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## RESEARCH PAPER

# A GEOSTATISTICAL APPROACH TO OPTIMAL DRILLING AND SAMPLING DESIGN: A CASE STUDY OF THE OBUASI GOLD DEPOSIT IN SOUTHERN GHANA

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## ABSTRACT

***This paper demonstrates the application of geostatistical techniques to the design of optimum drilling/sampling density, to an epithermal mixed vein – and disseminated sulphide type gold deposit. The Obuasi Mine is situated within the Ashanti gold belt of Ghana. The mine has past production and current reserves exceeding about 1,200 tonnes (t) of gold. The deposit is a typical shear zone type, characterised by non-uniform sulphide mineralisation distribution and boudinage auriferous quartz reefs having sharp boundaries. The main objectives of this study were; to determine the distribution of gold grades, and to use geostatistical approach to determine the optimum drilling and sampling intervals for the underground mine. The data for the study come from Block 1, Kwesi Mensah Shaft of the mine. It comprises of two data sets, diamond drill core and channel samples from cross-cuts. 507 drill hole cores were sampled at intervals of between 1.0 m, and 149 crosscuts, from which a total of 114488 channel samples were obtained and assayed by Atomic Absorption Spectroscopy (AAS) method for gold (Au). Statistical analysis showed that gold grade data had multiple-population characteristics. To analyse for spatial structure of gold mineralisation, 3D semi-variograms were computed in the 3 principal directions. Variability of the Au grades within the deposit were revealed, and nugget effect, $C_0$ defined as 3.7 $(g/t)^2$ and ranges (a's) ranged from 3.7, 16.1 to 27.5 in the across-strike, along strike, and down-dip directions, respectively. Sidewall channel sampling interval of 1 to 1.5 m across strike (used in crosscut and reef drives backs), and 30 m drill hole spacing for the down-dip section are adequate. Drill hole spacing in sections perpendicular to the strike of the deposit should be between 30 to 50 m, depending on the size, complexity of mineralization and structure of the orebody.***

**Keywords**: Geostatistics; variogram analysis; ore deposit; gold grade distribution; optimal drilling interval; Obuasi underground mine

# INTRODUCTION

Sample collection and sample data in resource/reserve estimation and grade control are very important to mining companies, where they serve as critical components in the making of decisions (Dominy et al., 2011; Pitard, 2019). Sampling above a certain critical interval does not add much to the accuracy of mineral resource/reserve estimation, however, over-sampling can result in a huge financial loss (Minnitt, 2007; Dominy, 2016). Annels (1991), reported that the cost of intense sampling of a low grade or low-value deposit may be prohibitive.

Samples are collected for several reasons and at different stages of the mineral development process for geological, environmental and metallurgical purposes (Minnitt, 2007; Dominy, 2016; Dominy et al., 2018). Joint Ore Reserves Committee (JORC) (2012) defined a sample as a representative part or a single item from a larger whole; a sample is that portion of the target population that is studied and used to characterise or make an inference of the target population. Accurate and representative sampling plays a significant role in the decision-making process and can help resolve some of the major challenges in a mining operation (Minnitt, 2007; Dominy, 2014).

Inappropriate sampling protocols/operations, and their inherent sampling errors can cause various consequences (Carrasco et al., 2004) including poor decisions and financial losses (Carrasco et al., 2004; Dominy, 2016). Some of the major problems faced by sampling teams in mining operations are the minimum number of samples to be collected, where and how each sample is collected and used to obtain an accurate resources/reserve estimation. This kind of estimation technique stated above is referred to as the optimum sample density (OSD).

In this study, OSD refers to the best overall minimum sampling interval for sample collection that takes into consideration the correlation of sample values. Gold grades, like many earth science variables, are recognised to be variables distributed in space, and referred to as regionalised variables (Armstrong, 1998); Bivand et al., 2013). They are spatially correlated variables. For an evaluation programme to give an accurate estimate, sampling characteristics of the deposit should be related to the geology of the mineralisation. The mode of occurrence, morphology and mineralisation of a mineral deposit has an impact on the expected sampling density (Annels, 1991). With the application of relevant assessment methods, definite deposit characteristics can be established to maximise ore extraction.

The background to this research stem from observations made from the operations of the mine. The reconciliation practice currently used by AGA involves comparing mined grade to mill head grade, called the Mine Call Factor (MCF) (de Jager, 1997). The MCF is regarded as the measure of the efficiency of the mining system. It is a ratio expressed as a percentage of the gold 'accounted for' divided by the gold 'called for' by the mine's measuring methods (de Jager, 1997): The MCF of AGA's Obuasi Mine indicates a MCF consistently lower than 100%, which at a time fell as low as 24 % (Amadu, 2006). Such low values of MCF achieved, despite the severe top cutting of assayed gold values in the data used for resource/reserves (Amadu, 2006) could be due to some inappropriate sampling practices leading to overestimation of grades, or some other sources of error. The quality and quantity of samples collected for defining orebodies can have significant implications on mine planning, level of confidence and the economic fortunes of AGA. There is therefore the need for sampling protocols at the Obuasi underground mine to be reviewed.

