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RESEARCH ARTICLE

COMPARISON OF ORDINARY KRIGING (OK) AND INVERSE DISTANCE WEIGHTING (IDW) METHODS FOR THE ESTIMATION OF A MODIFIED PALAEOPLACER GOLD DEPOSIT: A CASE STUDY OF THE TEBEREBIE GOLD DEPOSIT, SW GHANA

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ABSTRACT

The study described in this paper involves the application of a conventional resource estimation method, inverse distance weighting (IDW), and univariate geostatistical technique, ordinary kriging (OK) to the gold grades data from the modified palaeoplacer Teberebie gold deposit, in Ghana. The deposit consists of 4 layered well-defined orebodies referred to as A reef, CDE reef, F24 reef and G reef at the mine environment. Simple, reliable, and adequately accurate resource/reserve estimation are essential to mining operations. Data used for the research were collected by diamond and reverse circulation (RC) drilling. A total of 19353 one-meter composite samples, consisting of 18962 RC chip samples from 695 RC drill holes, and 391 diamond drill core samples from 11 DD holes. Samples were analysed by atomic absorption spectrometry (AAS) for gold (Au). Descriptive statistical treatment was conducted on grade values for the reefs. To analyse for spatial structure of Au mineralisation, experimental downhole, and several horizontal directional semi-variograms were computed, and models fitted. Ore reserves were estimated by OK and IDW methods, and results of the various reefs compared. Regression analysis of estimated results indicate that, the inverse distance square (ID^2) model produced estimates that compared well with the OK model in all the ore zones. It is therefore, appropriate to use ID^2 as an alternative estimation method to the OK method for purposes of mine planning and grade control.

KEYWORDS

Geostatistics, palaeoplacer gold deposit, ordinary kriging, inverse distance weighting, and regression analysis.

1. INTRODUCTION

Goldfields Ghana Limited's Tarkwa Mine is located in the Western Region of Ghana, about 300 km, west of Accra, Ghana's capital. The mine has been in operation since 1993 and consists of several low to moderately rich gold palaeoplacer deposits located within the Tarkwaian Group, close to Tarkwa township. Mining is done from several open pit operations using conventional trucks and backhoe excavator method. Operations are optimised by Dispatch Fleet Management System (DFMS). The company has as one of its core policies, the concept of continuous improvement in its resource/reserve estimation, aimed at establishing reliable ore reserves estimates for making decisions about future investments (Daya, 2015).

Implementation of an accurate and reliable estimation method is an important aspect in resource/reserve estimation (Shahbeik et al., 2014). Numerous approaches for mineral resources estimation are generally categorised into 2 main groups: (1) conventional/traditional methods, and (2) geostatistical methods (Isaaks and Srivastava, 1989; Rossi and Deutsch, 2014; Silva and Almeida, 2017). The conventional methods use sections and plan maps, while geostatistical approach, involves a computer-driven two- and three-dimensional (2D and 3D) approach to estimate grade and tonnage of the deposit. It is based on the theory of regionalized variables (ReV) proposed (Matheron, 1971).

Depending on the method of selecting auxiliary blocks, and the manner of computing average grades, conventional methods can further be classified into, inverse distance weighting (IDW), polygonal methods, triangular methods, method of sections, block matrices, and contour methods (Sinclair and Blackwell, 2002). IDW and geostatistical techniques such as ordinary kriging (OK) are extensively employed for ore grade estimation (Tahmasebi and Hezarkhani 2010). Geostatistical methods, recognizes, based on the theory of ReV, that, grade values in a mineral deposit are spatially correlated with one another (Matheron, 1971).

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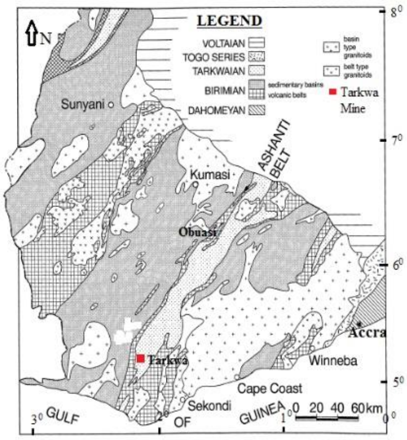
The underlying tool of geostatistical analysis is the semi-variogram (Wang et al., 2017; Amadu et al., 2021). Constructed semi-variograms allow the determination of the structural characteristics of the regionalized earth phenomenon. The range of estimation methods evolved from geostatistics is termed as "kriging", which generically describes a family of generalised least-squares regression algorithms for estimating ReVs (Daya, 2015). In terms of the purpose of kriging, two general classes can be identified, first, is the global *in-situ* reserve estimation (estimation without the imposition of mining and economic factors), and secondly, the estimation of recoverable reserves. Recoverable estimation takes into consideration the portion of the deposit that is technically recoverable when a cut-off grade is applied to selective mining units (SMUs): for example, in particular selective mining operations where various cut-off grade values are imposed (Annels, 1991; Sinclair and Blackwell, 2002).

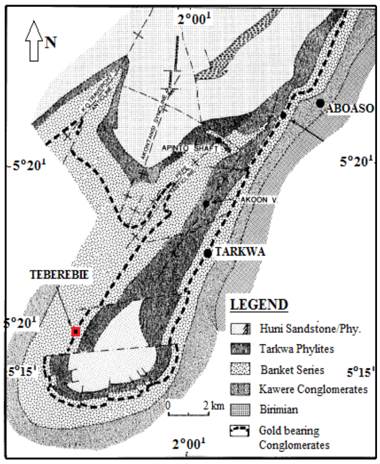
The selection of a resource/reserve estimation method depends on factors such as geology, ease of implementation of the method, kind of mining operation, robustness of the estimation method, accuracy and precision (Annels, 1991; JORC, 2012; Rossi and Deutsch, 2014). A group researchers noted that, improvement in grade estimation and mining methods leads to profitable mining and increase of the life of mine (LOM) (Baldwin et al., 2014). This paper is intended to investigate and evaluate the OK and IDW approaches to determine their relative merits in estimating the grade and tonnage of the modified palaeoplacer Teberebie gold deposit, on the basis of current mine operational demands. To preserve confidentiality, Au grades have been multiplied by a factor.

