Enhance South Deep variography by including flat inclined boreholes in the local direct estimation methodology

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This report is submitted to the faculty of Engineering and Built environment, University of Witwatersrand, Johannesburg. In partial fulfilment of the requirements for the degree of Master of Science in Mining Engineering.

25 -05- 2018

DECLARATION

I declare that this report is my own unaided work. This work was done on behalf of Goldfields Ltd. It has not been submitted before for any other degree or examination or any other University.

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Tyson Mutobvu

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ABSTRACT

The research project presented relates to the Mineral Resource evaluation of South Deep Gold Mine in Westonaria, South Africa. The aim of the project is to establish the impact of the inclusion of the samples from flatly inclined boreholes (FIBs) in the variography and Mineral Resource estimation of the individual Elsburg top conglomerate reef (ECT). The samples from FIB boreholes are traditionally excluded from the estimation process to reduce the possibility of smearing grade as stated in the Mine's Code of Practice. These are boreholes with a dip of greater than -55° or less than 55°. These boreholes provide the highest resolution into the orebody and thus the highest level of de-risking of the orebody and are therefore used for geological modelling. Although the addition of the samples from FIBs in brings a substantial increase in the number of samples in some geostatistical domains they do not introduce outliers. Adding the FIBs resulted in improved variogram models. Simple Kriging models considered are one using the Au (g/t) samples from the steeply inclined holes only and the other using the combined dataset. These Kriging models were post-processed through Local Direct Conditioning (LDC) and the results were compared. Reconciliation indicates that the model remains stable with 1% change at Mineral Resource and Mineral Reserve cut-off of 3.2g/t Au following the addition of Au (g/t) samples from FIBs in the mineral resource estimation. It is therefore concluded that adding the flatly inclined boreholes in the mineral resource estimation increases the confidence in Kriging and improves variogram models.

ACKNOWLEDGEMENTS

I would like to thank the following:

Goldfields Ltd for granting me a permission to use the data and the relevant software required for this research project,

Prof Christina Dohm (University of Witwatersrand) for supervision, continuous training and guidance and challenges,

Mr Daniel Kock for continuous and eye-opening discussions and support on Geostatistics,

Mrs Yegeshni Naidoo for the endless proof reading and Geostatistical discussions,

Miss Brenda Phaahla for allowing me to stay away on weekends while working on this project,

My parents for the encouragement, support and belief in me,

Mr Antonio Umpire for the informal Geostatistical discussions,

Mr Masala Mulaudzi for technical support and

The Technical Services department at South Deep Gold Mine.

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1 INTRODUCTION

The research project presented in this report pertains to South Deep Gold Mine. South Deep is situated in the district of Westonaria (Gauteng Province), some 45 km southwest of Johannesburg at latitude 26º 25'S and longitude 27º 40'E. It is accessed via the R28 provincial road between Westonaria and Vereeniging and is located in the major gold mining region of South Africa, the Witwatersrand Basin, see Figure1. In the West Rand area four primary reefs are exploited, the VCR located at the top of the Central Rand Group, the Carbon Leader Reef (CLR) near the base, the Middelvlei Reef (MVR) which occurs stratigraphically some 50m to 75m above the CLR and the stacked Upper Elsburg Reefs (UER) which sub-outcrop directly below the VCR as seen at South Deep Mine. The mine has been established to exploit the Ventersdorp Contact Reef (VCR), and the Upper and Lower Elsburg reefs.

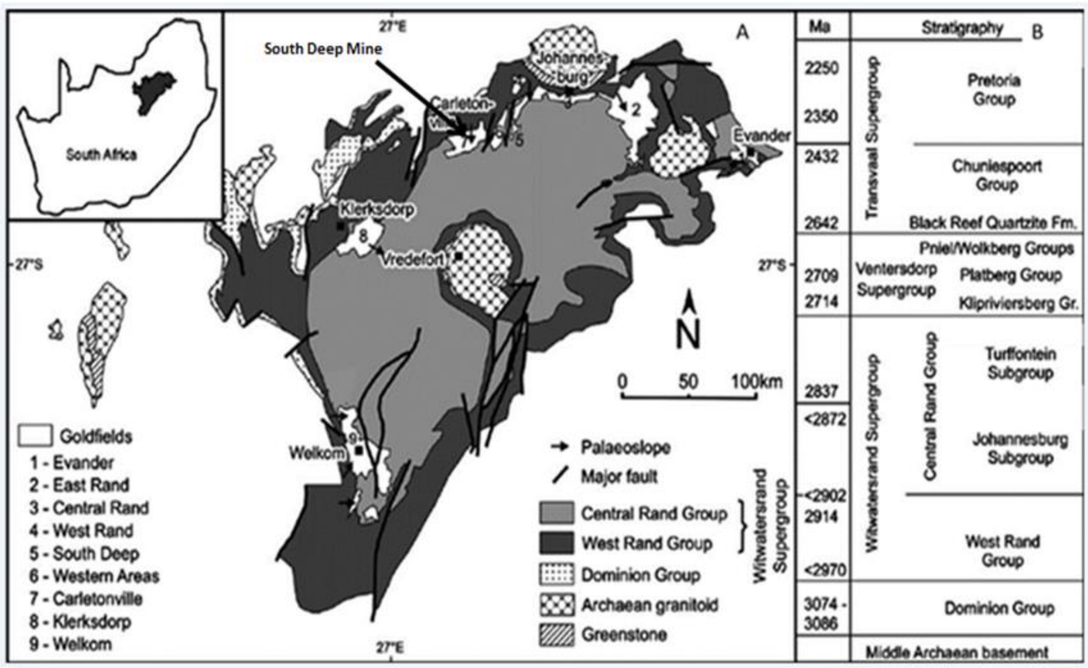

Figure 1 Map highlighting the project locality with respect to the geology and major towns. (Koglin, N., Zeh, A., Frimmel, H. E. & Gerdes, A., 2010)

In this research, the inclusion of Flatly Inclined Boreholes (FIBs) in the South Deep dataset, to be used for the resource estimation applied is investigated. The estimation methodology is based on geostatistics and the research is concentrated on the ECT reef of the Upper Elsburg Individuals. The ECT is the Individual Elsburg top band conglomerate.

The aim is to establish the impact of the FIB samples on the variography and consequently the Mineral Resource estimation results of the ECT reef. The estimation methodology at South Deep is simple kriging using Datamine® Studio and Minesoft® software packages. The Kriging models are post processed using local direct conditioning (LDC). The estimation is done within the geological model that has been constructed from borehole logs and an underground mapping database.

2 GEOLOGICAL BACKGROUND

2.1. Regional Geology

South Deep Mine is in the Witwatersrand Basin. The Witwatersrand Basin comprises a 60km vertical thickness of argillaceous and arenaceous sedimentary rocks situated within the Kaapvaal Craton, extending laterally for some 300km east-northeast and 150km south-southeast. The sedimentary rocks generally dip at shallow angles towards the centre of the basin, although this may vary locally. The Basin sediments crop out to the south of Johannesburg, but further to the west, south and east these are overlain by up to 4km of Archaean, Proterozoic and Mesozoic volcanic and sedimentary rocks. The Witwatersrand Basin sediments themselves are between 2,700 and 3,100 million years old. (Robb and Meyer, 1995)

The Lease Area is underlain by outliers of Karoo Supergroup shales and sandstones followed by the Pretoria Group sediments and the Chuniespoort Group dolomites. The Chuniespoort Group overlies the Klipriviersberg Group volcanic rocks, which in turn are underlain by the Central Rand Group that hosts the gold-bearing conglomerates (reefs), exploited by South Deep. (Goldfields, 2010)

Gold mineralisation in the Witwatersrand Basin occurs within quartz pebble conglomerate reefs. These reefs occur within seven separate goldfields located along the eastern and northern margins of the Basin. These goldfields are known as the Evander, East Rand, Central Rand, West Rand, Far West Rand, Klerksdorp and Free State Goldfields. Typically, within each goldfield, there are one or sometimes two major reef units present, which may be overlain by one or more secondary reef units. As a result of faulting and other primary controls on mineralization, the goldfields are not continuous and are characterised by the presence or dominance of different reef units. The reefs are generally less than 2m in thickness and are widely considered to represent laterally extensive braided fluvial deposits or unconfined flow deposits, which formed along the flanks of alluvial fan systems that developed around the edge of what was effectively an inland sea. (Pretorius, 1989)

All major reef units are developed above unconformity surfaces. The effect of the unconformities is typically greatest near the basin margin and decreases toward more distal areas. Complex patterns of syn-depositional faulting have caused complex variations in sediment thickness within the basin. Sub-vertical to over-folded reef structures is a characteristic of basin margin features within certain areas. (Goldfields, 2010)

Most early theories believed the gold to be deposited syngenetically with the conglomerates, but subsequent research has confirmed that metamorphism within the Witwatersrand Basin has caused some post depositional redistribution of gold. Other experts regard the gold to be totally epigenetic and to have been deposited solely by hydrothermal fluids sometime after deposition of the reef sediments. (Pretorius, 1989)

Despite these varied viewpoints, the most fundamental control to the gold distribution remains the association with quartz-pebble conglomerates on intra-basinal unconformities. The reefs are extremely continuous, as a consequence of the regional nature of the erosional surfaces. Bedrock (footwall) controls have been established governing the distribution of many of the reefs. Preferential reef development within channel systems and sedimentary features such as facies variations and channel frequency assist in mapping out local gold distributions. In all cases the grade of the ore bodies varies above and below the pay limit. Consequently, the identification and modelling of erosional/sedimentary features is the key to in-situ Resource estimation. (Goldfields, 2010)

2.2. Local Geology

The local geology of South Deep mine is summarised as described in various Goldfields reports (Goldfields Ltd 2010, 2012 & 2015). The West Rand/Panvlakte/Waterpan horst block is situated between the Kloof and South

Deep Gold Mines and regionally demarcates the western boundary of South Deep. A series of dykes also straddle the mine lease, and are roughly north-south oriented, and can attain thicknesses of up to 35 metres. Ventersdorp, Bushveld and Pilanesberg age structures are present in the West Rand Goldfield. Ventersdorp age structures generally strike in a NE-SW direction and have normal throws of less than 20m down to the NW. A conjugate set of Ventersdorp age structures may occur with a NW-SE strike and similar throws, but these are less well developed than the NE-SW trending features. Bushveld age structures strike in a W-E direction and have throws of 50-150m down to the north. These structures commonly also display wrench movements. Pilanesberg age structures have an N-S strike and are usually filled with diabase intrusives. The Central Rand Group in the West Rand Gold Field comprises some 2,000m of discrete sedimentary sequences deposited over successive unconformity surfaces in an expanding depositional basin. The conglomeratic reef units are most commonly deposited at the base of each depositional sequence, although channels may also occur as scours within a given formation. The occurrence of faulting and minor folding of Central Rand Group age has led to the conclusion that subtle tectonic warping of the basin with granite doming and subsequent normal block faulting on the margins, controlled deposition. (Robb and Meyer, 1995).

The stratigraphic thickness between the VCR and CLR increases west to east from 900m to over 1,300m, as a result of the relative angle of the VCR unconformity surface to the regional stratigraphic strike and dip. The CLR strikes ENE-WSW and dips to the south at 25°. The VCR strikes NE-SW and has a regional dip of 21° to the SE. Local variations in dip are largely due to the terrace and slope palaeotopographic surface developed during VCR deposition. The UERs strike E-W and dip to the south at 12°. The conglomerate units within the UER's and VCR are mined at South Deep Mine, whilst the CLR and MVR are not.