Geostatistics provides, via variography, a framework for spatial prediction (Pardo-Iguzquizaa and Dowd, 2005; Zhang and Yao, 2008). It can be used for the identification of grade trends and/or continuity of mineralisation. Variography of data, including non-linear transformations, can be useful for understanding the structure of mineral deposits. The structure of mineralisation provides a benchmark to guide the design of sampling protocols for mineral exploration and mining operations. Information on data variability derived using the geostatistical tool of variography, allows one to define an optimal sampling pattern and density (Dominy et al., 2000; Carranza, 2009).

The spatial patterns and the ranges of influence in different directions, produced by modelled variograms are important when deciding on drill spacing and patterns. Although determining the geostatistical structure of a mineral deposit is often a challenging exercise, it is one of the robust approaches in evaluating the mineralisation structure and variability. With geostatistics, the semi-variogram can be used to evaluate the variability of mineralisation (David, 1988; Sinclair and Blackwell, 2002). The objective of this study is to improve resource/reserve estimation, grade control and reconciliation practices, using a geostatistical approach to determine the optimum drilling/sampling interval for the Obuasi gold deposit.

## Geological setting

### Regional geology

A large proportion of southwestern Ghana is underlain by Palaeoproterozoic Birimian Supergroup rocks (Fig. 1).

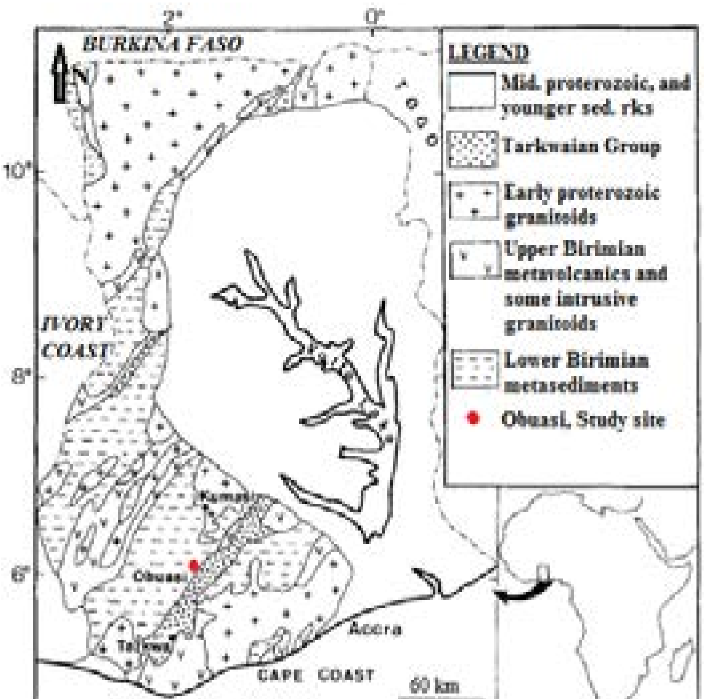


**Fig. 1 Geology map of Ghana (after Kesse, 1984)**

The lithologies are subdivided into volcanic/sedimentary Birimian Supergroup (2.2-2.1 Ga), the clastic sedimentary Tarkwaian Group, and various granitoid intrusions (Leube and

Hirdes, 1986; Leube et al., 1990). The Birimian is divided into two classical subdivisions, the Lower Birimian and the Upper Birimian (Alliborne et al. 2002); the Lower Birimian consists mainly of black and grey phyllites, schists, meta-wackes, argillites and chemical sediments, while the Upper Birimian rocks are predominantly tholeiitic basalts (Dechamps et al., 1986; Adjimah, 1988). The Lower Birimian unit occurs in basins between the northeast-southwest (NE-SW) trending Upper units. The entire Birimian sequence have undergone structural deformation and metamorphosed to greenschist and in some places, almandine-amphibolite facies that occurred during the tectono-thermal Eburnean orogenic event (Wright et al., 1985). Fault zones cut the sedimentary and mafic volcanic rocks and host numerous gold deposits that form one of the richest mesothermal lode gold provinces in the world (Alliborne et al, 2002). Several gold belts occur at or close to the contacts between metasedimentary and metavolcamc rock units (Adjimah, 1988: Robb et al., 1999; Alliborne et al., 2002).

**Local geology**

The AngloGold Ashanti Limited's (AGA) mine concession at Obuasi is located within the Ashanti gold belt of Ghana (Fig. 1) (Oberthur et al., 1997). Mining within the Obuasi District comprised both surface and underground mining. This study focuses on the underground mine. The underground mine has been in continuous operation since 1947 (Bowell et al., 1990). Two main gold deposit types: the shear-zone hosted lode-quartz veins (QVT), and/or the disseminated sulphides (DST) (Leube et al., 1990; Bowell et al., 1990) in metavolcano-sedimentary sequences, referred to as the Ashanti type (Oberthür et al., 1994; Yao and Robb, 2000) are recognised within the Ashanti deposit and environs. Also, some granitoid intrusions are found to host gold deposits (Yao and Robb, 2000).