2. Geological Setting and Mineralisation

Gold occurs in Ghana, principally from two major epigenetic gold-forming events, from: (1) palaeoplacer hematite and magnetite quartz-pebble conglomerates of Tarkwaian System, and (2) shear-hosted orogenic gold of the Birimian Supergroup (Pigois et al., 2003; Perrouty et al., 2012; Fougerouse et al, 2013; Hirdes and Nunoo, 1994). The Tarkwaian, is within the Ashanti Belt in the Tarkwa syncline, which unconformably overlies the Birimian Supergroup (Feybesse et al, 2006; Allibone et al., 2002) (Figures 1).



(a)



(b)

Figure 1: (a- Top) Geology map of southern Ghana showing the location of Tarkwa; (b- Bottom) Geological map of the Tarkwa syncline (Oberthür et al, 1997; Pigois et al., 2003)

The Tarkwaian Group is divided into four units (Table 1), in succession from the base as: the Kawere Group; the Banket Series, the Tarkwa Phyllite; and the Huni Sandstone.

Table 1: The divisions of the Tarkwaian System (Kesse, 1985)

Group	Series	Thickness in (m)	Composite lithology
Tarkwaian	Huni sandstone and (Dompim phyllite)	1370	Sandstones, grits, quartzites with bands of phyllites
	Tarkwaian phyllites	120- 400	Huni sandstone transitional beds, green and greenish grey chloritic and sericite phyllites
	Banket series	120-160	Tarkwa phyllite transitional beds, sandstones, quartzites, grits, breccias and conglomerates
	Kawere Group	250-700	Quartzites, grits conglomerates and phyllites

Recent investigations suggest the gold deposits within the Banket Series derived from a yet to be established source that is older than Birimian shear-hosted deposits (Hirdes and Nunoo, 1994; Fougerouse et al, 2013; Pigois et al., 2003). The Banket conglomerates gold deposit underwent tectonic deformation and metamorphic processes (greenschist facies). A group researcher reports, deformation and metamorphism changed a significant amount of the original features of the Tarkwaian rocks (Greer et al., 1988; Pigois et al., 2003). The focus of this study is on the Teberebie deposit, where the deposits exist as a modified palaeoplacer deposits, where, the geology is dominated by rocks of the Banket Series, bounded by barren footwall and hanging wall quartzites (Klemd et al., 1993; Pigois et al., 2003). The series consists of a sequence of mineralised auriferous reefs interlayered with barren immature quartzite units. A total of 9 reefs (Figure 2) have been identified within the mine, named for the purpose of identification as: AFa, AFc, A1, A3, B2, C, E, F2, and G (Karpeta, 2000; SRK, 2004).

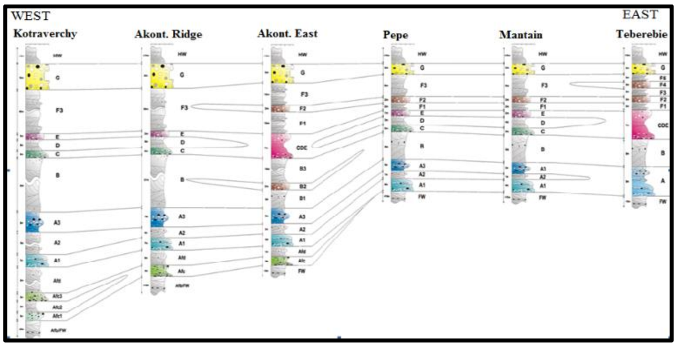


Figure 2: Tarkwa ore deposit model (Karpeta, 2000)

The reefs are usually lens-shaped, up to 400 m long and between 10 to 80 m wide (Karpeta, 2000). The units thicken to the west (Figure 3). Interpretation of the sedimentology and structure of the Tarkwaian, based on current flow parameters analysis, suggest a flow from the east and north-east (Strongen, 1988). The deposit is situated to the south most part of the Takwa Mine concession and occurs within the Banket Series of the Tarkwaian System (Figure 2). Exploration drill core logging and geophysical surveys, reveal the orebodies in the area trend generally NE-SW exceeding a strike length of 1.2 km, and dips to the east, between 12 º - 18º (Karpeta, 2000; SRK, 2004).

In terms of mineralisation, economic concentrations of gold is restricted to within the silicified interstitial matrix between conglomerate clasts (Klemd et al., 1993). Pebble assemblage consists of white and smoky quartz, cherts, lithic fragments, quartzite and shale. Gold (Au) occurs generally as native (Klemd et al., 1993). The grades range between 0.9 and 2.4 g/t (Pigois et al 2003). Accessory oxide minerals occurring in the ore include goethite, magnetite, rutile and ilmenite. Sulphides are occasionally present, usually associated with intrusive rocks or quartz veining. The sulphide minerals present include pyrite, chalcopyrite, pyrrhotite, sphalerite and galena.

3. MATERIALS AND METHODS

3.1 Borehole data and data processing

The portion of the Teberebie deposit used in this study was explored by diamond drilling (DD), reverse circulation (RC) drilling, photogeological and geophysical interpretation, and field mapping. The data set is made of a total of 19353 one-metre composite samples, consisting of 18962 RC chip samples from 695 RC holes and 391 diamond drill core samples from 11 DD holes. While the RC holes consisted consistently of 1 m composites, the DD hole cores were sampled with sample lengths respecting changes in lithological contacts. Samples obtained were assayed by Atomic Absorption Spectrometry (AAS) method for gold (Au), at the SGS Ghana Limited laboratories, Tarkwa. Coring was carried out using LTK46 (core diameter 35.6 mm) and BQ (core diameter 36.5 mm) equipment.

For the RC holes, MPD1500 (Rod diameter 32.60 mm) was used. The average depth of a drill hole was 85 m. All holes were drilled at vertical angle, extending over a strike length of 1.3 km (52 sections). Drill holes intersected a number of sedimentary rock units. DD core recovery of 90 % and over provided information on lithology. DD holes were exploratory in nature, at selected locations and less regular. Drilling grid for the RC drill holes was 25 × 25 m (Figure 3), although in some places additional boreholes were drilled for further information.