The VCR represents the final phase of sedimentation prior to the extrusion of the lavas of the Klipriviersberg Group and unconformably overly the UER's and the underlying strata. The VCR structure facies model was introduced for the VCR in

December 2007, it was aimed at more accurately 3D evaluation and a more efficient mine design and scheduling. VCR sedimentation is independent from that of the UER's and is characterised by quartzite dominated facies types. Two facies types are recognised with Sandy 1 defined as always having a basal conglomerate developed whereas the Sandy 2 type is predominantly of quartzite. These facies types tie in well with the younger peneplain facies identified in the distal areas of Kloof. By implication the Sandy 1 facies are considered as economically viable mining targets. (Goldfields, 2010)

The Upper Elsburgs represents a broad upward coarsening cycle of conglomerates and interbedded quartzites within which several smaller upward fining cycles occur. The discrete stratigraphic units of which currently 16 are described, are the products of these smaller upward fining cycles. The Upper Elsburg Reefs are made up of the Upper Elsburg Individuals (Waterpan Member) and the Upper Elsburg Massives (Modderfontein Member). The Upper Elsburg Individuals or EC/ED unit consists of four well defined conglomeratic units, separated vertically from each other by more poorly developed conglomeratic zones and immature quartz wackes. The reefs themselves exhibit widely varying lateral facies changes. The names of the reefs occurring within the EC unit are from bottom up the EC Basal Band (ECBA), the EC Bottom Band (ECB), the EC Middle Band (ECM) and the EC Top Band (ECT). The EC unit is separated from the overlying Upper Elsburg Massives (Modderfontein Member) by a well-defined quartz wacke known as the ED unit. (Goldfields, 2010)

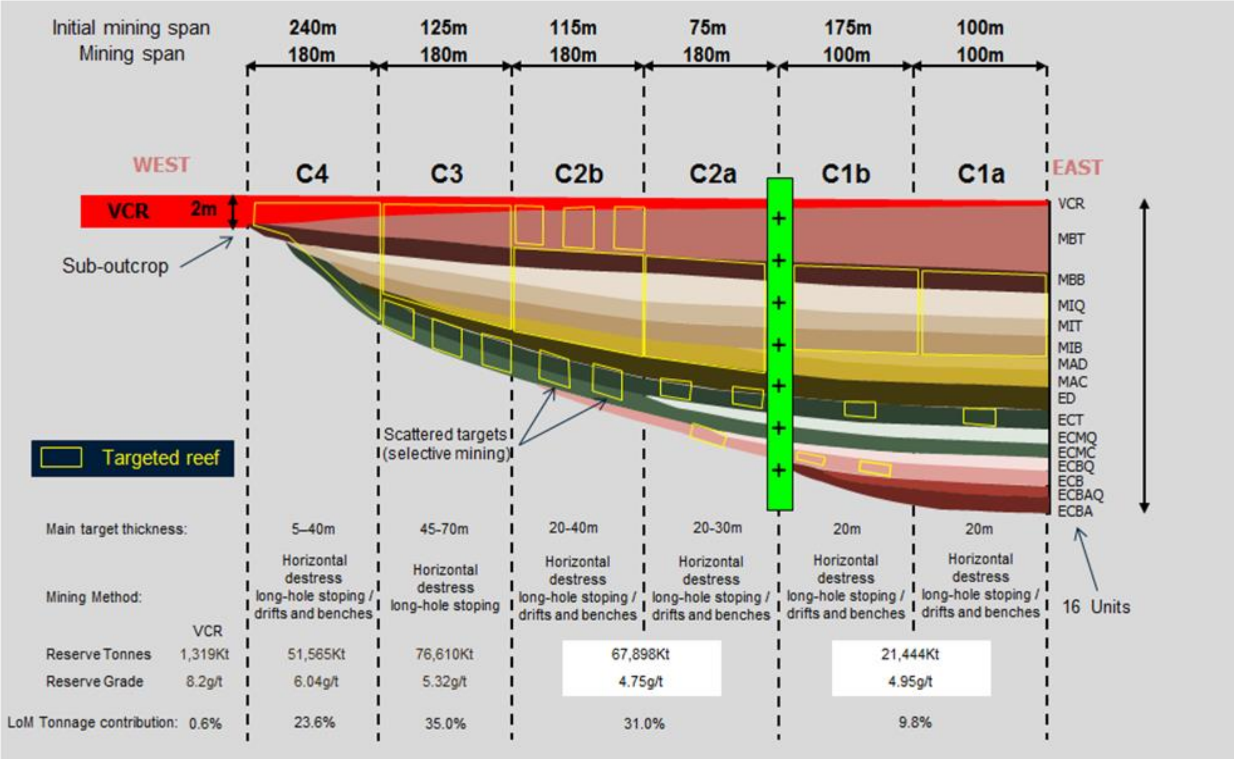

Figure 2 Section showing the geological West-East section linked with the mining method

The Upper Elsburg Massive Reefs also consist of four conglomeratic packages with widely varying lateral facies definitions. The reefs making up the Upper Elsburg Massives, from bottom to top are: the Modderfontein A Conglomerate (MAC), the Modderfontein Intermediate Bottom Band (MIB), the Modderfontein Intermediate Top Band (MIT) and the Modderfontein B Bottom Band (MBB). At the sub-outcrop line, the Upper Elsburg reef package attains a thickness of 0m, while in the east along the mine lease boundary; the total package maintains a constant thickness of 130m. The overall morphology and stratigraphic subdivision of the Upper Elsburg reef package is shown in Figure 2.

3 RESEARCH PROJECT BACKGROUND

The Mineral Resource estimation at South Deep Mine excludes flat inclined boreholes (FIB) from underground. The FIB are the boreholes with a dip of greater than -55° or less than 55^o. These FIB boreholes are traditionally excluded from the estimation process to reduce the possibility of smearing grade as stated in the Mine Code of Practice. At South Deep the FIBs are drilled for the purpose of gathering geological data to be used in the geological modelling. A quarterly dynamic geological model is built based on all information available such as mapping and borehole data.

The grade control grid that South Deep attempts to achieve is 30m x 30m spacing. The geological information of grade control data is generally used for facies determination, structural definition, stratigraphic modelling and the assay data from it for Mineral Resource estimation. This drilling strategy provides the highest resolution of information into the orebody and the highest level of de-risking the orebody. The boreholes in the 30m x 30m grade control drilling grid, are planned at a dip angle of 55^0 or greater (i.e. steep holes), to ensure intersection with the reef at 45^0, the results of this drilling are used for geological and Mineral Resource modelling.

Due to a lack of drilling platforms, geologists also attempt to collect data as far ahead of the face as practically possible by drilling flatter holes to de-risk the geological model. All the boreholes drilled at South Deep mine are assayed, amounting to a significant cost. However, due to the flatness of the angle, the FIB assay data is excluded from the Mineral Resource estimation process, it is perceived that these assays could introduce a bias in the database. A large part of this research project will focus on variography and grade estimation using the full dataset including the data from FIB in the estimation of EC Top Band (ECT) and Modderfontein Intermediate Top Band (MIT) of the Upper Elsburg reefs at South Deep mine.

3.1 Research Objectives

The focus and objective of this research project has been to assess whether including the flatter boreholes in the resource modelling could improve the Mineral Resource estimation confidence at South Deep.

In this research project, the fundamental concepts and processes in place at South Deep Mine from geological drilling, grade modelling, variography, to the geostatistical estimation processes such as kriging and Local direct conditioning estimation, have been reviewed and are applied in the estimation that follows.

3.2 Key Questions addressed by this research

Can the information from boreholes with a dip greater -55^0 or less than 55^0 be incorporated in the Mineral Resource estimation and evaluation process at South Deep Mine?

Is there a realistic method of introducing the flat inclined composites into the resource data base?

Are these composites comparable to the conventional composite samples? Is the spatial correlation of FIBs similar to the spatial correlation for the conventional composites? What would be the impact in resource estimation confidence and mine planning if these boreholes are included in the mineral resource estimation and evaluation?

Will this research assist in recovering some of the sunken costs of assaying by using this additional assayed information from the FIBs or would it be recommended that the FIBs only be logged for de-risking the geological model and not assayed, to save the costs but? In other words, is there a proposition of adding value by using the assay information of the FIB holes or is there an opportunity for cost saving by not performing these assays, when only the geological information is used.

4 LITERATURE REVIEW

Robb and Meyer (1995) describe the sedimentation and the cycles of gold mineralisation of the Witwatersrand rand reefs in detail. Providing a perspective on the general geology of the study area and their work has been important for understanding the regional geology relevant to this research and specifically South Deep Mine.

Pretorius, D.A (1989) discusses different theories on the formation of gold mineralisation in the Witwatersrand Basin. This paper gives an insight on the formation of gold which is fundamental to the geological background of this research project.

Magri, E.J (1987) investigated variability patterns within each borehole for a certain reef in order to maximize the level of confidence in the boreholes. This reference provides quantitative guidelines for maximising the number of boreholes and deflections for optimum economic return. The economic return is realised through the information from the deflections from the main borehole irrespective of the angles. It is however recommended that only four intersections per borehole are optimum in the Witwatersrand exploration.

Witley, J and Minnitt, R.C.A (2017) highlight the importance of understanding the representivity of the borehole, obtaining an estimate of the nugget effect**.** It was found that the short deflections improved the level of confidence above that of just using the single mother hole in the estimation process. The case study discussed in their research paper is similar to the problem considered in this research project. In both projects the flat boreholes are added into the dataset for variography analysis.

Dukas, B.A and Morkel, H.C (1983) discusses the technical aspects of different exploration drilling techniques. Since drilling is central to this project, their paper provided fundamental understanding of drilling techniques applied in exploration. The paper further provided insight on the factors that cause deviations and how they can be used to the advantage of different drilling techniques such as non-coring and diamond drilling.

Osburn, K et al (2014) summarised the modelling processes that are currently applied in the development of high-confidence, timeously produced geological models that are essential input for mineral resource estimation at South Deep Mine. The applications from this paper have been used in the geological modelling process of this research project.

Krige, D.G. (1981) provides a brief review of the developments in the application of Geostatistics in ore evaluation, mainly in the South African Gold mines. This paper provided the guidance and insight into understanding of customary practices in this field of resource estimation.

Emery, X and Ortiz, J.M (2005) in their paper discussed the Pitfalls of grade domaining through a case study in which the authors compared the performance of several estimation schemes and demonstrate the use of domains. Then, several conceptual limitations of the grade domaining approach are stressed, in particular the fact that it does not account for the spatial dependency between adjacent domains and for the uncertainty in the domain boundaries. This is relevant to the research project and was considered in the domaining as a supplement to the Goldfields guidelines.

Glacken, I.M. and Snowden, V (2001) provide the overview which gave a good insight in the understanding of the processes followed when doing mineral resource estimation.

Assibey-Bonsu, W. and Krige, D.G. (1999) introduces a direct approach technique for deriving recoverable resources, referred to as localized direct conditioning (LDC), which is designed to correct smoothing effects and also to provide support corrections. This is a post processing technique applied at South Deep.

Assibey-Bonsu, et al (2014) in their paper present an application of the direct approach technique for deriving recoverable resources, referred to as Localized Direct Conditioning (LDC), designed to correct smoothing effects and also provide support corrections for the estimates.

Dohm CE (2016 a and b) provides teachings for understanding the calculations followed in Mineral Resource estimation. The techniques from this author were employed in classical statistics and geostatistics in this project. The formulas used in the calculation of descriptive statistics and Kriging were adopted from these teachings.

5 DATA COLLECTION

5.1 Data Sources

The data for this research incorporates surface boreholes, underground boreholes, underground mapping information which is recorded from the location of geological features in three dimensional (3D) as well as from seismic data interpretation. The gold estimation was undertaken as a 3D estimation exercise, utilizing wireframe volumes of the current geological model. A total of 1694 surface and underground drill holes were available for the project. The entire ore body database is captured in Downhole Logger™ and stored in the Fusion database developed by Datamine®.

5.2 Borehole data

Three types of borehole drilling programs make up the borehole data set at South Deep, namely the grade control, underground long inclined borehole (LIB) from the footwall development and surface drilling programs.

The grade control drilling program aims at achieving a 30m x 30m grid covering a 0 to 2-year mining period ahead of the current working faces. This type of drilling data is generally used for local scale facies determination, structural definition, stratigraphic modelling and the assay results thereof for estimation. This drilling program provides the highest resolution into the orebody and thus the highest level of de-risking of the orebody.

The LIB drilling program attempts to provide information ahead of the face at a 300m grid. These holes are typically flatter than the grade control drilling as the site geologist endeavours to collect data as far ahead of the face as practically possible. LIB drilling provides additional data for structural definition, stratigraphic modelling and use the results of the assays as a grade indicator. This drilling program typically looks at a 2 to 10-year mining window ahead of the current working faces.

As specified in Section 3 of this research report that the boreholes in the 30m x 30m drilling grid are planned with a dip angle of 55^0 or greater to ensure intersection with the reef at 45^0 for geological and resource modelling. There always remains a challenge of finding suitable access for drilling platforms, which result in the drilling of flatter holes to de-risk the geological model.

All the boreholes drilled at South Deep Mine are assayed, which amounts to a significant cost. However, due to the flatness of the angle, the flat inclined boreholes (FIB) assays data is currently excluded from the Mineral Resource estimation process to reduce the possibility of smearing grade in the estimate.

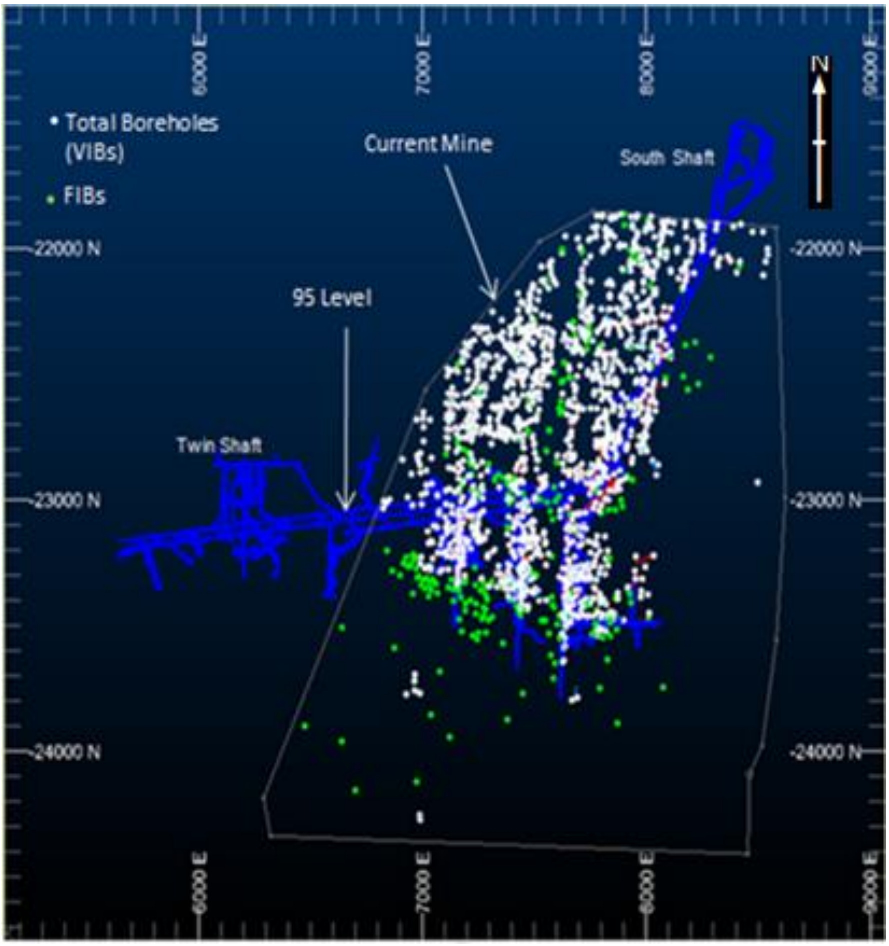

Figure 3 The current borehole intersections (Green being the flatly inclined boreholes (FIBs) and white being steeply inclined boreholes.