The structural setting of gold mineralisation of the Ashanti Belt conforms to the general regional structure of southwestern Ghana. It generally strike northeast-and dip steeply (75--85°) to the northwest (Bowell et al., 1990; Alliborne., 2002). The main ore-bearing shear zones within the Obuasi Mine concession form part of the about 260 km-long NNE-trending shear zone, considered as a major trans-crustal dislocation (Bowell et al., 1990). The shear zones as observed in the underground mine are characteristically associated with carbonaceous schist.

The shear structure acted as ore solution channels persistent both laterally and vertically to about 1700 metres below the surface in the northern section of the mine (Bowell et al., 1990; Eisenlohr and Hirdes, 1992; Oberthür et al., 1998). It is generally lenticular in shape both horizontally and vertically, strikes generally NE – SW and dips steeply to the west between 75 – 85º (Yao and Robb, 2000; Alliborne., 2002). Several authors have published analyses of the structural controls on gold mineralisation of the Obuasi deposit (e.g., Eisenlohr and Hirdes, 1992; Blenkinsop et al., 1994); Oberthür et al., 1996, 1998; Alliborne et al., 2002). They all suggest, based on exposures of shears/veins in underground developments, of pinch and swell structures controlling gold mineralisation,

The QVT gold occurs with carbonate vein-filling along with fractures in the quartz veins. This ore type previously formed the major orebodies within the mine and was reported to contain some exceptionally high gold grades (Oberthur et al., 1994; Alliborne et al., 2002) some of which was free-milling (Oberthür et al., 1994). The DST forms the sulphide lodes. They host refractory gold, lodged in variable disseminated arsenopyrite and pyrite grains (Oberthür et al., 1994). Due to largely reduced availability of the QVT ores, DST ores have increased in their relative economic importance within the mine in the past few decades. Petrographic, geochemical, and fluid evolution investigations of the Obuasi gold deposit by Bowell et al., (1990); Manu, (1991); Oberthür et al., (1996); Schwartz et al., (1992); Mücke and Dzigbodi-Adjimah, (1994); (Mumin et al., (1994), and Mumin and Fleet, (1995) stated the ore mineralogy comprises pyrite, arsenopyrite, galena, pyrrhotite, marcasite, chalcopyrite, and rare micro grains of native gold.

# MATERIALS AND METHODS

## Data acquisition and processing

The data is generated from the main Obuasi gold deposit lithological setting of proven geological continuity and limits defined in Table 1.

**Table 1 Limits of boundaries of data obtained for the study**

| Parameter | Boundary limits |
|---|---|
| Eastings | 14600 – 15200 |
| Northings | 10600 – 11000 |
| Elevation | (-675.03) – (-932.83) * |

**The negative sign (-) reflects elevations, where the ground level is the reference point*

The data consists of diamond drill (DD) core and sidewall channel samples from stopes and cross-cuts faces. Single channels of about 5 cm to 8 cm wide and about 3 cm deep were cut across the rock face at orientations apparently perpendicular to geology. No grab sample data from stockpiles nor trump tracks were incorporated into the data sets for statistical and geostatistical analyses. Drilling was done from development inclines and working faces at varied inclinations and azimuths to depths of about 120 m, using the LTK46 and BQ rigs with core diameters of 35.6 and 36.5 mm, respectively. Occasionally, multiples holes are drilled from one location. All boreholes were surveyed at an average depth of 15 m, and at end-of-hole (EOH) using an Eastman single-shot camera. In all, 507 borehole cores were sampled at intervals of 1.0 m, from which a total of 114,488 samples were obtained and assayed by AAS method for gold (Au) at the AGA Laboratories. The entire shear/ mineralised zones and at least 1-3 m outside this zone were sampled. Individual sample lengths were selected based on lithological boundaries and mineralisation style. Also, 7,667 channel samples were collected and assayed for Au. The channel sampling covered a strike length of 375 m. Summary statistics of the sample data are presented in Table 2.

**Table 2 Summary of sample data statistics**

| Data | No. of samples | Minimum (g/t) | Maximum (g/t) | Mean (g/t) | Variance (g/t)2 | Coefficient of variation |
|---|---|---|---|---|---|---|
| DD core | 14488 | 0.01 | 144.70 | 2.89 | 34.22 | 1.92 |
| Channel | 7667 | 0.01 | 289.6 | 5.57 | 31.81 | 1.24 |

*(A factor was applied to the original assay data to preserve confidentiality)*

To create section plots and orebody models, the initial data organization required the production of three main separate ASCII files, namely COLLAR, ASSAY and SURVEY containing information on borehole collar co-ordinates, logged rock type of the particular sample, and downhole orientation survey into a database using the ADHOLE system of the datamine software. The channel sample data set was stored as XCUT file which contains information on channel sample assays, reference peg coordinates of the start of the channel sampling line (CSL) and lithology.