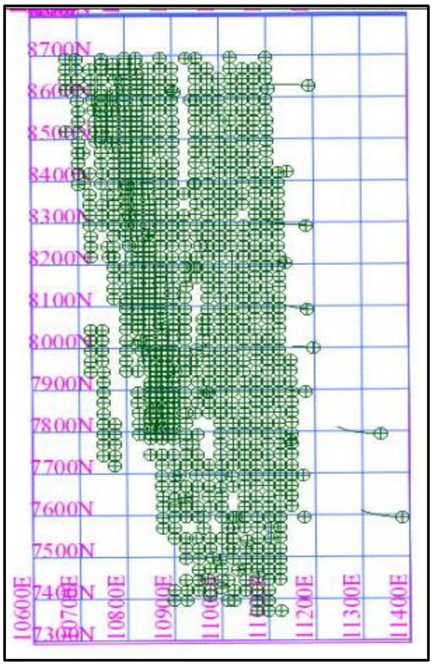


Figure 3: Borehole location plan

For the purpose of orebody modelling, and in order to obtain a reliable geometry and grade of the orebodies within the study area, ASCII files of collars to the drill holes, assay and mapping surveys were developed, saved in comma-delimited formats and imported into Gemcom Surpac software (Anon, 1998). Geological interpretation was carried out based on gold (Au) grade values, structural and lithological information from diamond drill core and RC chip logs. Geological interpretation of folding, faulting and litho-stratigraphic units were hand performed on vertical section plots developed in Y-Z plane at separations of 25 m. In this study, focus was on the limits between Eastings: 10750 – 11400, Northings: 7400 – 8700, and Elevation: (150) - (-150) m. This area was selected for this study because, the area showed well defined ore reefs and had adequate sample values, which is relevant for geostatistical and other techniques used in ore reserve estimation (Annels, 1991; Rossi and Deutsch, 2014).

3.2 Delineation of ore zones

Based on the intersections of drill holes within the study area on the various layers of rock units, zoning was carried out. This was carried out from the base of the hole to the top, using reefs characteristics such as: thickness, pebble characteristics and assemblages and grade distribution. The reef zones identified at the Teberebie area include A, CDE, F24, and G. An example of zoning is shown in Table 2.

Table 2: Example of zone information

Hole ID	Depth from (m)	Depth to (m)	Zone
DEP18	0	4	OVB
DEP18	4	10	HW
DEP18	10	13	G
DEP18	13	15	F5
DEP18	15	21	F24
DEP18	21	23	F1
DEP18	23	30	CDE
DEP18	30	38	B
DEP18	38	46	A
DEP18	46	50	FW

Information from zones were used to digitize ore outlines that are distinguished by colour codes (Figure 4a), followed by a 3-D wireframe model (Figure 4b), with the Surpac software.

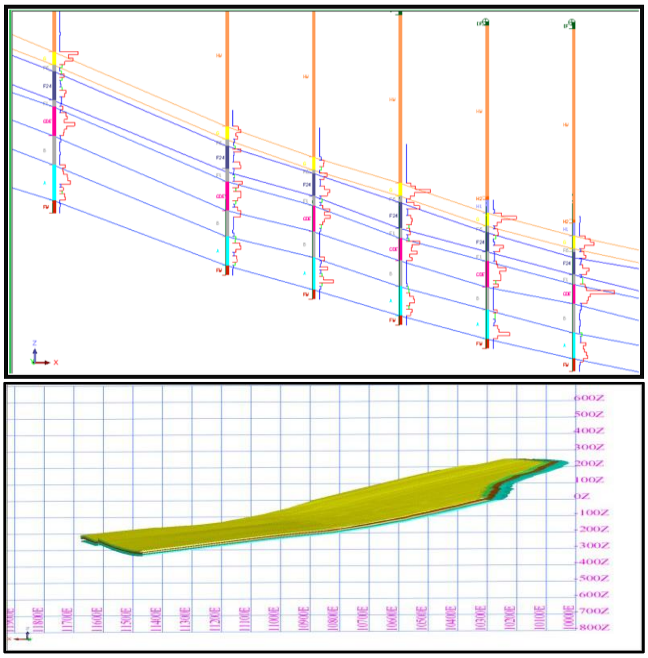


Figure 4: (a) Section 7625N of the Study Area and (b) 3D wireframe solids generated

The segments defined in each section were linked to their corresponding segments in the other sections, to form a three-dimensional (3D) wireframe of the mineralisation extending over the strike length from 7400N to 8700N. The 3D wireframe solids were validated to ensure triangles forming the solids were not overlapping. Output files created from the digitisation were used as the ore boundary string files and saved in Surpac. The assay data, bounded by the ore boundary string files were selected and used for: 1) assessing the continuity of ore and waste layers, 2) statistical and geostatistical analysis, and 3) defining the wireframe and block modelling.

3.3 Statistical analysis on data

Borehole sample comprising of DD and RC samples were analyzed by AAS method, and grades reported in g/t or ppm. DD samples were of unequal lengths. They were thus constrained and composited to 1 m lengths, as it is important to work with samples of equal support (Isaaks and Srivastava, 1989; Daya, 2015). Statistical compatibility of DD and RC data sets were verified using the F – and t – tests as suggested (Al-Hassan and Annels, 1994; Al-Hassan and Boamah, 2015). There was no significant difference statistically, between DD core and RC chip sample types. They were thus combined and used for further statistical analysis. The determination of univariate statistics is a fundamental step in the resource/reserve evaluation, irrespective of whatever estimation method is to be employed (Arthur and Annels, 1994; Glacken et al., 2001). Statistical analysis provides evidence of the distribution of the data, while Frequency distribution analysis and defines sub-populations, and indicates distinct geological domains that are treated separately during evaluation (Rossi and Deutsch, 2014; Rezaei et al., 2019). Separate descriptive statistical treatments were conducted for the reefs.

3.4 Block modelling

The deposit block models (BMs), describe the 3D volumes of the orebodies with relatively small-sized blocks known as cells. Block modelling is carried out by grouping data and object features into a single space (Gibbs, 1992). Information regarding features in the BM is referenced through its intersection with spatial objects like digital terrain models (DTMs), drill data, 3D models of geologic features, plane surfaces, etc. Creation of BMs use coordinate systems to locate relevant attributes or properties (Rossi and Deutsch, 2014). The orebodies are represented by series of arbitrary solids. An unconstrained BM of the study area was generated, and the 3Ds of orebodies and their relative positions in space visualised in Surpac.

A constraint was applied in the form of imposing the mineralised zone wireframes, as suggested (Gibbs, 1992):

1. Creation of empty block model;
2. Addition of geologic codes for lithology, degree of oxidation, alteration etc;
3. Addition of constraints, such as structural information (e. g. faults); and
4. Filling the model with numeric and character attribute records, such as mineralization type, degree of oxidation, and alteration, etc.