5.3 Borehole compositing

The samples in the borehole dataset from South Deep range from 10cm up to 80cm in length. Due to the range in sample length and the final resolution needed in reef grade variation, compositing of the raw data is done to an interval as close as possible to 1m - depending on the reef thickness with a maximum acceptable gap of half the compositing length (0.5m) and a minimum composite accepted of 0.2m. The one metre compositing is used to enable the Mineral Resource estimation model to cater for the selective mining units (‘‘SMU’’) of 5m x 5m x 1m.

The objective of this project as explained in the previous section is to include the flatly inclined boreholes in the estimation process. Compositing was done in both borehole dataset (Flat and steep inclined). Due to the comparatively few number of samples in the FIB (637) versus steep holes (4403) it was decided to use boxplots rather than histograms to graphically compare the statistical distributions of the two data sets.

The boxplots of Gold (Au (g/t)) were independently created for the data from flat and steep inclined boreholes respectively and are shown in Figure 4, both are on the same grade (g/t) scale to enhance interpretation of the results. The grade distribution of both datasets is positively skewed. The FIB and the steep holes have similar shapes and they also appear to have similar centres with the samples from steep boreholes having a larger variability. This is due to the larger number of samples in this dataset and therefore they capture more variability.

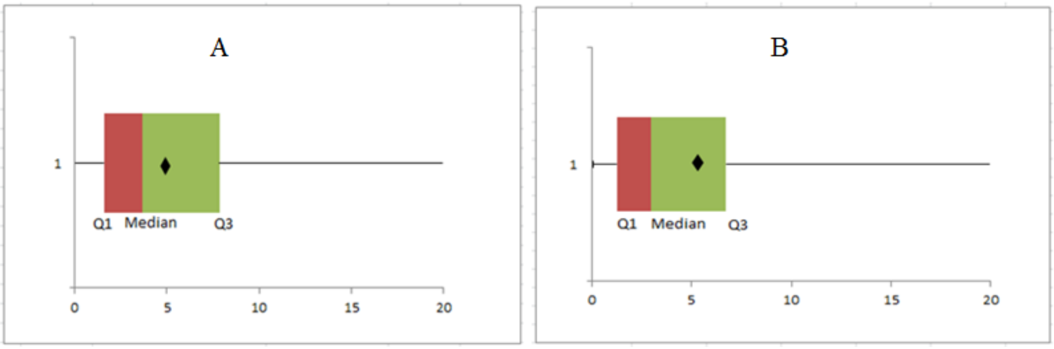

Figure 4 The Box plots of 1m composites of Au (g/t) samples from flatly inclined (A) and steeply inclined boreholes (B).

The 1m Au (g/t) sample composites from flat and steep inclined boreholes were combined to form a total dataset from all the boreholes drilled at the mine. Then a visual composite validation was carried out. The distribution of the composite length shown in Figure 5, below highlights that the compositing is done correctly, the distribution is symmetrical around 1m, with the majority between 0.75 and 1.25 meters.

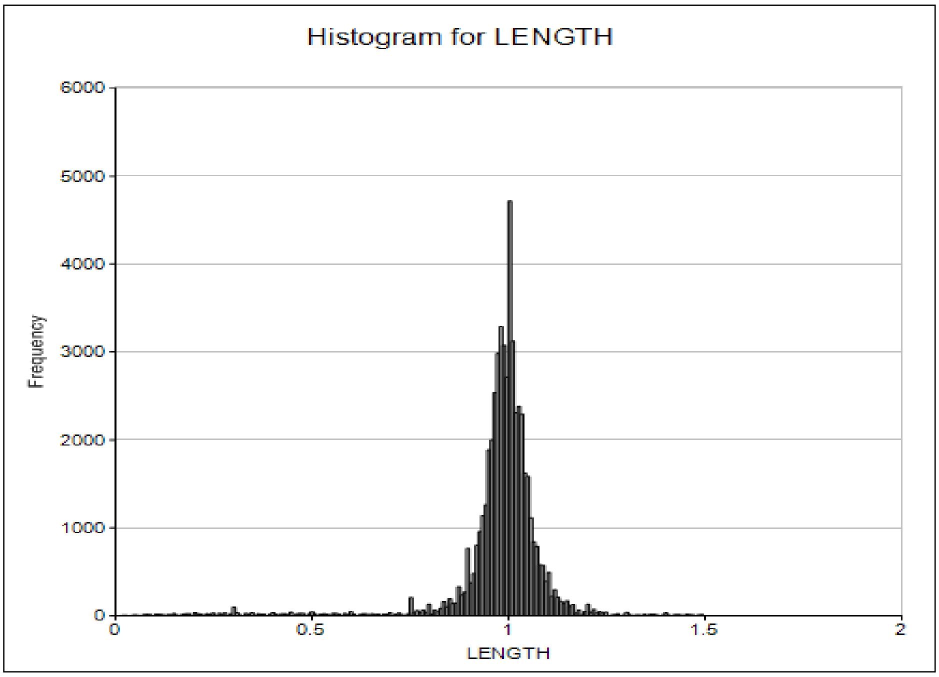

Figure 5 Histogram of 1m composite lengths from the combined flat and steep inclined boreholes

In compositing the borehole data, the reef channel width is corrected to reflect the true vertical thickness of the channel. The formula for calculating True Width is:

$$True\ Width = TW = \frac{\text{Channel Width}}{cosine(\theta)} = \frac{CW}{cos(\theta)}$$

Where, θ is the acute angle at which the borehole intersected the reef bedding.

Following the corrections, the FIBs had an average of three 1m composite samples for ECT reef which is similar to the samples from steeply inclined boreholes for this reef.

5.4 Seismic data

A 3D seismic survey was conducted in 2004 at 20m interval geophone spacing. This survey was optimally used in the geological modelling. The data assisted to confirm the base of the lava position as well as major structures. This survey looked at providing long-term resolution (10 to 70-years) ahead of the current mine workings at the current rate of exploitation.

Raw 3D seismic data from all available data sets has been combined and reprocessed to produce a single consolidated seismic image of the subsurface strata. The accuracy of the seismic data has been confirmed by drilling results, with the majority of the reef intersections being within 20m of the modelled depth (see Figure 6). No seismic data was used in this project, but the background information is discussed as some blocks in the geological models were generated from this dataset.

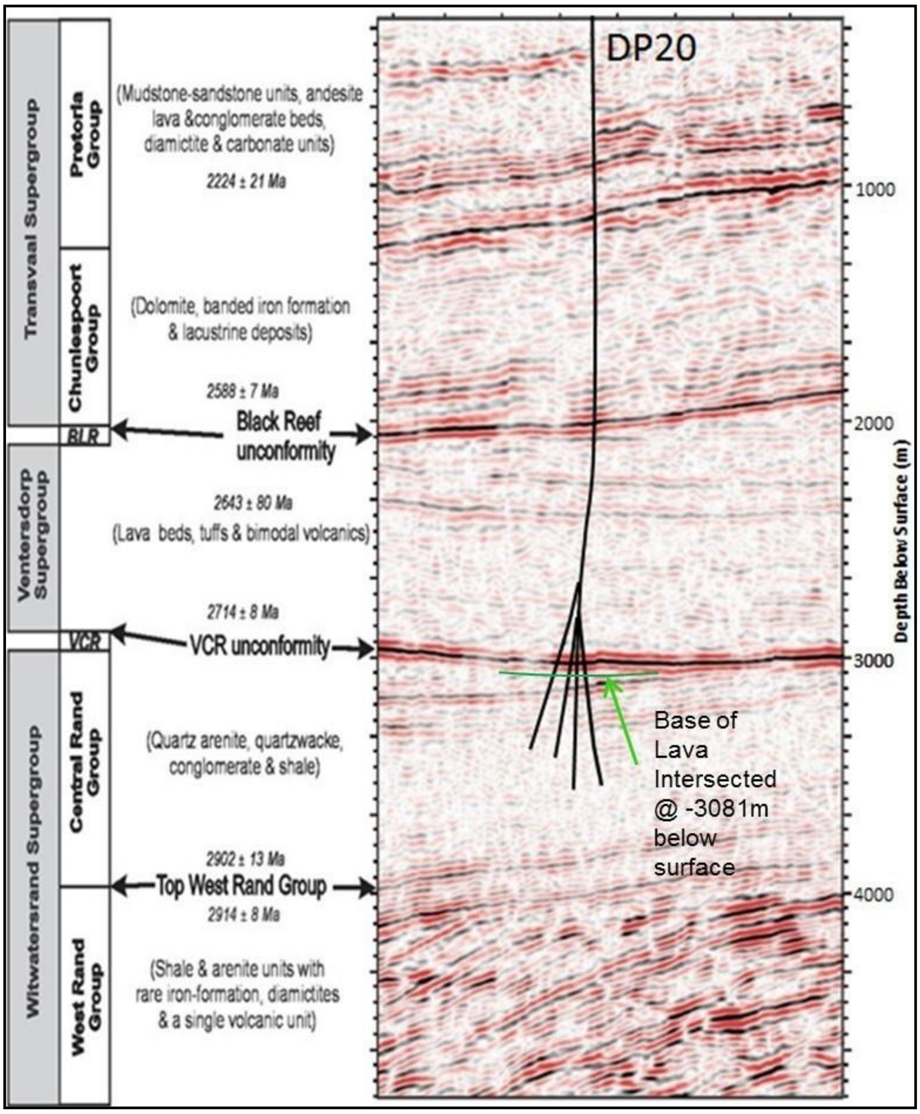

Figure 6 A section view looking north showing a VCR sub surface predicted by seismic survey vs the intersected reef elevations through the surface drilling. (Goldfields, 2010)

5.5 Data validation

All data underwent a validation process where the sample data was scrutinized for exact duplicates on X and Y co-ordinates, spatial duplicates on X and Y co-ordinates, incorrect co-ordinates, anomalous values, data falling within the major loss zones (faults and dykes), and data outside lease boundary. Only reliable assay data that have passed QA/QC is considered valid and is used in this project.

5.6 QA/QC on the sample Assays

All Borehole samples undergo rigorous quality assurance and quality control (QA/QC) checking. This takes the form of certified Au and U_3O_8 standards being inserted at regular 20 sample intervals to conform to the batch size utilised at the laboratory. By the same means, blank samples, repeat samples and planned task observations are some of the QA/QC procedures used to ensure sampling protocol is maintained. Blanks are used to check for contamination during the sample preparation phase at the laboratory, whilst certified standards and repeat samples are used to check assay accuracy and precision respectively.

As part of the QA/QC procedure, blank samples, repeat assays and inter-laboratory programmes are used to ensure that the laboratories adhere to assay standards and protocols. QA/QC procedures exist for each of the assay laboratories used, underground sampling and borehole sampling systems. South Deep uses DHLogger and the Fusion software of Datamine® for data capturing and storage. A detailed QA/QC report is compiled quarterly, with an objective to measure the performance of the assay laboratories with regards to accuracy and precision for assays conducted during the month. This is complimented by a quarterly lab audit which highlights short to long term trends and possible issues with the performance of the reference materials inserted.

A lot of sample handling occurs during the processing stage, from sample receipt through to the crushing and milling phase. Within each twenty sample batch blanks are inserted randomly, and where applicable, preferentially between expected high-grade samples to test for signs of contamination. The upper limits of blanks are set at 3 times the detection limit at 0.06g/t. Any blank recording above this limit will fail the batch in which it occurs, and the batch will be deemed contaminated, see Figure 7 as an example.