The development of string file and the peg coordinate file of the CSLs were used to obtain CSL profiles as pseudo boreholes. ASCII output files from the dbase data entry system were imported into the DATAMINE system. To enable the extraction of sections and plans for geological interpretation and digitisation of ore outlines, three-dimensional (3-D) borehole and channel samples were generated within the block. This was done by, merging the assay, collar, geology and survey files into one single file referred to as the 'de-surveyed' file.

## Geological interpretation and digitisation of ore boundaries

To facilitate orebody modelling, ore grade boundaries were digitised. Underground level plans and interpreted geological sections were generated using a combination of crosscut, reef drive and borehole data. Interpretation based mainly on grade was hand performed on the level plans and vertical section plots and envelopes of economic mineralisation digitized using the AUTOCAD software and imported into DATAMINE as perimeter string files. Perimeters formed by envelopes served as the basis for selecting assayed gold values for statistical and geostatistical analyses. The volume enveloped by the zones of mineralisation considered for statistical and geostatistical analyses were constrained between coordinates shown in Table 3.

**Table 3 Limit of ore demarcated in Block 1**

| Coordinate | Minimum | Maximum |
|---|---|---|
| Eastings | 14650 | 15175 |
| Northings | 10700 | 10950 |
| Elevation | (-714.58) | (-900.50) * |

**The negative sign (-) reflects elevations, where the ground level is the reference point*

## Statistical treatment of data

### *Combination of DD and Channel samples*

A relationship exists between a sample's volume and shapes referred to as 'support' and the statistical distribution of the samples; 'support' is defined as the geostatistical term for the physical ore parcel, which supports the ore grade being studied as a variable (Isaaks and Srivastava, 1989; Al-Hassan and Annels, 1994). The variance, frequency and other statistical parameters of grade are affected by changes in the 'support'. To combine the core and channel samples for statistical and geostatistical analyses, both datasets must belong to statistically similar populations (Al-Hassan and Annels, 1994). In this study, the combination verification assessment the sample types were done using the F – and t-tests, as suggested by Al-Hassan and Annels (1994) and Al-Hassan (2002). Having shown that both datasets are indistinguishable, they were combined for frequency distribution analyses, before calculating variograms.

### *Frequency Distribution*

To characterize the spread and statistical distribution of data values, univariate statistics, histograms and probability plots were constructed as shown in Fig. 2.

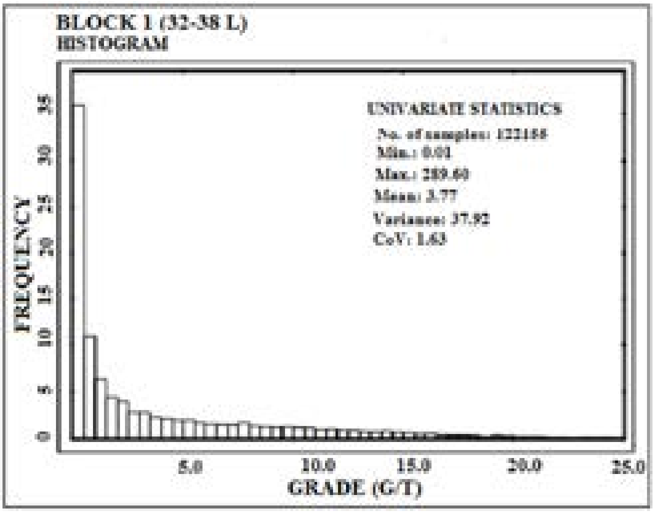


**Fig. 2 Histogram of the gold grades of the combined diamond DD core and X-cut samples**

After a lower truncation of the very low-grade values (< 0.6 g/t) and log-transforming the sample grades, the log-transformed va1ues approximated to a normal distribution, (i.e. the log values plotted on a log probability graph as a straight line). The data was therefore used further, to produce semi-variograms. Summary statistics of combined samples are shown in Table 4.

**Table 4 Summary Statistics for combined samples (DD and channel)**

| Description | No. of Samples | Min. (g/t) | Max. (g/t) | Mean (g/t) | Variance $(g/t)^2$ | Coef. of variation |
|---|---|---|---|---|---|---|
| Combined samples | 122155 | 0.01 | 289.60 | 3.77 | 37.92 | 1.63 |

## Variogram calculations and analysis

Variography is the process of calculating experimental variograms that can fit an appropriate model (Guibal, 2001). The determination of an appropriate and acceptable model that depicts geological characteristics and spatial correlation of mineralisation is referred to as structural modelling (Marinoni, 2003). Variogram models were constructed using the VARIO processes of DATAMINE in the strike-plunge, across-strike and down-dip directions. The 3D structure of the gold deposit was investigated by calculating Omni-directional and the three principal directions. Several experimented lag spaces, the most reliable one was found to be 15 m and correspond with the crosscut channel sample spacing along strike in the mine. Spherical models as used by Journel and Huijbregts (1978), were fitted to the sample semivariograms in all cases.