The orebodies are divided into fixed-size blocks and dimensions determined using sample spacing, grade variability, dip of deposit, planned mining bench heights and other engineering considerations (Francois-Bongarcon and Guibal 1982; Al-Hassan and Boamah 2015). A user block size of 10 x 10 x 3 m corresponding to half the average drill hole interval was adopted. Block model parameters used, and the model generated is shown in Table 3, Figure 5, respectively.

Table 3: Block model parameters

BLOCK MODEL NAME: Teb_0610_10m_Project			
Block Model Geometry			
Min. Coordinate	Y = 7300	X = 10650	Z = -150
Max. Coordinate	Y = 8600	X = 11410	Z = 150
User Block size	Y = 10	X = 10	Z = 3
Min. Block size	Y = 10	X = 10	Z = 3
Attribute		***Description***	
ok		Ordinary Kriging	
au_id4		IDW to the power 4	
au_id3		IDW cubed	
au_id2		IDW Squared	
au_id		IDW Squared to the power 1	
Material type		Ore and waste of material considered	
SG		Specific Gravity of material	
Constrains used		***Description***	
Reef Con.		Ore zones within the solids	
Topo Con.		DTM of the topography of the area	

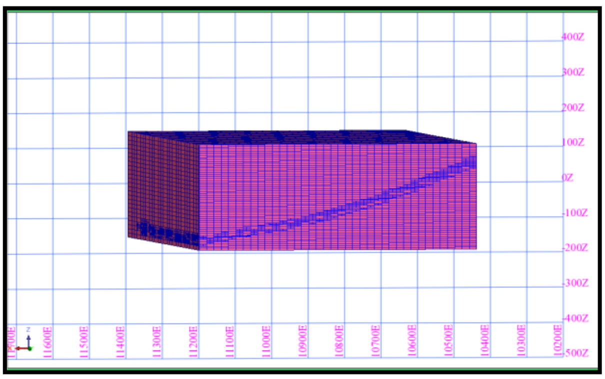


Figure 5: Block model of Study Area

The BM for the study area was validated by visual examination (in sections) of color-coded drill hole assay values and intersections.

3.5 Reserve estimation

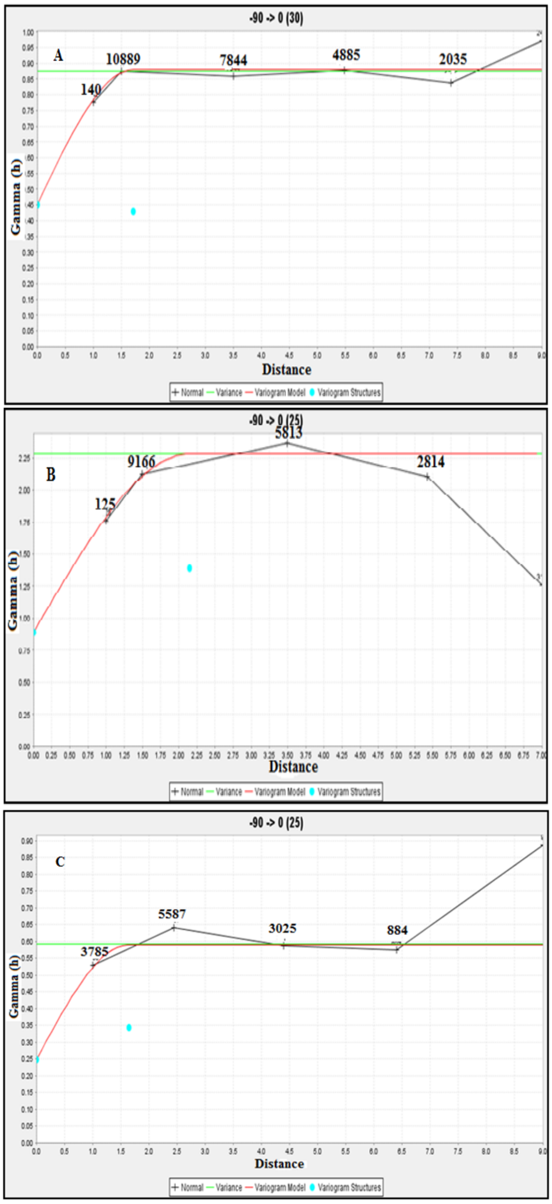
3.5.1 Variography for ordinary kriging (OK)

OK method call for quantification of the spatial correlation structure, by semi-variogram modelling (Annels, 1991; Lee et al., 2011; Gol et al., 2017; Kang et al., 2019). Composited drillhole data within the individual wireframes of the reefs were used for variography, in accordance to a study and a series of variograms in several directions of mineralisation were calculated, using the equation (Michel, 1982; Webster and Oliver, 2007; Wang et al., 2017):

$$\gamma^{*}(h) = \frac{1}{2n}\sum_{i=1}^{n}\{Z(x_i) - Z(x_i + h)\}^2 \qquad (1)$$

where, $\gamma^{*}(h)$ defines the experimental variogram, $Z(x_i) =$ the value of sample grade at point x_i; $Z(x_i + h) =$ grade of sample at distant *h* from point x_i and, n = count of sample pairs.

To determine the nugget variance C_0, for the four reefs, downhole direction spherical semi-variograms were computed, on the basis that it has the closest sampling interval, which is the shortest lag spacing of 1 m. Downhole variograms depicted single structure spherical models (Figure 6). These were generated using the *Geostatistics variogram modeling* in Surpac, and the derived parameters shown in Table 4.



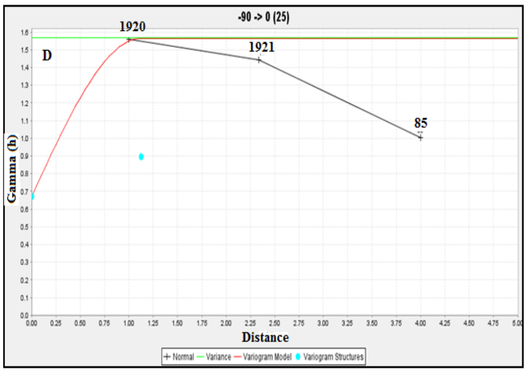


Figure 6: Fitted experimental downhole semi-variograms for the reefs: (A) A-Reef, (B) CDE-Reef, (C) F-24 Reef, and (D) G-Reef.