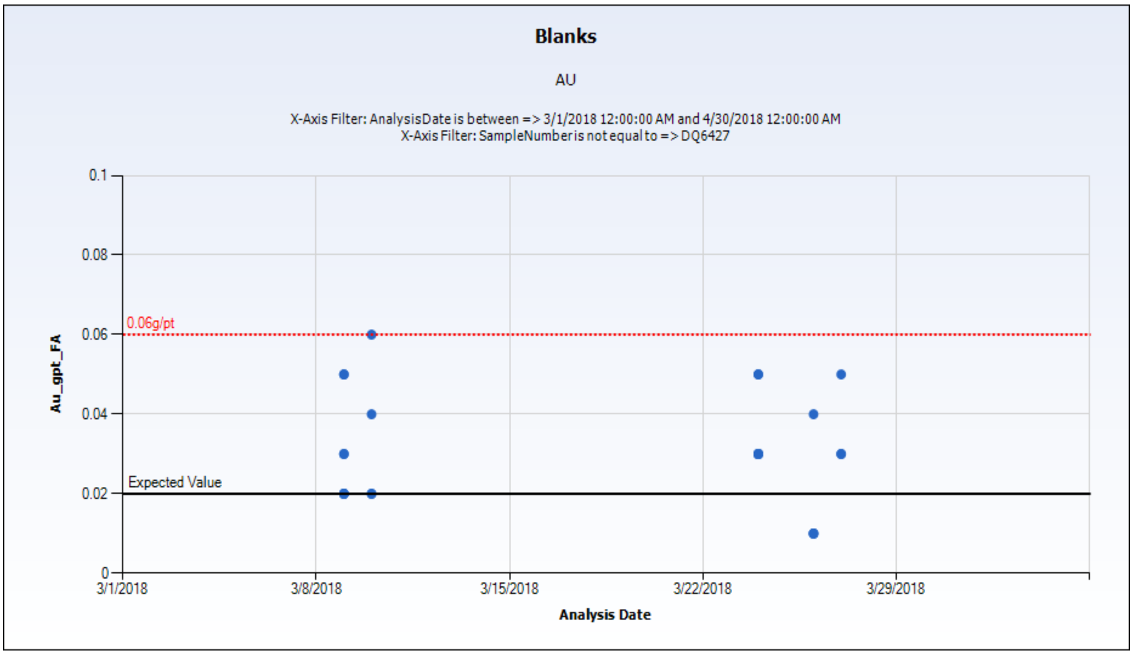

Figure 7 The performance of blanks on a monthly basis.

Different standard reference materials (8 in total) are used at South Deep. This is to cater for the different grade classes associated with the orebody, where high grade typically occurs close to subcrop and lower grade occurring distally from subcrop. In a batch of twenty samples one standard reference material (SRM) sample would be inserted to check the accuracy of the batch. The upper/lower limits and the mean of the SRM are statistically determined through inter lab assaying and are certified accordingly. For underground grade control drilling, 3SD (standard deviation) are used to determine the upper and lower limits for the SRM performance. Any sample outside of the limits are deemed to have failed the accuracy test and hence the entire 20 sample batch fails and are resent for re-assaying with new standards and blanks. Figure 8 gives an example of an acceptable batch.

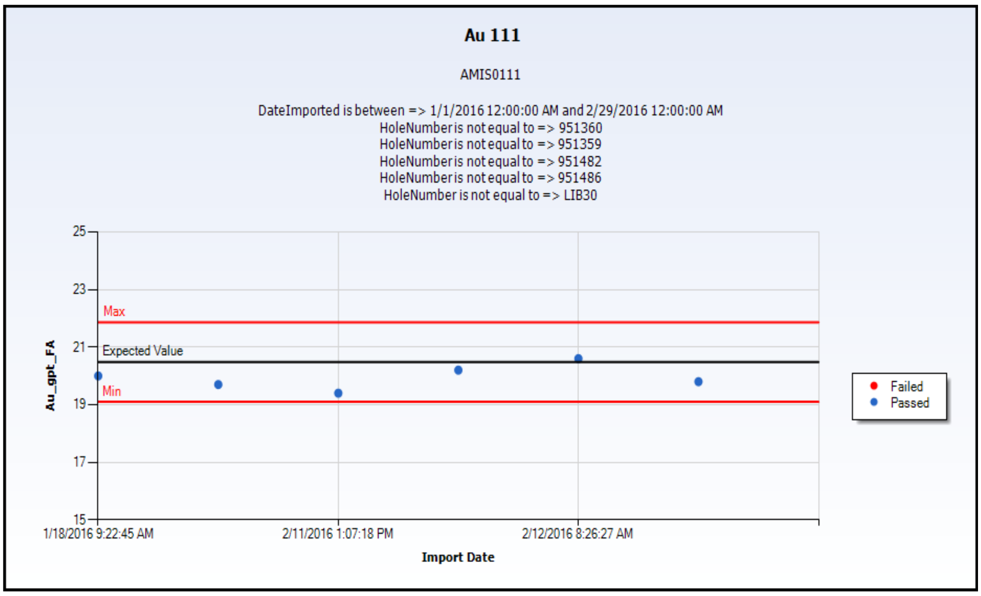

Figure 8 The monthly performance of the Au SRMs.

For every batch of 20 samples send to the lab, one duplicate coarse crush sample is randomly chosen to test for precision within the batch. On a quarterly basis, 5% of all the samples assayed are re-submitted for precision testing (see Figure 9). This is additional to the ongoing monthly duplicates. The aim is to have 90% of the samples within 10% difference. Figure 9 is an example of where the 90% target was not met.

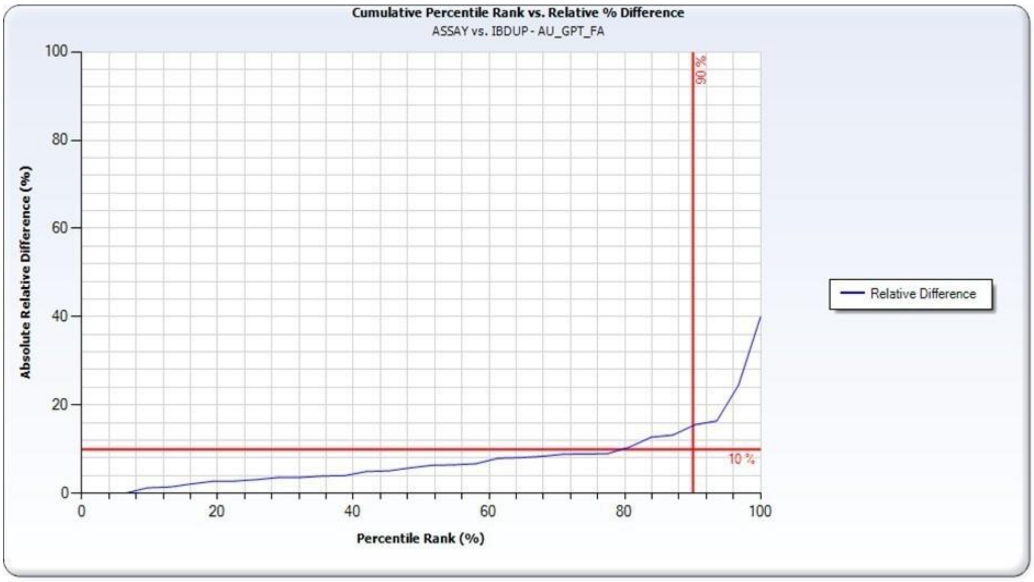

Figure 9 The quarterly precision performance for AU (g/t) samples

6 GEOLOGICAL MODELLING

6.1 Geological Modelling History

The first geological model was derived from the seismic survey points in the late 1980s. At the time, it was general knowledge that the orebody comprised the Upper Elsburg reefs as well as the VCR. Since the early 2000's the Upper Elsburg reefs have been modelled as four major sedimentological and stratigraphic units. Close to the subcrop, these four units, predominantly composed of juxtaposed conglomerates, were modelled as one unit, and termed the "Shore Line Composite (SLC)".

A second seismic survey was commissioned in 2004 due to vast improvements in data acquisition and processing. These survey results were utilised together with drilling and mapping information to develop an enhanced geological model. The initial four major sedimentary units were further refined and subdivided into first seven and later sixteen 3D-modelled units with the seismic data locating the contact between the VCR and Ventersdorp lavas. (Osburn et al, 2014)

During 2010, the limitation of straight lining between borehole intersections became evident from irregularities between observed and modelled data. The available data revealed that the clastic wedge does not always diverge to the east at a constant rate due to reactivation of syn-depositional faults. In certain localities, the divergence ratio is greater than other areas, while towards the east, the Upper Elsburg reefs reach a maximum thickness of approximately 130m and the units become sub-parallel and conformable to each other. These observations triggered the introduction of type-sections, based on palinspastic reconstructions at regular intervals throughout the orebody. The sections were linked to the actual borehole intersections to obtain correct channel width (CW) values for localised areas.

These sections formed the basis of a representative depositional model, yielding robust CW to be used during geological modelling and estimation. Figure 10 provides a graphic illustration of the evolution of the South Deep geological models. (Goldfields, 2017)

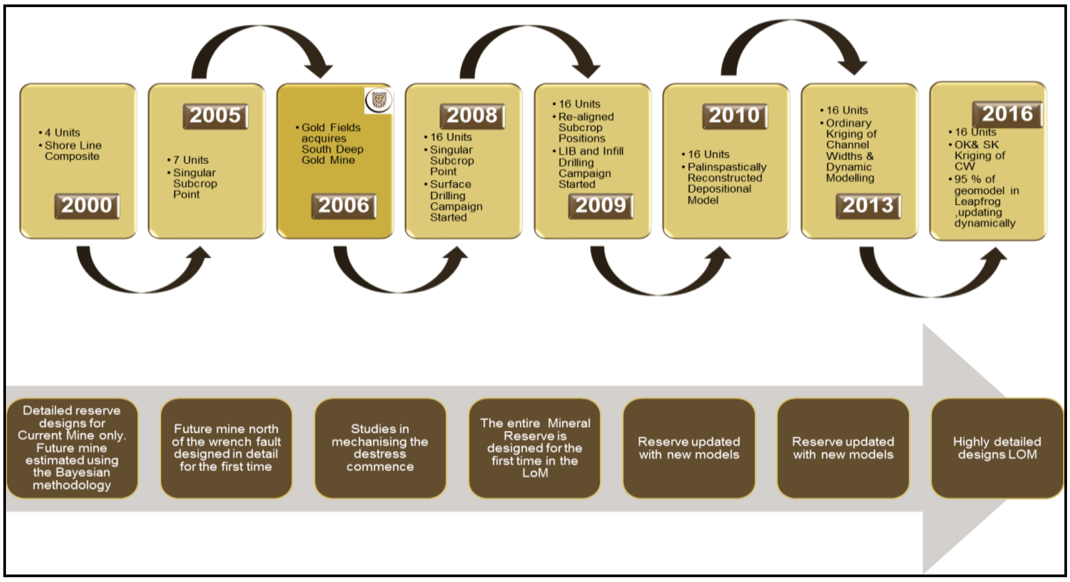

Figure 10 Graphic representation of the evolution of the South Deep geological model illustrating the increase in accuracy as well as confidence (Goldfields, 2017).

6.2 Current Geological Modelling Osburn et al (2014)

Osburn et al (2014) describes the current South Deep Mine modelling methodology, for CW estimation which ensures that different users obtain identical results, with a full audit trail compliant to all reporting codes that enhances the transparency of the geological model construction process. To mitigate the subjectivity of geological modelling processes, emphasis has been placed on the estimation of the CW. Currently, uneconomic quarzitic units become thicker towards the east, while the mature conglomeratic units are more consistent in CW throughout the mine lease boundary as illustrated n the contour plots in Figure 11.

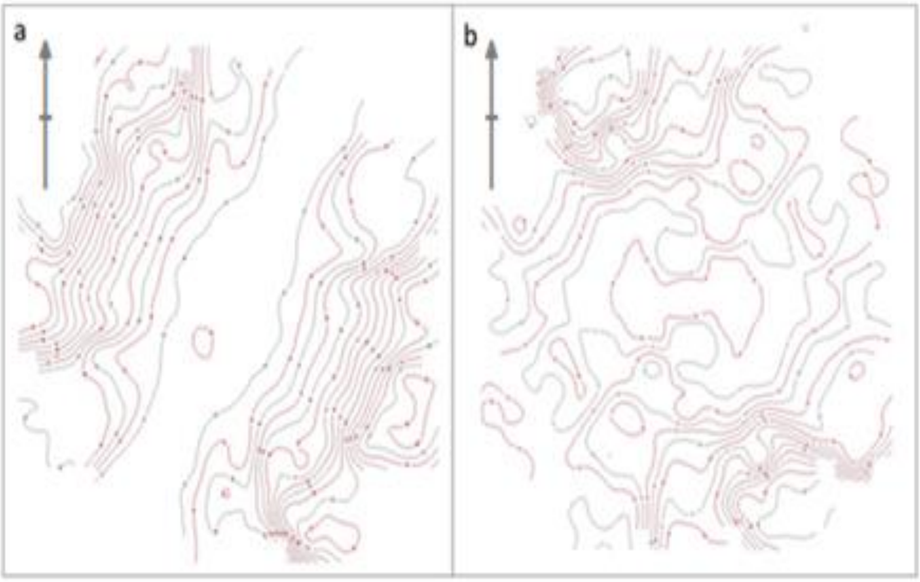

Figure 11 Variogram contours of (a) Quartzitic units illustrating a clear continuation direction parallel to subcrop, and (b) Mature conglomeratic units illustrating a more isotropic distribution with some continuation experienced in the subcrop direction. (Osburn et al 2014).

In modelling the variograms and constructing the variogram contours, Osburn et al (2014) selected a specific unit of the respective lithology (quartzite or conglomerate) that was representative of the deposit as a whole.

Their anisotropic variogram model for the conglomerate units indicates a range exceeding 800m parallel to the subcrop, while the quartzite shows a range of about 400m with potential trends, as shown in Figure 12.