## Determination of optimal drilling/sampling density

Various criteria may be used to define for optimum drilling densities (ODD) (Bertoli et al., 2013; Verly et al., 2014). In this study, ODD was defined as the minimum amount of drilling or sampling interval in which samples are auto-correlated that can be used to determine accurate reserve estimation for the particular ore deposit. ODD for the deposit under study was determined based on parameters calculated from variogram models.

Parameters that quantify the variability of mineralisation are the range, ***a***, and the nugget effect, $C_0$ derived from variogram models (Isaaks and Srivastava, 1989; Humphreys and Shrivastava, 1996). They provide a rational basis for sampling pattern design. The models adopted for the Obuasi deposit is given in Table 5. Some researchers suggest that optimal sample spacing should not exceed 80 % of the range of influence of samples (e.g., Sarkar et al., 1988).

**Table 5 Parameters for Gold Value Semi-variogram models**

| Direction | $C_0$ (g/t)$^2$ | $C_1$ (g/t)$^2$ | $C_2$ g(/t)$^2$ | $a_1$ (m) | $a_2$ (m) | Sill g(/t)$^2$ |
|---|---|---|---|---|---|---|
| Directionless | 3.7 | 20.6 | 8.4 | 11.1 | 48.0 | 32.7 |
| Across Strike | 3.7 | 19.6 | 25.2 | 3.7 | 7.9 | 48.5 |
| Along Strike | 3.7 | 16.0 | 12.8 | 16.1 | 49.1 | 32.5 |
| Down Dip | 3.7 | 16.8 | 11.7 | 27.5 | 42.5 | 32.2 |

$C_0$ = nugget variance, $C_1$ and $C_2$ = spatial variance of first and second structure respectively.

# RESULTS

## Sample data distribution analysis

From the histogram of the grades (Fig. 2), the frequency distribution model shows it is positively skewed, which is typical of gold grades and other precious metals (Krige, 1993), where, the grade value increases with fewer numbers of samples. The coefficient of variation (CoV) is 1.63 (Table 4), higher than what is expected for a normal distribution (i.e. must be less than 0.5) as noted by Kock and Link (1970). The variance associated with the distribution is 37.92 (g/t)$^2$ (Table 4). Plots of logarithms and cumulative probability graphs of gold grades of the combined data are shown in Fig. 3.

Inspection of the log-histogram plot (Fig. 3A) shows a polymodal global distribution of the grades. This is probably due to the combination of the two main types of mineralisation (i.e., the QVT and DST) of the Obuasi deposit. The cumulative log-probability plot (Fig 3B) of the grades indicates it is possible to fit at least four straight lines to the data points possibly indicating the presence of four populations distinguished by a threshold value between 0.01 and 0.1 g/t, 0.1 and 10.0 g/t, 10.0 and 40.0 g/t. The population below about 0.1 to 0.6 g/t g/t represents the 'unmineralised' or background population, while, values beyond about 40.0 g/t can be considered as extreme values or outliers. Generally, there is no natural break in the assay value trends that relate to the choice of an economic cut-off of 3.43g/t that is currently being used by AGA in their resource evaluation. The cut-off of 3.43 g/t is probably presumed by the company to be the grade at which the deposit has the potential for economic benefit.

## Variography of assay values

The experimental variograms for the Omni-directional, across-strike, along strike, down dip appeared to depict two structures. They were fitted with two-structure spherical models (Figs. 4, 5, 6, 7 and 8). The parameters of the spherical models fitted to the gold variograms are given in Table 4. The forms of the experimental semi-variograms were fitted with a two-structure spherical model, which shows a discontinuous nature, where γ(h) does not become zero as h tends to zero. Down dip direction was taken as 81º corresponding to the general dip of the block.

