16	16	16	16	16
Range along z for structure 1 (m)	2	2	2	2	1.6	1.6
Sill 1	0.789	0.113	0.817	0.474	0.692	0.229
Variogram model type	Spherical (1)	1	1	1	1	1
Range along x for structure 2	85	85	85	85	85	85
Range along y for structure 2	120	120	120	120	120	120
Range along z for structure 2	10	10	10	10	4	4
Sill 2	0.568	0.096	0.588	0.341	0.498	0.165

Table 8 Resource Search Volume Parameters for Kriging

Search Volume Parameter for kriging into Exploration Block Size *(5x25x6)*	Parameter value for the ore zones					
	A1	A2	B1	B2	C	D
Search volume shape	Ellipsoid (2)	2	2	2	2	2
Max. distance in x direction (m)	85	85	85	85	127.5	127.5
Max. distance in y direction (m)	120	120	120	120	180	180
Max. distance in z direction (m)	10	10	10	10	6	6
1st rotation for search volume (^{o})	6	6	6	6	6	6
2nd rotation for search volume (^{o})	-32	-32	-32	-32	-32	-32
3rd rotation for search volume (^{o})	0	0	0	0	0	0
Axis for first rotation	3	3	3	3	3	3
Axis for second rotation	2	2	2	2	2	2
Axis for third rotation	3	3	3	3	3	3
Min. No. of samples for search	4	4	4	4	4	4
Max. No. of samples for search	125	125	125	125	150	150

10. Observations

The following observations were made from the re-evaluation of the Teberebie mineral resources:

- There was overall reduction in grade of the new resource compared with the old resource at a cut off grade of 0.56g/t depleted to the end of December 2007.
- The tonnes for the new resource model for Teberebie were higher than that of the old.
- The new resource yielded about 8,200 ounces more than the old model.

To find out what could be the possible causes for the high tonnage but low grades within the new resource, wireframes for the new resource were used to extract old exploration drillholes of the old resource. Descriptive statistics were run for the extracted drillhole data. The same statistical analysis was performed on the old exploration drillhole data after using old resource wireframes to extract them. Summaries of the analysis are found in Table 9.

Table 9 Statistical summary of old exploration data flagged by new resource wireframe

		NEW DATA					OLD DATA				
ZONE	**FIELD**	**NSAMPLE**	**MIN**	**MAX**	**RANGE**	**MEAN**	**NSAMPLE**	**MIN**	**MAX**	**RANGE**	**MEAN**
A1	**Au**	**2241**	**0.01**	**26.38**	**26.37**	**1.32**	**2113**	**0.01**	**26.28**	**26.37**	**1.35**
A2	**Au**	**450**	**0.01**	**4.3**	**4.29**	**0.58**	**567**	**0.035**	**4.3**	**4.27**	**0.59**
B1	**Au**	**2988**	**0.01**	**19.23**	**19.22**	**2.19**	**2837**	**0.01**	**19.23**	**19.22**	**2.31**
B2	**Au**	**2284**	**0**	**8.56**	**8.56**	**1.42**	**2352**	**0**	**8.56**	**8.56**	**1.41**
C	**Au**	**1642**	**0.01**	**16.86**	**16.85**	**1.99**	**2596**	**0.01**	**16.86**	**16.85**	**2.09**
D	**Au**	**268**	**0.01**	**8.5**	**8.49**	**0.73**	**-**	**-**	**-**	**-**	**-**

From Table 9 it may be observed that some marginal grades from the exploration drill holes (DD) were picked when the ore zones were being re-delineated. Though insignificant for some of the reefs, that of A1 and B1 were quite substantial in terms of both the extra samples brought into the new resource and the difference in the mean grades. The D ore zone which was not included in the old resource model was modeled as part of the new resource. The D ore zone has poor gold mineralisation. As an additional reef in the new resource with an average grade of 0.73 g/t, it has contributed in reducing the overall new resource grade.

11. Discussions

The ore zones of the two (old and new) resources models were respectively reconciled with similar ore zones of the old GC model. Figs. 6.1 to 6.5 are scatter plots representing the block on block (BOB) reconciliation of the various ore zones with similar GC ore zones.

From the scatter plots, apart from A2 ore zone, it can be observed that generally, the variables grade control (GCAU) and resource models (AU) are positively related. A2 plots are negatively related which may be attributable to the inadequacy of data and the presence of some outliers of AU. The correlation coefficient (R) which measures the strength of the relationship between GCAU and AU is relatively higher for the new resource than for the old resource in all cases. As in Fig. 6.1 it can be observed that the A1 zone of the new resource correlates better with that of the existing GC model than A1 zone of the old resource with the same zone in the GC model. This observation is the same for all zones (Figs. 6.2 to 6.4), confirming that the new resource model will reconcile better with the grade control model than the old model

12. Conclusions

Based on the studies carried out the following conclusions can be made:

- Although some marginal ore was picked during the modeling, resulting in overall lower grade for the resource extra 8,208.30 ounces have been added to the resource.
- The new resource model will reconcile better with the grade control model than the old model.
- The new resource, unlike the old has D zone as part of it. The average grade of the D zone within the current resource is 0.73 g/t, this can be mined as medium grade and used to blend high grade.

13. Recommendations

Based on the findings and conclusion from the study it is recommended that Grade control drilling, sampling and modeling should include the D zone.

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