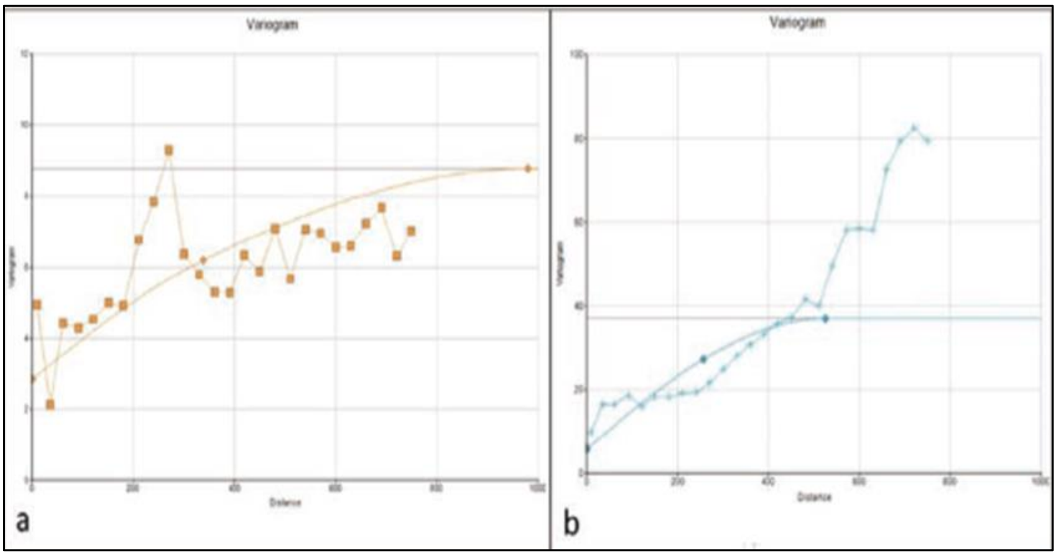

Figure 12 Variogram models of (a) Conglomeratic unit parallel to subcrop yielding ranges of more than 800m, and (b) Conglomerate unit perpendicular to subcrop showing ranges of more than 500m with potential trend (Osburn et al 2014).

At South Deep Mine the variograms are used in the estimation of the channel width which is then added as an attribute to a point file; from there the points are draped onto a wireframe surface of a reef unit. Once these points conform to the surface, they are translated by the CW value to the elevation where the following reef unit would be encountered. The digital terrain model obtained from the estimated locations is then further integrated with the actual borehole intersections. The process of CW estimation combined with the tagging of boreholes and inclusion of mapping data result in geological model comprising of wireframe volumes representing the reef underground as seen in Figure 13.

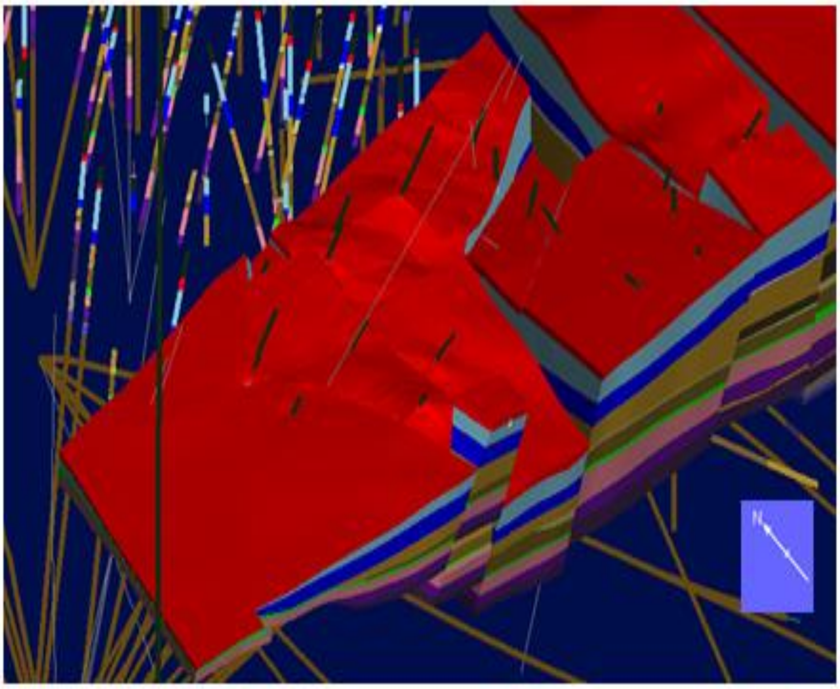

Figure 13 Geological model Wireframe volumes of the Elsburg reefs generated from Channel Width Estimation, boreholes and geological mapping

7 EXPLORATORY DATA ANALYSIS

7.1. Domaining

Domains are defined as zones which are geologically and statistically homogenous (Duke and Hanna, 2001).

The domains used in the gold estimation of ECT were delineated from the global geological domain zones (Facies) that runs from the Current Mine based on their larger scale and stability through the entire mine lease (See Figures 14 and15). Domains that fall within a defined project perimeter are selected based on the structural and geological models.,

The VCR and Upper Elsburg Reefs were subdivided into various domains, which are used as the basis for the geostatistical zones or geozones. The broad geological domains were delineated from a combination of the major fault boundaries, gold content (cm.g/t), channel width (CW) data and accumulations over channel width. The domains are used to constrain the statistical and geostatistical analyses that form the basis of the estimation process.

The following paragraphs and figures summarise the domain delineation process and results:

7.2. Facies

Each of the Upper Elsburg Reefs have a detailed facies plan constructed, based on sedimentary and gold grade factors. The factors considered were:

- Channel Width
- Gold Grade (g/t)
- Gold Content (cm.g/t)
- Average Clast Size
- Cumulative Conglomerate Percentage.

The facies zones per reef unit are delineated using the above-mentioned factors by means of hard and soft boundaries into High, Moderate and Low potential zones; the ECT Reef is shown below in Figures14 and 15. (Goldfields, 2012)

These facies plans have been used to direct major capital and working cost exploration drilling programmes over the years, including the Long-Inclined Borehole (LIB) and the 30m x 30m grid drilling projects. The LIB drilling programme has been initiated on the below infrastructure ground, while the grid drilling is aimed at evaluation of the current mine potential working areas above infrastructure. Infill and grade control drilling is also planned for the production mega sections and corridors. The Geological facies plans are updated as additional information is collected. (Goldfields, 2012)

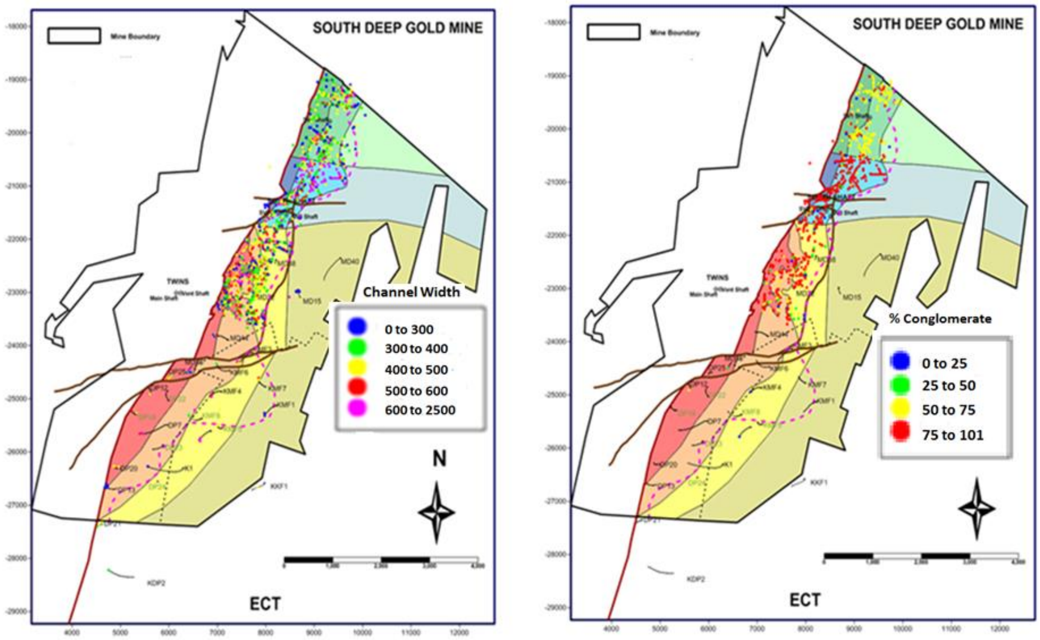

Figure 14 ECT facies plan based on channel width and percentage conglomerate (Goldfields, 2012)

The geological facies provide a platform for the geostatistical domains, where the geostatistical domains are areas within a facies zone with consistent grade distribution (see Figure 16). Spatial plots of grade are employed to define homogeneous geozones. All estimation is confined within the boundaries of the defined geozones ('hard boundary'). 'Soft' boundaries are drawn as a perimeter around the hard boundaries and have been introduced to facilitate estimation along the edge of a geozone where insufficient data is available within the defined search radius. There are currently 13 geostatistical domains in the current mine. The soft boundaries are applied only where a geological relationship exists with the adjacent geozone, i.e. where geological evidence suggests that the boundary in question coincides with a gradual transition between geological environments, such as proximal/distal relationships. The soft boundary of a geozone will incorporate the samples of the transition zone, i.e. the area between the hard and soft boundaries. (Goldfields, 2012)

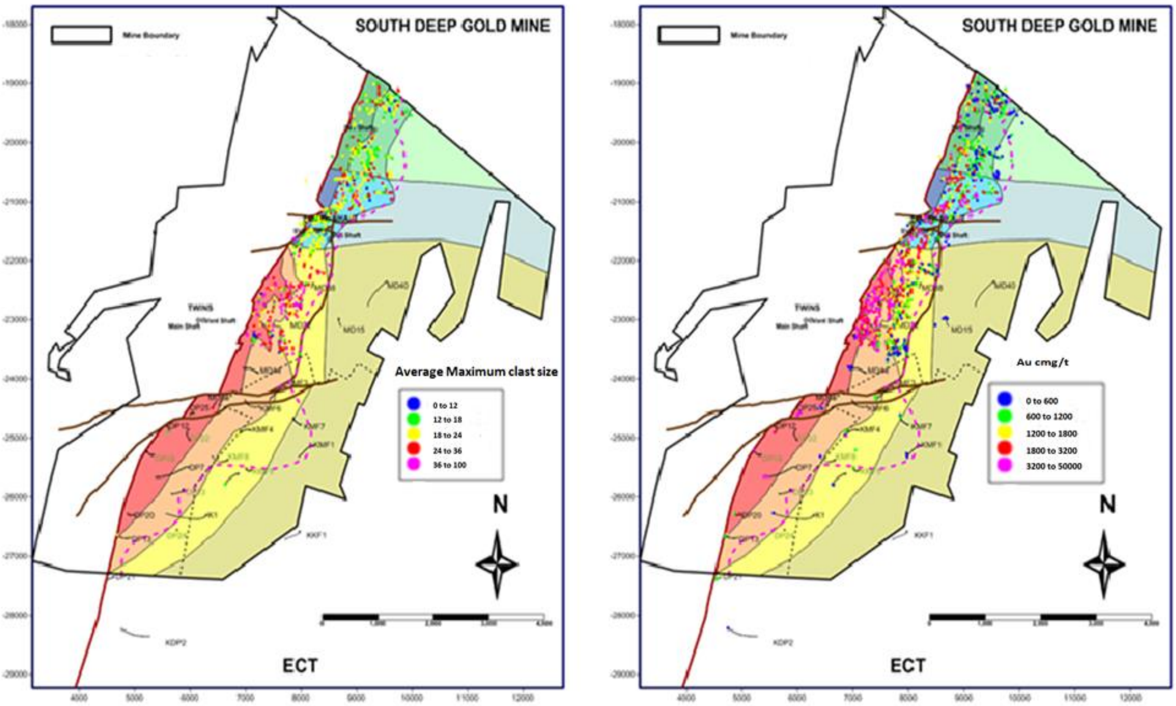

Figure 15 ECT Facies plan based on average Au (g/t) and Au (cmg/t) (Goldfields, 2012)

The incorporation of additional data improves the confidence of the estimate. In the absence of geological continuity across a geozone boundary (i.e. where samples at close proximity to each other are deemed unrelated), such samples will be excluded by the hard boundary and have no influence on the estimation. Typically, this occurs where geozones are separated by faults that are known to have a significant lateral displacement (Osburn et al, 2014).

In this research no changes were made to the geostatistical domains in place on the mine since the results will be compared with the current model. The sample grades were regularised on a 30m x 30m grid, using the REGMOD routine in Datamine ®. The regularised point grid data was used to check the validity of the current 13 geostatistical domains based on the similarity of the grades.