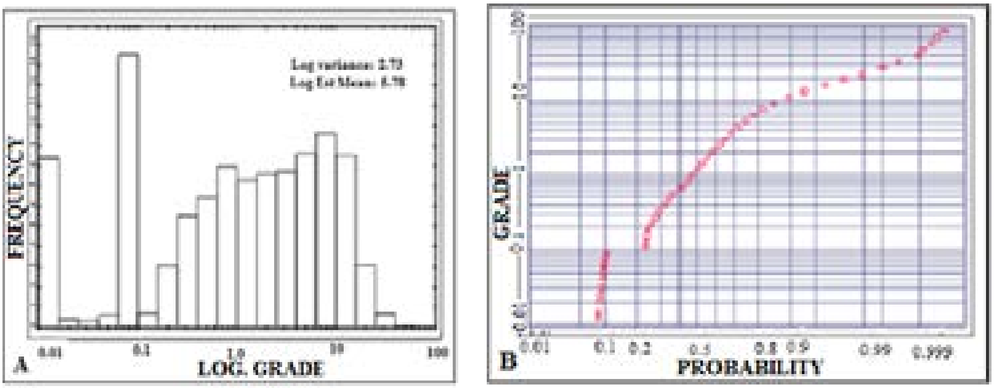


**Fig. 3 Statistics for combined data sets: (A) Log histogram; (B) Cumulative probability plot**

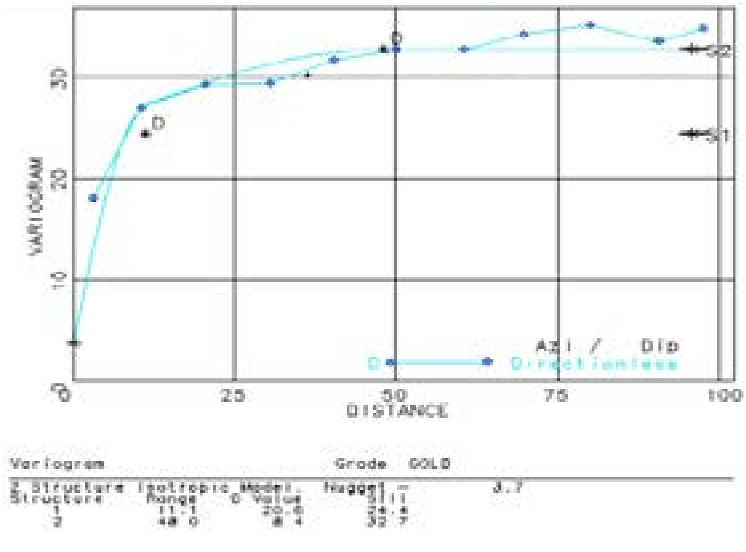


**Fig. 4: The two-structure spherical model fitted to Omni-directional experimental semi-variogram fitted Au grades for the deposit**