To detect anisotropy in the horizontal plane, variograms were computed in various directions, separated by successive clockwise rotations of 30º from the north. Experimental variograms were calculated in 12 to 14 directions for Au grade values within each of the reefs for the following purposes (Isaaks and Srivastava, 1989):

- Quantify the variability of data sets with respect to spatial distribution
- Determine the ranges in the principal directions,
- determine the existence or otherwise of anisotropy.
- Define mathematical equations that represents fully, the grade variations of the orebodies.

A lag distance *h*, of 25 m, as the average drillhole spacing, and angular tolerance of 22.5º were used for the horizontal semi-variograms search, for appropriate variogram or structural models to be fitted to the experimental variograms (Wang et al., 2017).

Table 4: Downhole semi-variogram model parameters of the various reefs on Azimuth of (0º)

Reef	Lag Spac. (m)	Plunge/Dip (º)	Spread	Spread Limit	C_0	C	a (m)
A		-90	25	100	0.450842	0.450842	1.70
CDE		-90	25	100	0.89000	1.390166	2.15
F24		-90	25	100	0.247006	0.343113	1.643
G		-90	25	100	0.670232	0.895638	1.125

C_o represents nugget variance, 'a' is range and C is the spatial variance

3.5.2 *Verification of variograms through cross validation*

Accuracy the various variogram models were done by cross validation with point kriging, after the convention (Isaaks and Srivastava 1989). The *Geostatistics–Variogram Validation* menu in Surpac was used to carry out the validation process. Figure 7 shows examples of the scatter plot of the actual versus the estimated value using OK.

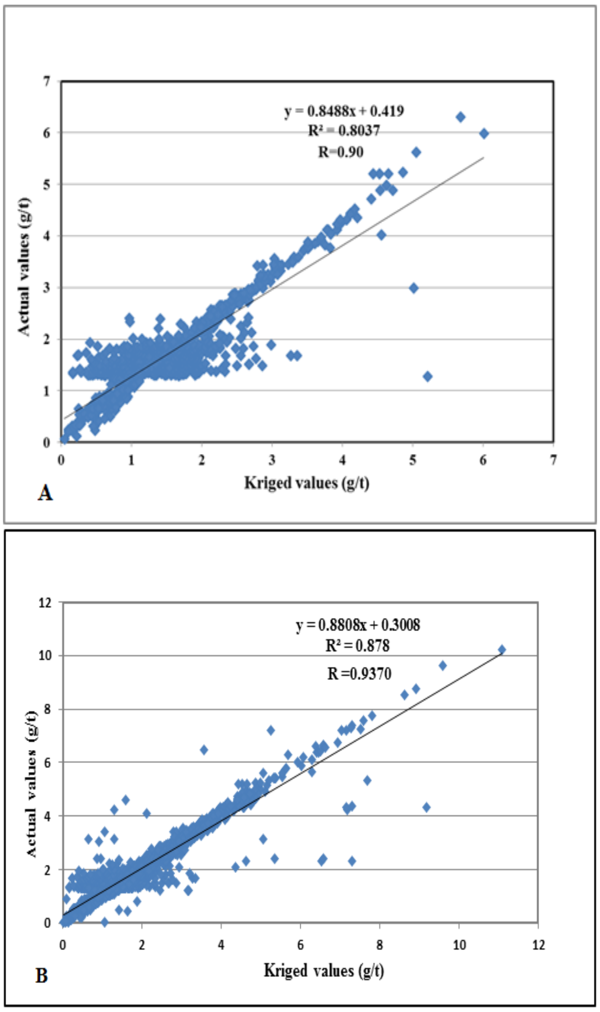


Figure 7: Scatter plot of actual on kriged values, (A) A reef, (B), CDE reef

Regression values were used to assess the agreement between predicted and actual values. The linear regression parameters for the four reefs (Table 5), approximate to those expected for perfect correlation (Davis, 1986). The models were thus considered to satisfactorily characterize the spatial variability of the Au grades for the orebodies.

Table 5: Regression equations of actual on kriged values for the ore zones

Reef	Linear equation	Correlation coefficient (R)
A	Actual = 0.0.419+0.8488* Estimate	0.900
CDE	Actual = 0.3008+0.8808* Estimate	0.9370
F24	Actual = 0.3004+0.8291* Estimate	0.8533
G	Actual = 0.2769+0.8321* Estimate	0.9122

3.5.3 *Reserve estimation using OK method*

Having established spatial continuity of gold mineralisation for the various reefs by variogram analyses and modelling, local grade estimation was modelled using OK and IDW methods. Grade values within the resource wireframe were used for estimation. Kriging, in general, is defined as a minimum variance estimator (Matheron, 1971; Sinclair and Blackwell, 2002; Shahbeik et al., 2014). The average block grades were estimated by weighting samples according to derived parameters from the fitted semi-variogram models (Section 3.5.1). Tonnage estimation for all blocks were domained by rock type, degree of weathering and mean rock bulk density, ρ values for each domain, and computed as, the product of average thickness of reef, plan area of the block (reef), and the tonnage factor or bulk density, 2.80 t/m³.

3.5.4 *Reserve estimation using IDW method*

IDW approach is probably one of the oldest spatial prediction techniques (Shepard, 1968) that employs a weighting factor, based on an exponential distance function to each sample within a defined search neighbourhood about the central point of a block (Annels, 1991; Harman et al., 2016). Sample values within the neighbourhood are weighted by the inverse of the distance of the sample from this central point, and raised to a power '*n*', and computed as: (Harman et al., 2016):

$$\text{IDW} = \quad Z_B^* = \frac{\sum Z_i \frac{1}{d_i^n}}{\sum_{i=1}^{n} \frac{1}{d_i^n}} \qquad (2)$$

where: Z_B^* is the estimated variable of the block (of grade, thickness, accumulation etc.)

Z_i is the value of the sample at location i

d_i is the separation distance from point i, to the point of reference, and, n is the power index.

In this study, different weighting powers, 1, 2, 3, and 4 were employed. Bench by bench OK model grades were compared with that of IDW powers of 1, 2, 3, and 4 model grades.