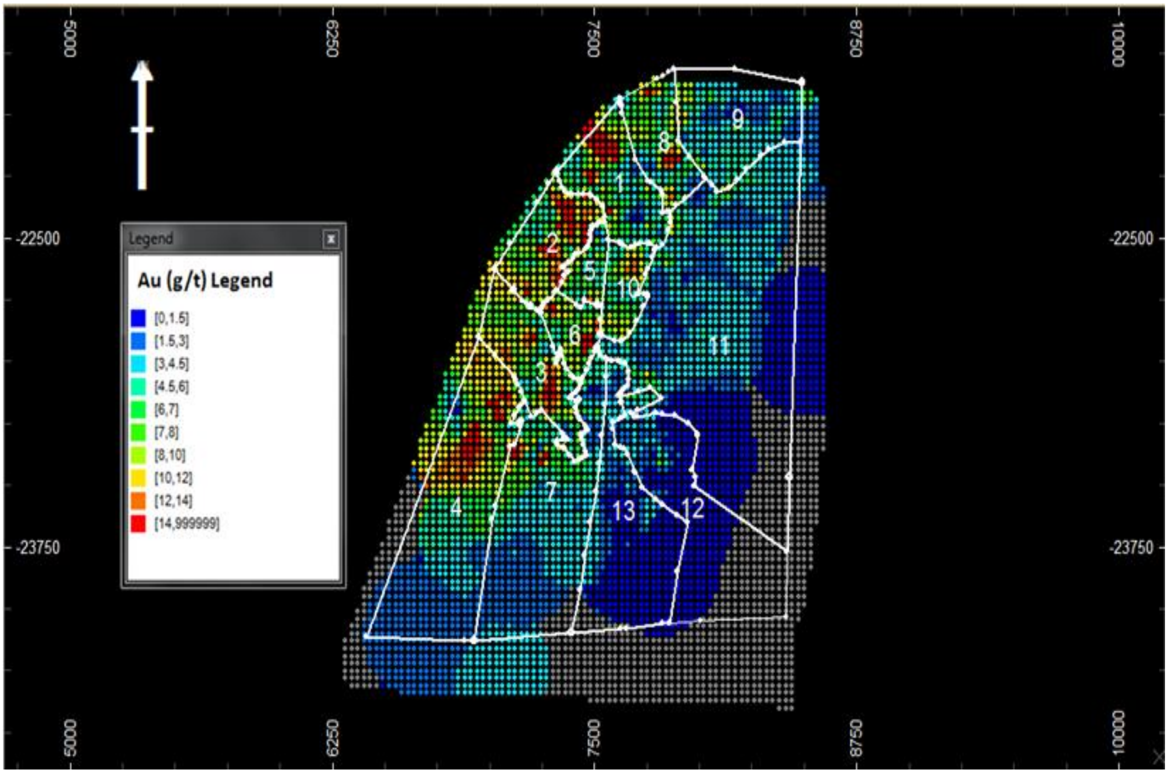

Figure 16 ECT Geostatistical domains in the current mine area with 30m x 30m gridded Au values.

7.3. Descriptive Statistics

Statistical analyses were performed to develop an understanding of the statistical characteristics and sample population distribution relationships. Table 1 summarises the statistics for the ECT geozones in terms of the steep inclined boreholes, the FIB holes and the combined data set.

Table 1 Descriptive Statistics of ECT reef, Au (g/t) for 1-meter composites.

	Domain	Number of Samples	Minimum g/t	Maximum g/t	Average g/t	Variance $(g/t)^2$	Standard Deviation g/t	CV
Steep Inclined Boreholes	1	266	0.00	106.35	7.40	108.19	10.40	1.4
	2	382	0.02	127.11	11.03	165.43	12.86	1.2
	3	288	0.48	38.90	7.39	49.19	7.01	0.9
	4	131	0.22	40.48	8.81	76.39	8.74	1.0
	5	211	0.26	28.36	6.20	33.95	5.83	0.9
	6	143	0.60	81.25	9.00	101.30	10.06	1.1
	7	274	0.01	29.19	4.58	23.06	4.80	1.0
	8	211	0.01	78.66	6.26	58.93	7.68	1.2
	9	198	0.01	39.18	4.91	37.13	6.09	1.2
	10	114	0.75	53.57	8.34	58.48	7.65	0.9
	11	637	0.00	31.33	3.18	15.81	3.98	1.3
	12	197	0.05	41.23	2.60	16.39	4.05	1.6
	13	65	0.10	10.10	2.38	5.33	2.31	1.0
Flat inclined Boreholes	1	33	0.62	44.90	8.07	72.29	8.50	1.1
	2	5	8.41	15.63	10.60	9.25	3.04	0.3
	3	24	0.68	30.51	6.11	67.42	8.21	1.3
	4	77	0.14	43.63	9.14	70.49	8.40	0.9
	5	8	0.92	7.56	3.50	6.02	2.45	0.7
	6	56	0.53	49.94	7.88	88.83	9.42	1.2
	7	204	0.25	121.99	7.57	205.78	14.34	1.9
	8							
	9	9	0.46	7.77	3.57	7.50	2.74	0.8
	10							
	11	95	0.12	20.07	3.08	13.80	3.71	1.2
	12	79	0.04	10.76	1.53	3.12	1.77	1.2
	13	47	0.10	10.17	1.56	3.34	1.83	1.2
Total Combined Boreholes	1	299	0.00	106.35	7.48	104.02	10.20	1.4
	2	387	0.02	127.11	11.03	163.39	12.78	1.2
	3	312	0.48	38.90	7.29	50.50	7.11	1.0
	4	208	0.14	43.63	8.94	73.88	8.60	1.0
	5	219	0.26	28.36	6.10	33.15	5.76	0.9
	6	199	0.53	81.25	8.68	97.58	9.88	1.1
	7	478	0.01	121.99	5.86	102.95	10.15	1.7
	8	211	0.01	78.66	6.26	58.93	7.68	1.2
	9	207	0.01	39.18	4.86	35.87	5.99	1.2
	10	114	0.75	53.57	8.34	58.48	7.65	0.9
	11	736	0.00	31.33	3.17	15.46	3.93	1.2
	12	281	0.04	41.23	2.36	13.04	3.61	1.5
	13	115	0.10	11.16	2.11	5.23	2.29	1.1

The Coefficient of Variation ('CV) is a relative measure of dispersion in a data set. It is the ratio between the standard deviation and the mean and is useful in comparing one data set to another. Typically, a CV <.7 indicates low variance within the data set. The CV for the ECT Reef ranges from 0.91 to 1.4 denoting that the population distribution of gold grade for the South Deep Mine represents a highly skewed ore body.

Statistical analyses provided a basis for final data verification and were used to establish specific information on population distributions and assisted in identifying the impact of the additional data from the flat boreholes in the ECT domains

Descriptive statistics in the form of histograms (frequency distributions) and probability plots (to evaluate the normality and log-normality of the distribution of a variable) were used to develop an understanding of the statistical relationships of Au (g/t) samples from Flat and steep boreholes for ECT reef at South Deep Mine.

These samples were later combined to form a combined database which is referred to as the Total sample dataset in this project. The 637, Au (g/t) samples from Flat inclined boreholes were combined with the 3336, Au (g/t) samples from steep boreholes to make up the new total dataset of 3973, Au (g/t) samples. The summary statistics of the samples from the combined dataset is in Table 2 below.

Table 2 Descriptive statistics of ECT reef, Au (g/t) for all 1-meter samples from the combined borehole dataset

Number of samples	Minimum g/t	Maximum g/t	Average g/t	Variance $(g/t)^2$	Standard deviation g/t	CV
3973	0.00	127.11	6.10	71.41	8.45	1.35

The FIBs boreholes resulted in new samples being added across all the domains. A data analysis was conducted within each domain. With substantial additional data coming from the flatly inclined in Domain 1, 4, 6, 7, 11, 12 and 13 as depicted in Table 1 above. The number of boreholes will increase if the two datasets are combined.

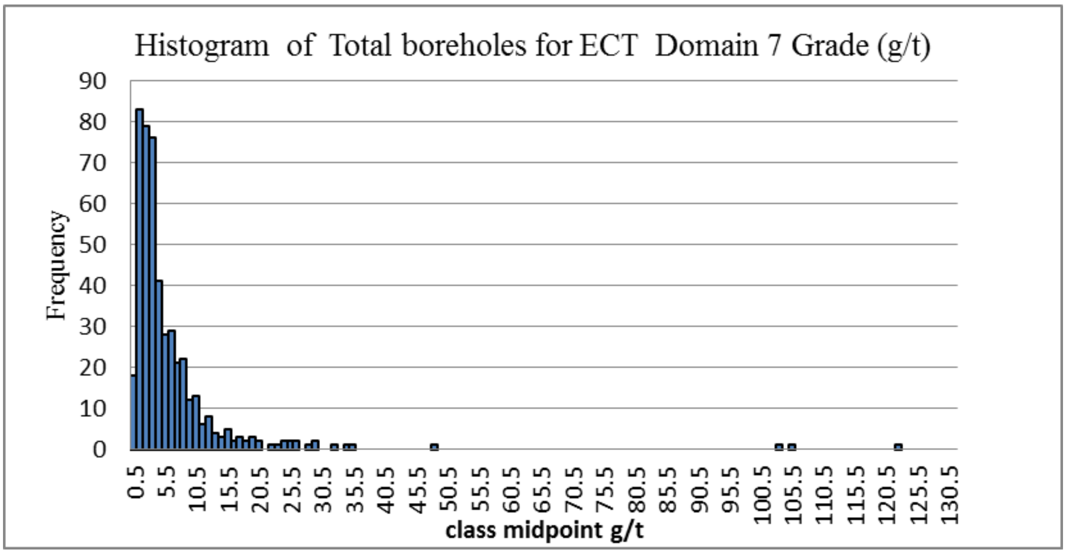

Figure 17 Histogram of total and steep boreholes (Domain 7)

From the Descriptive statistics (Table 1) it can be observed that there do not appear to be any outliers were introduced in other domains except for domain 7 where the maximum has increased from 29 g/t to 121 g/t and the CV increased from 1 to 1.7 indicated that the new maximum might be an outlier. This evidence is depicted in the histograms in Figure 17. The histograms of other domains are in the Appendix.

The histograms also guide us in applying top capping/cutting. Top capping is applied on the outliers or samples with high grade values which may unduly influence the mean grade of the population. Top cutting is applied in the variography to avoid the higher variance that comes with the outliers; therefore, in top cutting the outliers are completely removed from the dataset, for Kriging the outliers are top capped.

In this research, the number of high-grade values was found to be less than 2% and these were cut for the purpose of semi-variogram modelling only but were included in the sample population used for the final grade interpolation. The data in all the domains display a positively skewed distribution, which indicates that the ECT reef is highly erratic. The data has therefore been log transformed to produce a more normal type distribution for a smooth estimation process; an example for Zone 7 is show in Figure 18 below.

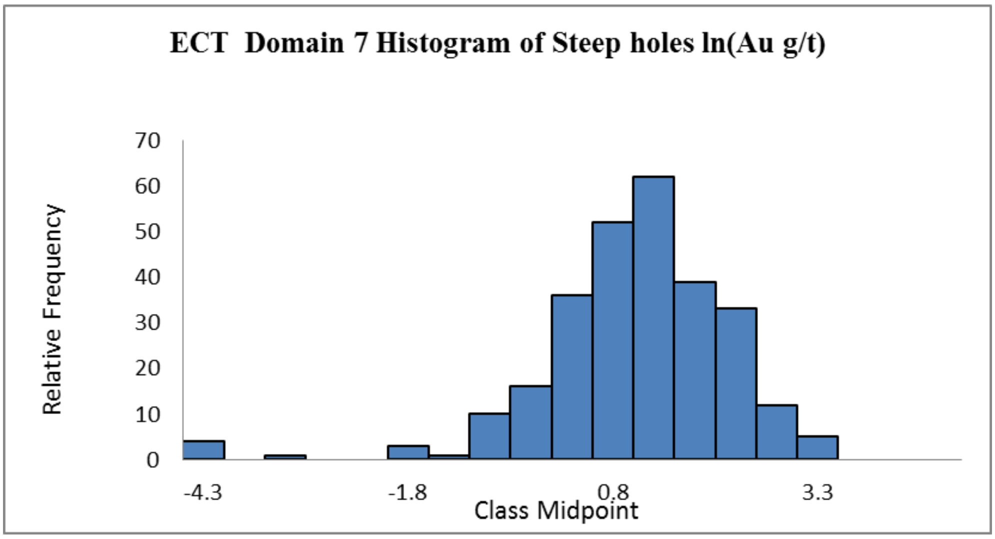

Figure 18 Domain7 ECT: Log transformed grade ln (Au g/t) histogram of the combined FIB and Steep borehole data set (Domain 7).

The cumulative frequency distribution (CFD) is used to estimate the central tendency (Median, mean and the Interquartile range (IQR)). In this project the IQR was used to assist in identifying the outliers. In Figure 19 for Domain 7 is shown as an example where the first quartile (Q1) is 3 g/t with Q3 as 8 g/t and the IQR in the data within this domain is 5 g/t. The CFDs of the rest of the domains are in the appendices attached to this report.