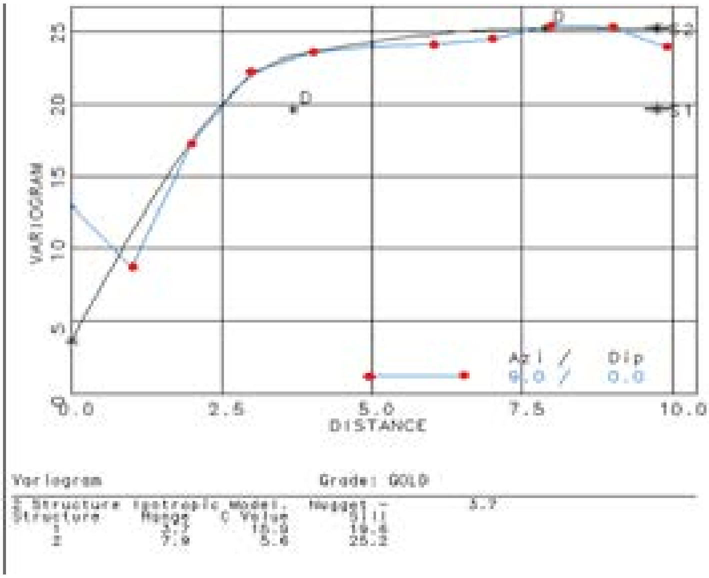


**Fig. 5 Semi-variogram of Au values in the across strike direction**

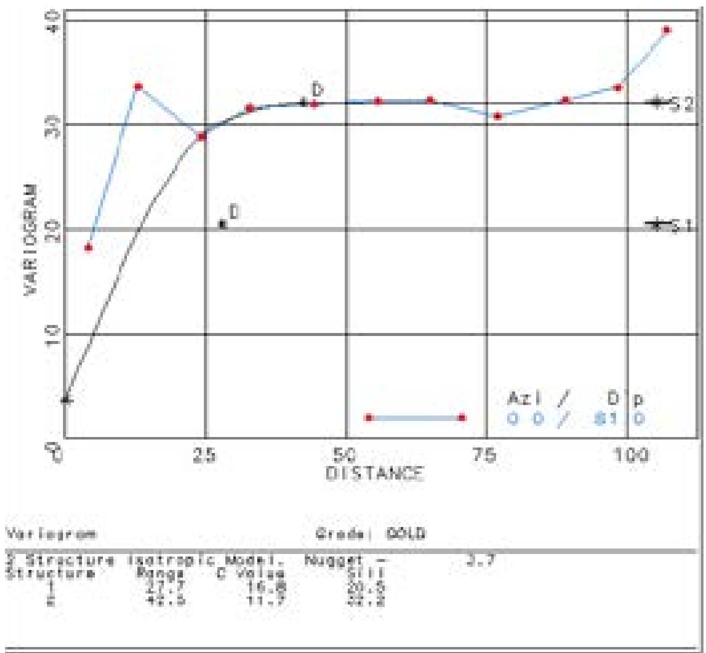


**Fig. 6 Semi-variogram of Au values in the along-strike direction**

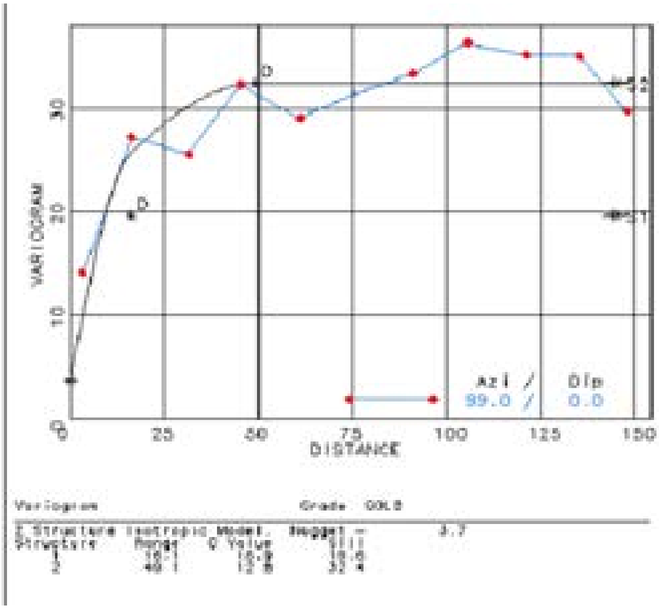


**Fig. 7 Semi-variogram of Au values in the down-dip direction**

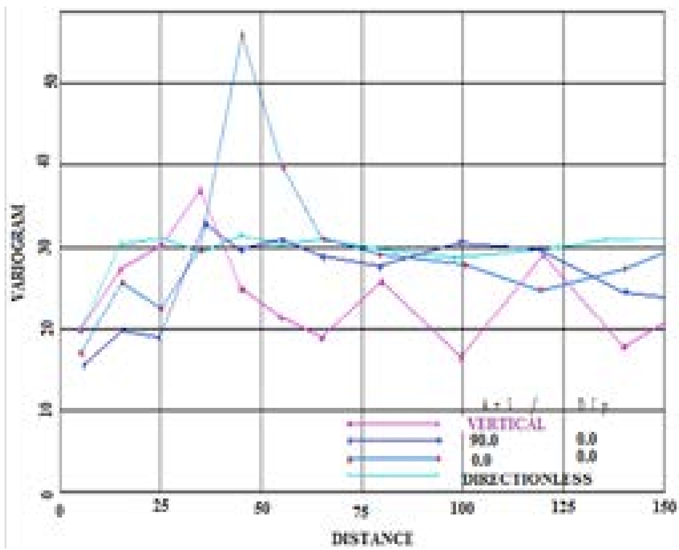


**Fig. 8: Semi-variograms of Au values to the Omni-directional experimental variogram, in the across strike, the along strike and down dip directions**

The general equation for this nested model (Journel and Huijbregts1978) is:

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

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

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

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.

The nugget variance (or nugget effect) $C_0$ is expressed as $\gamma(0) = C_0$. $C_0$ represents the random portion of the variability of the regionalised variable, i. e the variogram value γ(h) at a distance of zero (i.e. when '*h*' equal to zero). It is partly a measure of the variability between samples at, or very close to zero distance apart and partly the presence of sampling errors. The parameters of the fitted spherical models are presented in Table 5.

**Table 5 Parameters for Au value semi-variogram models**

| Direction | $C_0$ (g/t)$^2$ | $C_1$ (g/t)$^2$ | $C_2$ g(/t)$^2$ | $a_1$ (m) | $a_2$ (m) | Sill g(/t)$^2$ |
|---|---|---|---|---|---|---|
| Directionless | 3.7 | 20.6 | 8.4 | 11.1 | 48.0 | 32.7 |
| Across strike | 3.7 | 19.6 | 25.2 | 3.7 | 7.9 | 48.5 |
| Along strike | 3.7 | 16.0 | 12.8 | 16.1 | 49.1 | 32.5 |
| Down dip | 3.7 | 16.8 | 11.7 | 27.5 | 42.5 | 32.2 |

Variograms for the different directions demonstrate similar spatial structure and variance proportions. As expected, experimental variography revealed the structured direction of maximum continuity plunging about 81° toward the south-east, which corresponds to the geological controls of mineralisation. The variogram displaying the longest range is the down-dip direction and shortest range is the across strike. Along strike of the deposit is about 11.0 m.

## Optimum drilling interval

The optimum drilling or sampling interval for the deposit in the across-strike (sections perpendicular to strike of orebodies) is 30 m (i.e. taking into consideration the maximum influence of samples as suggested by Sarkar et al. (1988)), and 30 to 50 m in the down-dip direction. Adjustments can be made when necessary to detail certain geological structures affecting the continuity of the mineralisation, such as dykes and faults.