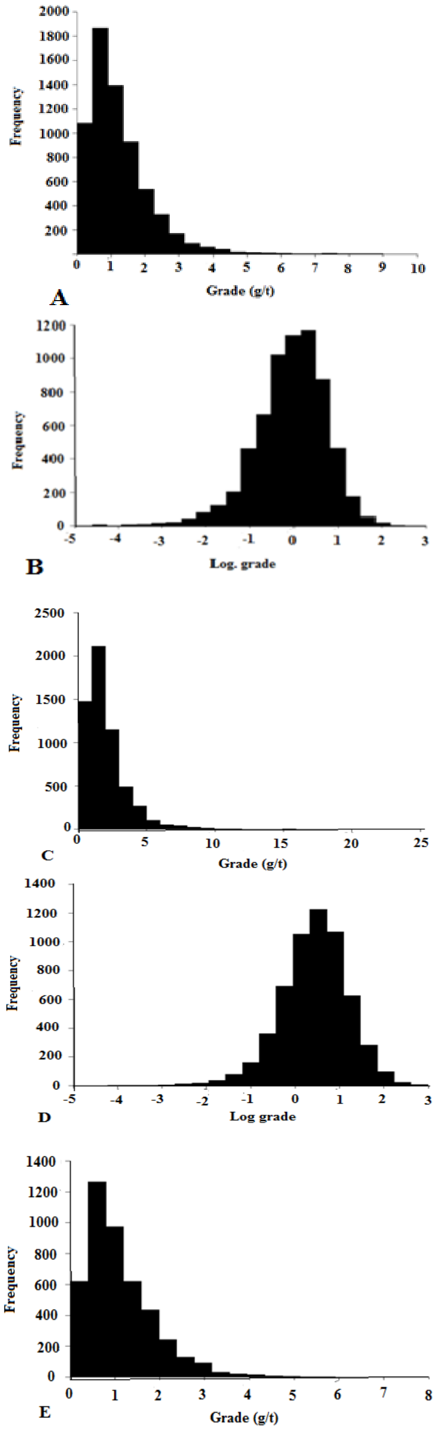
4. Results and Discussions

4.1 Delineation of the ore zones

The orebodies are well developed, strikes generally NE–SW and dips 12 º-18º E.

4.2 Sample data distribution analysis

Histograms of raw data and logarithms of grades for the separate reefs are shown in Figure 8.



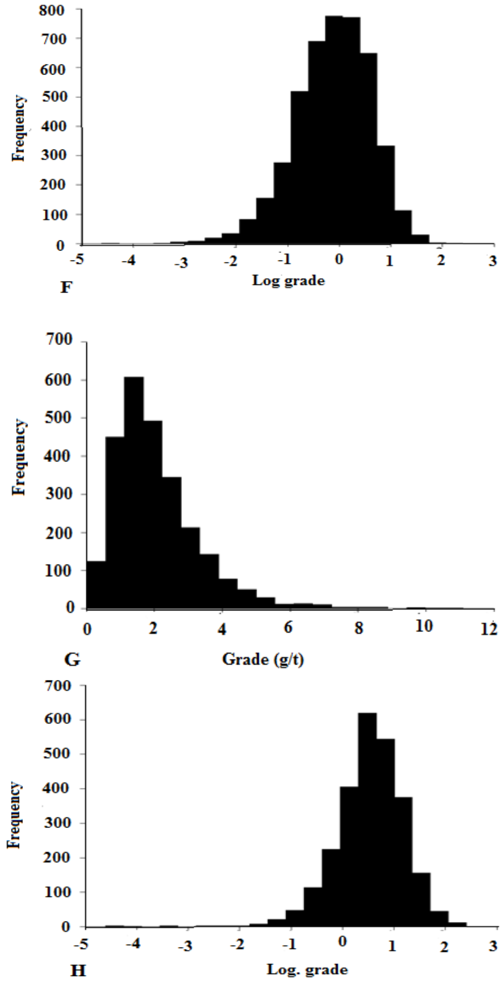


Figure 8: Plots of the histograms of the raw data and logarithms of grades for the separate reefs: (A) Frequency distributions of Au grades for A reef, (B) Logarithms of grade for A reef, (C) Frequency distributions of Au grades for CDE reef, (D) Logarithms of grade for CDE reef, (E) Frequency distributions of Au grades for F24 reef, (F) Logarithms of grade for CDE reef, (G) Frequency distributions of Au grades for G reef, (H) Logarithms of grade for G reef

Figure 8, the distribution is positively skewed, typical of gold grades, and show quite similar population distribution for the different reefs, hence the population can be described as a single population (Davis, 1986). Plots of log-transformed values (Figure 8 B, D, F and H), and probability plots of the raw Au grades show a one-parameter lognormal and unimodal global distribution. This is indicative of a single main mineralization style, resulting from sporadic sediments depositional processes accompanied by syngenetic gold mineralization. The probability graph (Figure 9) shows a distinct sub-population, and inflexion, e.g., at about 7.5 g/t for the A reef, which are outliers (Rossi and Deutsch, 2014).

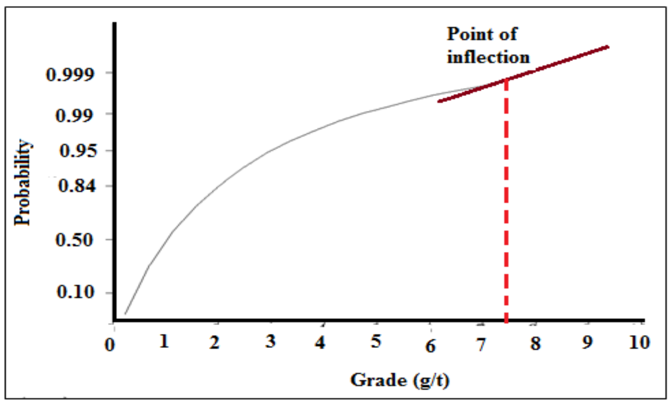


Figure 9: Example of probability plots, the case for A Reef

Results of statistical analysis carried out on the raw data for the reefs are presented in Table 6.

Table 6: Statistical parameters of Au samples, minimum (Min.), maximum (Max.), standard deviation (SD) and coefficient of variation (CoV) for the four ore zones

Ore zone	Values	Min. (g/t)	Max. (g/t)	Mean (g/t)	Variance (g/t)²	SD (g/t)	CoV
A Reef	6555	0.01	9.00	1.230	0.902	0.95	0.772
CDE Reef	5753	0.01	19.9.	2.005	2.528	1.59	0.795
F24 Reef	4464	0.01	7.89	1.118	0.615	0.784	0.696
G Reef	2641	0.01	11.00	2.059	1.665	1.290	0.626

From the summary statistics, the CDE reef and G reef are showing relatively higher mean grade with high variance and standard deviations (SD) compared to those of the A and F24 reefs. This is probably resulting from depositional history and source of the gold mineralization were under favorable environment of formation conditions, sediments and sedimentary rocks act selectively as enriched elements potential economic zones (Deutsch, 2010). The number of Au samples differ for the reefs because, there is differences in the thickness of the reefs. The A reef is the thickest, while the G reef is the thinnest. The CDE recorded the highest grade of 19.9 g/t and coefficient of variation (CoV) of 0.795. This probably is why the reef has the highest variance and standard deviation (SD). CoV is an expression of the relative variation of the data, and expresses the degree of homogeneity of the distribution (Davis, 1986). CoVs for the reefs show close differences (Table 6), this may be an indication of similar geological and geochemical processes in their formation. Generally, data sets with CoV of less than 1, produce reasonable variogram models (Annels, 1991; Deutsch, 2010). In this study, the CoVs are found to be less than 1 for all the reefs.