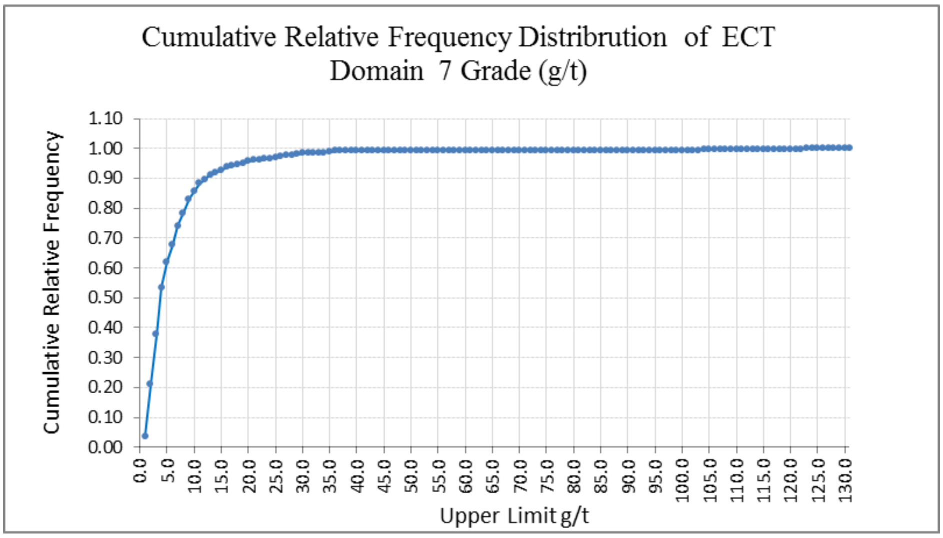

Figure 19 The cumulative relative frequency distribution for Domain 7 using the total borehole dataset.

Since we are dealing with an erratic data, the top cap of the data was identified using the Histograms and were validated using the cumulative frequency distribution. The kriging top cap per domain is populated in Table 2.

Table 3 ECT Gold (g/t) Kriging Top cap per Domain from the Histogram analysis

REEF	DOMAIN	PARAMETER	CAP (g/t)
ECT	1	AU	60
ECT	2	AU	80
ECT	3	AU	37
ECT	4	AU	35
ECT	5	AU	25
ECT	6	AU	50
ECT	7	AU	40
ECT	8	AU	35
ECT	9	AU	27
ECT	10	AU	25
ECT	11	AU	25
ECT	12	AU	17
ECT	13	AU	6

7.4 Declustered Statistics

Declustering is the process of adjusting the full data set to give a more representative set of samples. The method involves placing a regular 3D grid over the sample data and assigning a single value to each grid cell. This process results in a declustered mean which is also known as the global mean per domain which plays a pivotal role in simple kriging, mostly in the areas with little or no data.

In the cell declustering approach, the entire area is divided into rectangular regions called cells. Each sample receives a weight inversely proportional to the number of samples that fall within the same cell. This allows for clustered cells to receive lower weights because the cells in which they are located will also contain several other samples. (Deutsch, 2017)

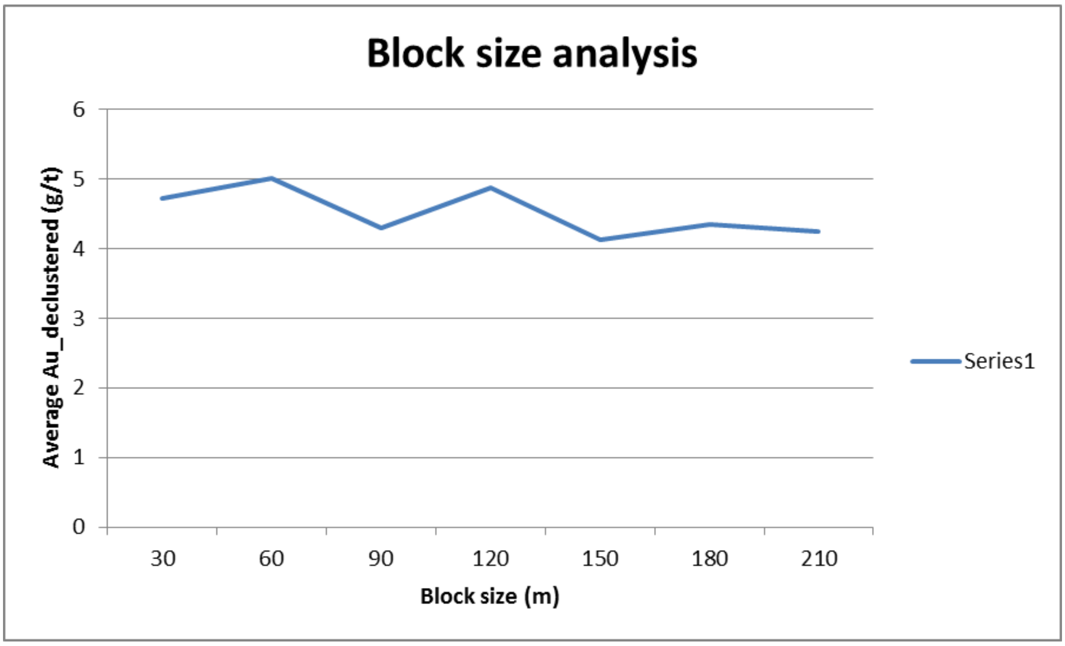

Figure 20 Average gold (Au g/t) in different block sizes in Domain 1, the declustered mean was selected at 90m x 90m blocks

The regularised block sizes vary between 90m and 180m and a minimum of 20 samples currently informs the declustering of the data. At South Deep Gold Mine, the sampling grid is currently 30m x 30m.

This suggests that 30m x 30m would be a good cell size to decluster the data or alternatively the data can be declustered on cell sizes that are multiples of 30. Since the 30m x 30 m drilling or sampling pattern at the mine, it is not yet achieved, it is worthwhile to test for the proper cell size. This was done by plotting block size against the mean, the declustered mean will be picked at a point where the average is the lowest. (See Figure 20)

A Z-cell size of 1000m was used for this declustering. This ensures that all the data that fall within a 90m x 90m grid is included in the z-dimension. The Goldfields internal code of practice advises that, in the current mine environment with the sub-domains it is recommended to stick to a grid of 90m x 90m or not to exceed 120m x 120m as the domains are small and very few blocks of size 120m x 120m or more can fit into one of the current mine domains. The declustered mean is also referred as the global mean which is used during Simple Kriging (SK).

An internal study by the Resource Geology team (of which the author of this research is a member) was conducted at South Deep with the aim of calculating the optimal number of samples leading to a more representative localised mean of the area in question. In determining the minimum number of samples to be used for the global and local mean estimation for each reef, consideration was given to the average thickness of the reef and the fact that the borehole data has been composited. As a rule of thumb for this orebody, four samples (Boreholes) around a point to be estimated provide a good estimate. Since the average thickness of the ECT reef is 3m, it means that on average one borehole can yield 3 samples. In this case the minimum number of samples used, to ensure that at least 4 boreholes are considered would be 12 samples. (See Table 4).

Table 4 Number of samples per reef, for calculating the local mean (LM)

Local Mean Minimum Number of Samples		
Reef	**Average CW (m)**	**Number of samples**
ECBA	5	20
ECBAQ	5	20
ECB	5	20
ECBQ	5	20
ECMC	3	12
ECMQ	2	8
ECT	3	12
ED	10	40
MAC	5	20
MAD	5	20
MIB	7.5	30
MIT	5	20
MIQ	2	8
MBB	5	20
MBT	7.5	30
VCR	2	8

In the case where a specific block complies to the minimum number of samples needed to calculate a local mean, the global mean value will be overwritten with a local mean value, therefore in areas with sufficient (grade control drilling) the sampling density is considered to be adequate to use a local mean rather than a global mean during simple kriging

For this exercise however, the global means were kept so that it could be easier to compare the model derived from the combined FIB and steep holes dataset. (See Table 5)

Table 5 Global mean per domain

Domain	Global Mean
1	7.16
2	9.97
3	8.44
4	8.21
5	6.94
6	9.45
7	4.3
8	5.89
9	4.37
10	7.9
11	3.37
12	2.34
13	4.3

8 VARIOGRAPHY

8.1 Variogram models

An experimental variogram is defined as a description of spatial continuity of the data. It can be plotted on a graph where the data pairs represent measurements of the same variable made some distance apart in a certain direction. It is important to model the empirical semivariogram for kriging,

At South Deep a spherical model (single/double structure model depending on isotropy) is modelled in all the reefs (See figure 21). (Dohm, 2016b)

Double structured spherical variogram model

$\gamma(h) =$	0	If $h = 0$
$\gamma(h) =$	$C_0 + C_1 [1.5\, h/a_1 - 0.5\, (h/a_1)^3] + C_2 [1.5\, h/a_2 - 0.5\, (h/a_2)^3]$	if $0 < h <= a_1$
$\gamma(h) =$	$C_0 + C_1 + C_2 [1.5\, h/a_2 - 0.5\, (h/a_2)^3]$	if $a_1 < h <= a_2$
$\gamma(h) =$	$C_0 + C_1 + C_2$	if $h > a_2$

Where: h represents a lag distance

a represents range

C represents sill

C_0 represents a nugget

Figure 21 Formula of calculating the spherical variogram model adopted from Dohm (2016b)

The following are the characteristics (Parameters) of the semivariogram in a specific direction

Sill: The Semivariogram value at which the variogram levels off (Total variance)

Range: The lag distance at which the semivariogram reaches the sill value.

Nugget: The semivariogram value at a small distance from the origin, the nugget represents variability at distances smaller the typical sampling space including the measurement error.

These parameters ensure that the interpreted anisotropy of the mineralisation is mathematically captured; the graphic representation of these parameters can be seen in Figure 22.

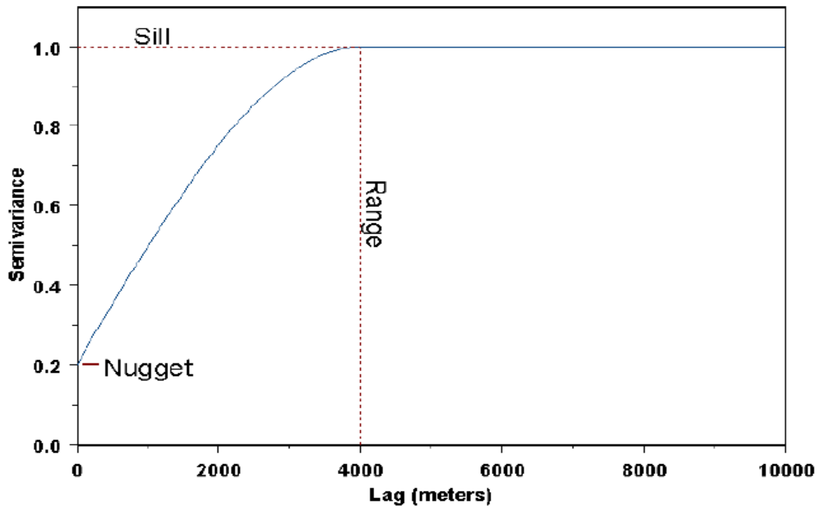

Figure 22 Experimental semivariogram model (Source: Dohm (2016))

Prior to modelling the directions of continuity are evaluated by making use of variogram contours on the horizontal, across strike and dip planes.

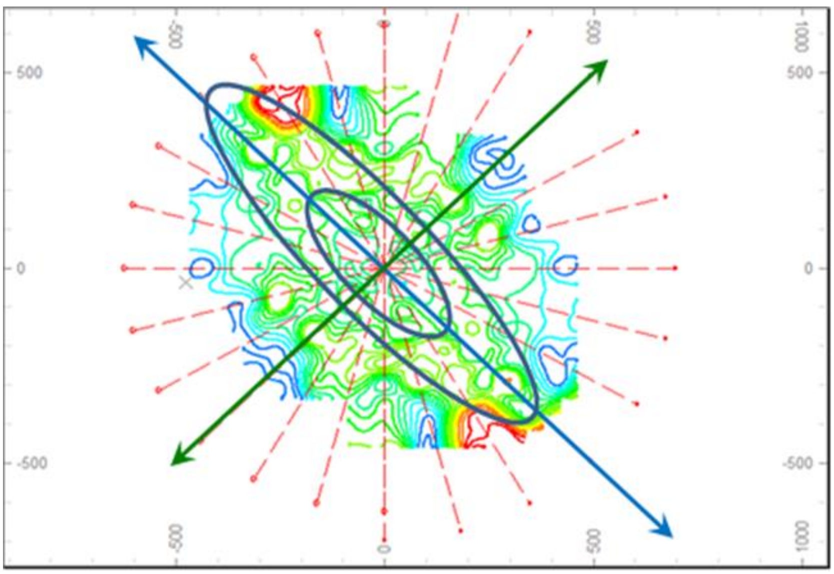

Figure 23 A Variogram contour map for Domain 1 using the total boreholes (using Datamine® Studio RM)

The continuity is represented by the contours on the plot that are tight together. From Figure 23 the blue double headed arrow indicates the direction of longest continuity as represented by the data in this domain which is the NW – SE direction. This direction is perpendicular to the Subcrop of the Elsburg reefs. The contour plots of other domains are in the appendix with their resultant variograms.

To define anisotropy, we look for the direction that is perpendicular to it, to which in this case is NE – SW direction represented by a green double headed arrow. To generate the contours the sample pairs were searched using the lag of 30 meters across the strike, this process was conducted at a horizontal angle of 15° and vertical of 90. These parameters were optimised to ensure that maximum number of samples is found.