# DISCUSSIONS

## Constraints from sample data distribution and assay values

The histogram of Au values of the deposit is highly-skewed (Fig. 2). Log histogram and cumulative plots indicate the presence of at least 3 populations distinguished by a threshold value between 0.01 and 0.1 g/t, 0.1 and 10.0 g/t, 10.0 and 40.0 g/t. A background gold mineralisation of below to 0.6 g/t and a threshold grade of about 40.0 g/t represent outliers. The current cut-off of 3.43g/t is probably based on other mining cost factors and appears not to be based on a statistical analysis of assay values, as 'mineralised' grades could be ≥ 0.6 g/t as suggested by Matschullat et al. (2002) and Owusu (2002). The practical significance of grade distribution is in the choice of an estimation method (Annels, 1991) since the accuracy of recoverable estimation is influenced by the method used (Annels, 1991). Also, grade distribution determines whether the estimation methods are to be parametric or non-parametric (Issaks and Srivsatava, 1989).

## Variogram models for spatial structure and variance of the data

Geostatistical structural model parameters such as nugget effect, ranges and anisotropy axes dictate sample design patterns. Spatial variability of grades is characterized by the fitting of appropriate variogram models in the three principal directions of the deposit. As a case of study, the study area is a well-informed domain of gold deposit. The sample data was adequate for the calculation of variogram models, which defined the nugget $C_0$ as 3.7 $(g/t)^2$, and ranges from 3.7, 16.1 to 27.5 in the across-strike, along strike, and down-dip directions, respectively. The presence of the $C_0$ is an indication of a lack of local homogeneity, resulting from small-scale natural variations in mineralisation.

It could also be caused by sampling and assaying errors, as well as other human errors in the data processing, as suggested by Annels, (1991). It is important that, documents on sampling and assaying protocols at the Obuasi Mine be periodically reviewed and revised. This would reduce errors inherent in some sampling practices, which in turn would ensure that modelled spatial structure reflect only real features of mineralization of the deposit. $C$ is the spatial variance and denotes the remaining variance of the sample data, which is the spatial component of the mineralisation. The presence of two spatial variances, $C_1$ and $C_2$ is an indication of a nested structure (Issaks and Srivsatava, 1989; Barnes, 1991; Sinclair and Blackwell, 2002). $C_1$ and $C_2$ represents initial and second structure respectively. Sinclair and Blackwell, (2002) attributes nested structures to the presence of more than one underlying structures in the data set. In this study, nested structures for the spatial variation exhibited in the variograms, are probably due to secondary properties and characteristics of the host rocks of the Obuasi deposit, such as intensity of mineralization, quartz veining and degree of alteration. $C+C_0$ represents the sill, a constant value of the semi-variogram model, which occurs beyond the range and is used to estimate the population variance (Barnes, 1991; Sinclair and Blackwell, 2002). At this value, the variance no longer increases with increase in the lag distance, $h$. It effectively becomes constant.

The short-range (in the across strike), and long-range (down-dip) are indications of an anisotropic characteristic identifiable with various geospatial datasets resulting from geological phenomena (Goovaerts, 1997). The short-range corresponds to the thickness of the orebody. The long-range in the down-dip direction reflects the greater global continuity of the mixed vein and disseminated sulphide ores. The Obuasi deposit is a typical orogenic shear-hosted gold deposit (Leube et al., 1990; Alliborne et al., 2002). The orebodies are characterised by long lateral extent (along strike), long vertical extent (down dip), and relatively short thickness. The differences in variogram parameters demonstrate the anisotropy exhibited in gold grades. Implications are that, sampling patterns should be based on spatial behavior of mineralization. For the Obuasi deposit, the range in the across strike (thickness of orebody) is 3.7 m, along strike of 16.1 m, and down-dip is 27.5 m. The optimal sidewall channel sampling interval should be about 3.5 m, and drill hole spacing for the down-dip and sections perpendicular to the strike of the deposit should be 27.5 m and 16.0 m respectively. Sampling interval, sampling density or drilling interval less than the range values, would have no significant improvement in the accuracy and precision of estimation of tonnage and grade even though there might be an increase in the sampling costs.

## CONCLUSIONS

The study established that the distribution of the gold grades from the Obuasi Mine is positively skewed with high variability and extreme values. Background gold values for this study, without any parameters of mining operations, was established as < 0.6 g/t. It has been demonstrated that geostatistical analysis is a useful way to determine the architecture of gold mineralisation at the deposit scale. Spatial variability is adequately characterized by fitting models on experimental variograms. The current channel sampling interval of 1 to 1.5 m across strike (used in crosscut and reef drives) and 30 m drill hole spacing for the down-dip is adequate and could be maintained unless it becomes necessary to detail certain geological structures (e.g., dykes, faults, among others) affecting the continuity of the mineralisation, when there may be reduced. Drill hole spacing in sections perpendicular to the strike of the deposit should be between 30 and 50 m, depending on the size, complexity of mineralization and structure of the orebody.

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