4.3 Ore reserve estimation

4.3.1 Variogram analysis

As mentioned in Section 3.5.1, to determine the nugget variance (nugget effect), C_0, for the various reefs, downhole spherical semi-variograms were computed. C_0 values obtained were 0.45, 0.89, 0.25, and 0.67 for the A reef, CDE reef, F24 reef, and G reef respectively. Directional experimental semi-variograms in this study, in all cases of the ore zones were fitted with two structure spherical models. Examples of variograms generated for some directions are shown in Figure 10. Table 7 is model parameters obtained for directional experimental variograms for the A reef (presented as an example of parameters generated for the reefs).

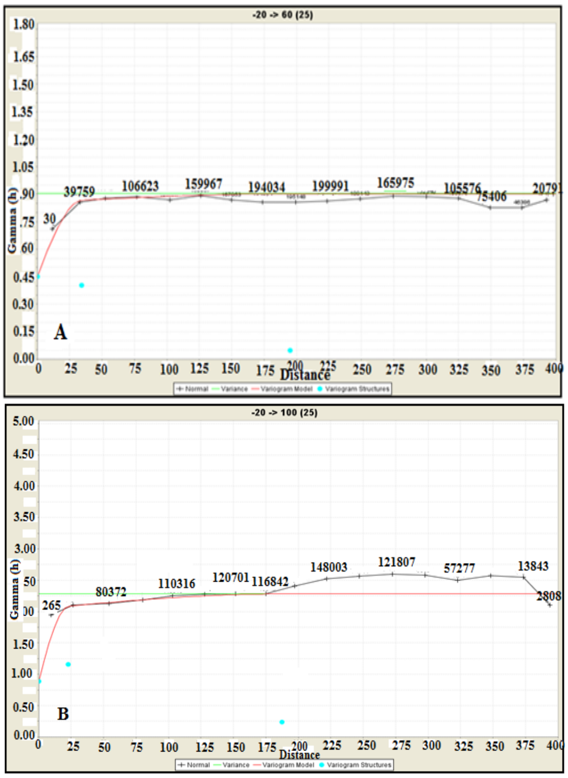


Figure 10: Examples of directional variograms: (A) A along 60º, (B) CDE along 100º

Table 7: A reef directional spherical semi-variogram parameters

Azi. (º)	Direction	C_0	C_1	C_2	a_1	a_2	Major/Semi major ratio	Major/Minor ratio
0		0.450842	0.035739	0.035739	12.83	58.628		
30		0.450842	0.420617	0.015961	16.71	53.875		
60	Major	0.450842	0.403515	0.048064	34.30	195.161	1.6915	114.7331
90		0.450842	0.397422	0.027352	11.62	85.199		
120		0.450842	0.344493	0.082192	31.41	99.679		
150	Semi-major	0.450842	0.342148	0.083957	25.68	115.379		
180		0.450842	0.335964	0.088483	24.85	83.833		
210		0.450842	0.283046	0.127976	24.99	80.303		
240		0.450842	0.271529	0.147762	11.73	33.472		
270		0.450842	0.271529	0.147762	10.30	33.116		
300		0.450842	0.399124	0.037568	18.62	35.849		
330		0.450842	0.382503	0.020441	9.706	62.229		

The general equation for this nested model agrees with those predicted (Sinclair and Blackwell, 2002; Journel and Huijbregts, 1978). It is expressed as:

$$\gamma(h) = C_0 + C_1\left[\frac{3h}{2a_1} - \frac{h^3}{2a_1^3}\right] + C_2\left[\frac{3h}{2a_2} - 0.5\left(\frac{h}{a_2}\right)^3\right] \quad \text{for } h < a_1,$$

$$\gamma(h) = C_0 + C_1 + C_2\left[\frac{3h}{2a_2} - 0.5\left(\frac{h}{a_2}\right)^3\right] \quad \text{for } a_1 \le h < a_2 \text{ and,} \tag{3}$$

$$\gamma(h) = C_0 + C_1 + C_2 \quad \text{for } h \ge a_2 .$$

where, C_0 = nugget variance, C_1 and C_2 = spatial variance of first and second structure respectively, a_1 and a_2 = range of first and second structure, h = distance separating pairs of sample values. C_0 represents the random portion of the variability of the regionalised variable, i. e the variogram value $\gamma(h)$ at a distance of zero (i.e. when 'h' equal to zero). It is partly an expression of the variability between samples at, or very close to zero distance apart and partly the presence of sampling errors (Annels, 1991). From plots of variograms and parameters obtained from variogram models, it was observed variograms differed with different directions, since different ranges and sills were obtained for different directions, an indication of anisotropy (Sinclair and Blackwell, 2002).

Two major horizontal directions were worth noting, N60ºE showed maximum continuity ot mineralisation, which is along strike, and an azimuth of 150º which is across strike, indicated a semi-major continuity. Ranges along strike were, 34.30 m, 32.516 m, 26.74 m and 33.44 m for the

A reef, CDE reef, F24 reef, and G reef respectively, indicating drill hole intervals are within the ranges in the strike direction of the orebodies. The shortest range was in the downhole direction, which reflect thickness of the reefs. They ranged from 1.13 to 2.20 m. This agrees with observations made for layer sedimentary mineralisation (Hayward et al., 2005).

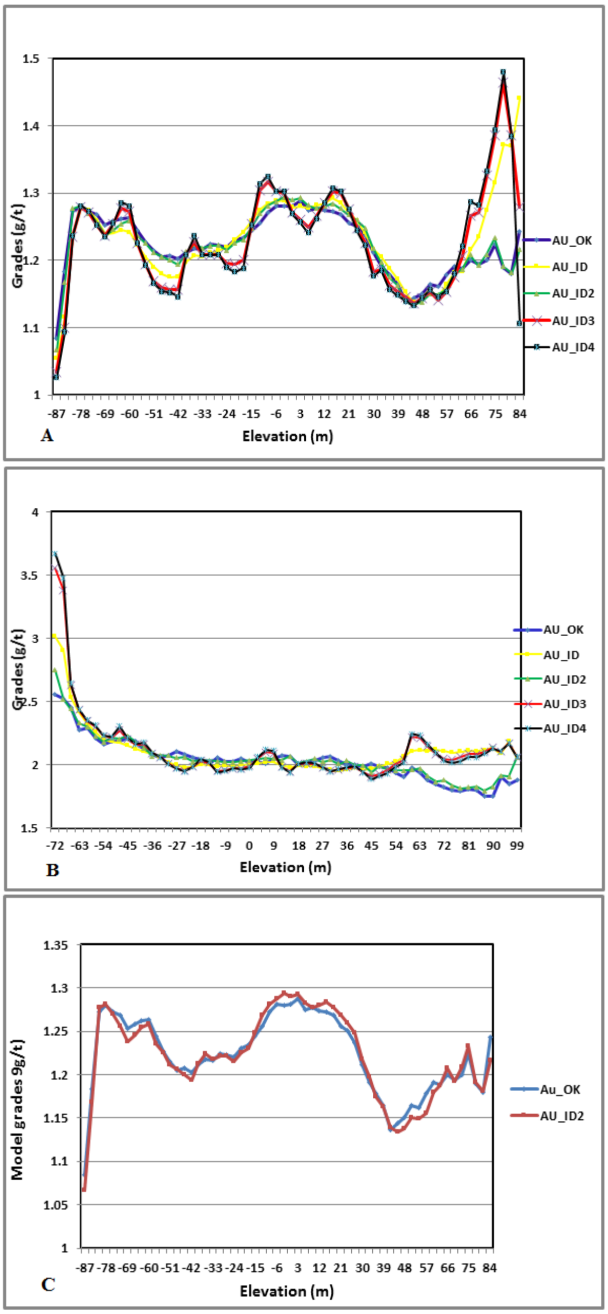
4.3.2 *Comparison of estimated grades*

Table 8 presents grades and tonnages estimated by OK and IDW methods.

Table 8: Comparison of estimated grades using OK and ID² methods

OK				ID²			
Reef	**Vol.(m³)**	**Tonnes (t)**	**Ave. grade (g/t)**	**Reef**	**Vol. (m³)**	**Tonnes (t)**	**Ave. grade (g/t)**
A	3716700	9849255	1.233	A	3716700	9849255	1.233
CDE	3122700	8275155	2.042	CDE	3122700	8275155	2.046
F24	2892000	7663800	1.095	F24	2892000	7663800	1.096
G	1694700	4490955	2.088	G	1694700	4490955	2.084

A number of criteria for comparing estimation methods exist, they include analysis of the correlation between estimates, and the use of grade and tonnage curves (Ravenscroft, 1992). To avoid arbitrary weighting approach using IDW method, results produced by various weighting powers (1, 2, 3, and 4) were compared to those produced by OK method. Goodness - of - fit statistics showed that, inverse distance squared, ID² compared well with OK as compared to IDW- 1, IDW-3 and IDW- 4 (Figure 11 and Table 9).



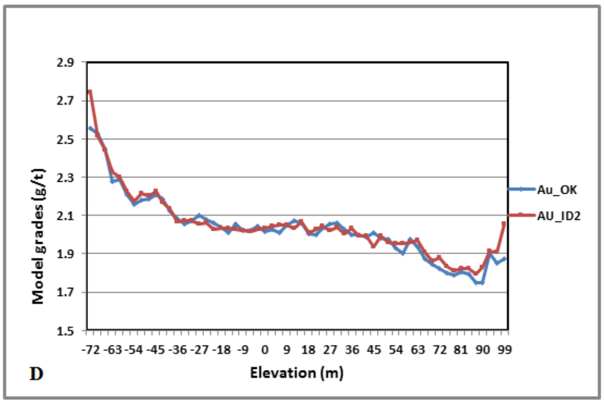


Figure 13: Comparison of estimated grades: (A) OK, ID, ID², ID³, and ID⁴ model for A reef, (B) OK, ID, ID², ID³, and ID⁴ model for CDE reef, (C) OK and ID² model for A reef, (D) OK, and ID² model for CDE reef.

Table 9: Results of regression analysis of block-by-block OK against ID² model grades

Ore zones	**Power index**	**Correlation coefficient (R)**
A	2	0.934
CDE	2	0.947
F24	2	0.912
G	2	0.917

The regression parameters (Tables 9) indicate the ID² model compared strongly well with the OK model in all the four reefs and is therefore a satisfactorily accurate estimation alternative method to OK for mine planning and grade control for the Teberebie deposit. Generally, conventional methods such as IDW have some drawbacks in the accuracy of reserve estimation (Daya, 2015). Errors in estimating thickness of orebodies can occur when assuming that the thickness/grade of a block is equal to the thickness of grade of a single point about which the block has been drawn. However, this problem is minimized in a situation of relatively uniform thickness as in with this study area. Prior to grade interpolation, OK method is preceded by the determination of spatial structure of the mineralization by construction of semi-variograms (Lee et al., 2011). This make OK lengthier and much complex compared to IDW. The selection of one estimation approach or a combination of approaches by an exploration/mining company can be a matter of familiarity, ease of employment, or peculiar usefulness.

5. Conclusion

The main objective of mineral resource/reserve estimation is to help in deciding whether a mineral deposit is worth mining, and to guide in the mine planning and operations. The fundamental focus is for economic decisions, and the appropriateness of those decisions depend on the accuracy of resource/reserve estimation. It can therefore be concluded that both OK and inverse distance square, ID² can be employed to reliably model and estimate the modified palaeplacer gold deposit. In this study, the vertical downhole and directional variogram models of gold grades of the deposits showed two-structure spherical models, with a nugget effect ranging from 0.24 to 0.89 m, and maximum range in the along strike direction of 34.30 m for A reef. Variography results in different directions show that, the ore deposit is anisotropic. Ore reserves were evaluated using OK and IDW methods, and regression analysis of estimated results indicate the inverse square, ID^2 model compared strongly well with the OK model in all the ore zones. ID^2 model is therefore, appropriate to be used as an alternative resource/reserve evaluation method to the OK method for mine planning and grade control for the for the Teberebie deposits.

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