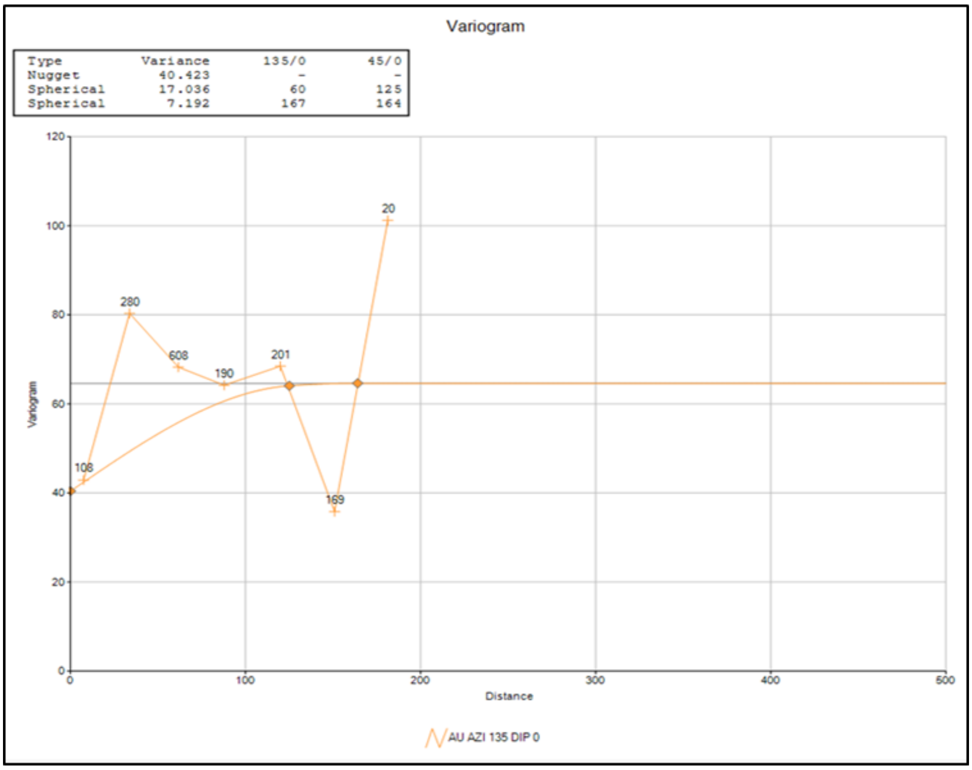

Figure 24 A fitted variogram model from 135^0 for Domain 2 using the dataset from total boreholes.

The resultant calculated experimental variograms are modelled by standardising the sill and modelling the nugget effect through extrapolating the first 2 points on the Y axis (see Figures 24 and 25). For anisotropic variograms, both longest and shortest continuity variograms were modelled using the Au (g/t) sample dataset that includes the FIBs. This was followed by modelling of variograms using the samples from steep boreholes only.

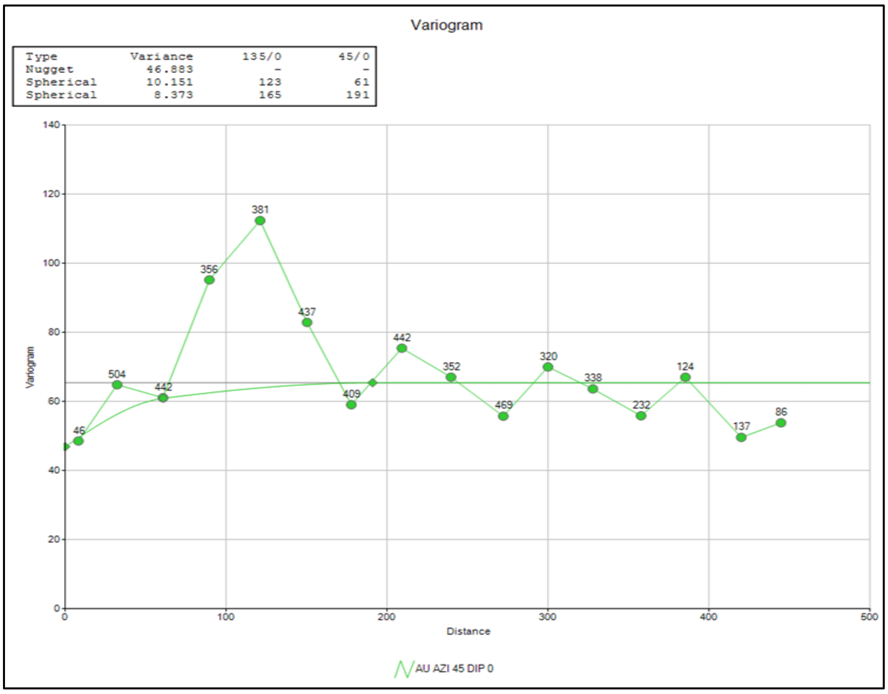

Figure 25 A fitted variogram model at 45^{o} for Domain 2 using the dataset from steep boreholes.

8.2 Discussion of Results

The results of the modelled variograms are given in Table 6 below.

Most domains have isotropic single structure spherical variograms models except for domains 2, 4, 5 and 9. The first point in the experimental data has low number of sample pairs, in cases like this the first point was ignored when fitting the model. The shape of the variograms show a linear character, especially near the origin, this fits with the spherical models (see the variogram contour maps and models of all the domains in the Appendices).

The percentage of the nugget values vary between 20% and 70 % in both datasets (Total and steeply inclined dataset. The sills were identified visually followed by the modelling of variogram ranges.

Table 6 Fitted spherical variogram models for each domain for the ECT reef using the total borehole

Domain	Nugget	Sill1	Sill2	Range 1	Range 2
1	0.30	0.41	0.29	90	244
2	0.72	0.16	0.13	61	123
3	0.74	0.26		253	
4	0.51	0.49		116	
5	0.35	0.37	0.28	18	33
6	0.64	0.36		183	
7	0.31	0.69		316	
8	0.69	0.31		372	
9	0.44	0.26	0.30	56	89
10	0.65	0.35		29	
11	0.71	0.29		98	
12	0.77	0.23		98	
13	0.38	0.62		30	

Contour plots were generated for the steeply inclined borehole dataset and the directions of longest continuity established are similar to the ones from the total borehole dataset. The modelled parameters of this dataset are presented in Table 7 below

Table 7 Fitted spherical variogram models for each domain for ECT reef using the Steep borehole dataset only

Domain	Nugget	Sill1	Sill2	Range 1	Range 2
1	0.45	0.14	0.41	86	200
2	0.66	0.21	0.13	61	123
3	0.74	0.26		250	
4	0.41	0.59		48	
5	0.66	0.34		21	
6	0.55	0.45		179	
7	0.68	0.32		110	
8	0.67	0.33		372	
9	0.56	0.01	0.44	86	89
10	0.66	0.34		31	
11	0.78	0.22		99	
12	0.72	0.28		97	
13	0.51	0.50		31	

As Carrasco (2010) in Witley and Minnitt (2017) noted that the magnitude of the Nugget effect is dependent on sample support, sample density, sampling quality and the nature of the phenomenon under study. The modelled nugget effects changes significantly in the domains with substantial additional samples from flat boreholes. In these domains it dropped from well over 50% to about 40%. This probably due to the FIB holes providing additional information at short ranges nature of the dataset in the project area. No major changes in the ranges were observed when comparing the Variogram results from Table 6 and 7. A major change was noted in Domain 7 in both first and second structure. It was noted in Chapter 7 (Table 1) that the number of samples in this domain increased by 43%.

9 GRADE ESTIMATION

9.1 Estimation Technique

Simple Kriging is the estimation technique used in grade estimation for this exercise. Simple kriging was used as preferred method due to large areas covered in the domains and in accordance with the spacing and density of the data. Simple kriging is carried out using all available data within the search radius, but the estimation algorithm treats the domain as a soft boundary and for blocks near the edge of the domain, the search can include composites within a 30 m skin of the adjoining domain (''soft boundary''). This results in a reduction of the edge effect and therefore reduces conditional bias for blocks around the edge of the domain. Simple Kriging assigns some weight to the average or mean grade in the area.

Simple Kriged estimate: $Z^*_{SK} = \Sigma w_i z_i + (1 - \Sigma w_i) \times \text{Mean}$

With:

Z^*_{SK} – Simple Kriging Estimate

$w_i z_i$ – Weight of the sample times the grade of the sample

Mean – The global mean within the domain.

9.2 Estimation Process

At South Deep Mine, the process of geostatistical resource estimation commences after the interpretation of the 3D wireframe solids representing the geological model of all reef surfaces within a project area have been completed. The wireframes for the reef surfaces are developed to ensure that the grade models generated are constrained within geological populations. In addition, geo-domains within the respective geological wireframes are developed to further improve the statistical zones (domains) as described in section 7. The grade estimate is constrained by these domains.

The following inputs are required from the geology/evaluation departments before the resource estimation process can start**,**

- A merged Borehole data and de-surveyed file containing the following fields: Collar File, Assay File, Survey File,
- Geological File; Wireframe Solids of all reef surfaces combined to form individual reef units (in this case ECT reef); and Geological Domains

At South Deep Mine the data used (wireframes and drill holes) are rotated to a flat plane before modelling commences. The Datamine® function ''CDTRAN'' was used to rotate geological models into a flat plane. The dip and plunge attitude of the geological model is first determined by loading the model in the Datamine® design window and viewing the model in north-south direction as well as in the west-east direction. A string is then drawn, according to the orientation in these directions at an average dip to the top most model surface to determine the approximate rotation parameters in these directions. The rotated data is projected to a datum to ensure that the data is in a flat plane as shown in Figure 26. This provides effective data search regime during the kriging process.

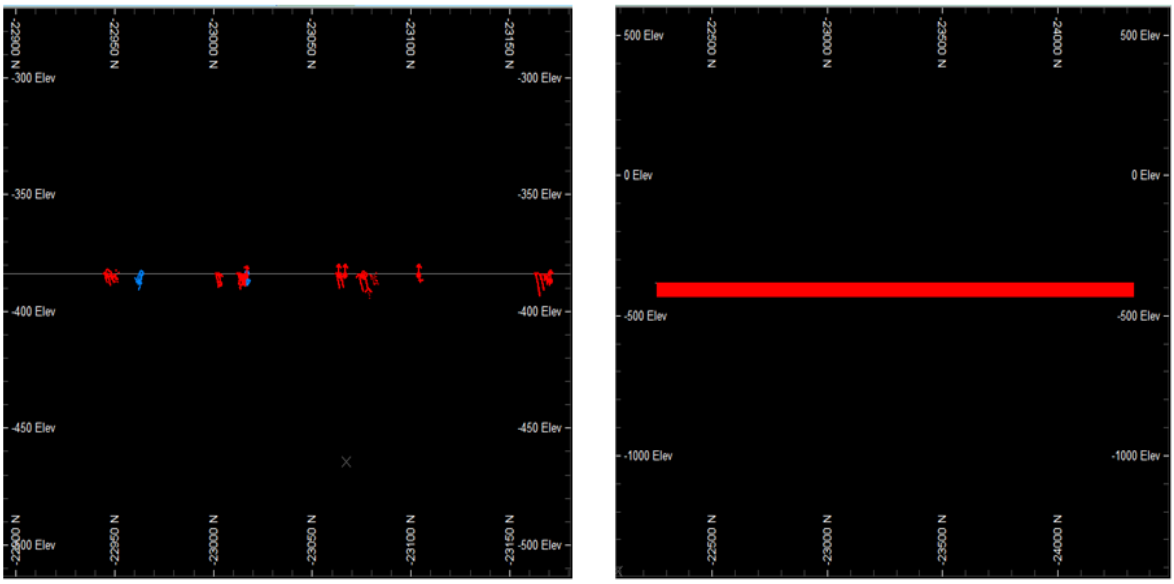

Figure 26 Flattened data (left) and start model (right) in the flat space at a datum of -384 m

Grade estimation is conducted within the so-called start models. The start models are generated by filling the wireframes with cells of defined sizes. The start models were also created in the flat space on 30m x 30m x 1m blocks sizes (Figure 26). The start model process is used to create empty seam models below the datum. For this exercise, a proportional model on 30m x 30m x 1m blocks sizes was created to calculate the volumes of these parent blocks. A dip domain model is created for each domain based on the strike and dip of the triangulation surfaces, which make up that particular reef model within the domain.

9.3 Grade Estimation

In this research two separate estimation models were considered; one is using the 1m Au (g/t) composites from the steeply inclined holes and another using the samples from the combined dataset of the steep and the FIB boreholes. To produce these models, grade is interpolated into a block model size of 30m x 30m x 1m based on the current data density. As mentioned in the previous section, due to data spacing the estimation method at South Deep is Simple Kriging.

A summary of the Kriging results from the Steep and FIB models can be seen in Table 8 and 9 it can be observed from these tables that the Kriging grade estimate remain stable following the addition of the samples from the FIBs.

In domain 7 where there was a substantial addition of samples the Simple Kriging grade changed slightly by 0.016 g/t (Which is insignificant).

Table 8: Simple Kriging results of the block model estimated using the Au g/t samples from the combined borehole dataset

Domain	Parameter	Soft boundary		Hard boundary		AUSK Weighted Mean g/t
		Total number of samples	Mean g/t	Total number of samples	Mean g/t	
1	AU	299	7.28	296	7.23	7.32
2	AU	478	10.48	390	10.85	11.16
3	AU	322	7.34	300	7.26	7.95
4	AU	297	8.16	209	8.80	7.65
5	AU	365	6.74	219	6.06	6.18
6	AU	372	7.95	205	8.42	8.47
7	AU	932	5.68	483	5.47	4.18
8	AU	265	5.89	211	6.058	5.9
9	AU	246	4.9	207	4.74	4.6
10	AU	189	7.59	114	7.93	7.79
11	AU	918	3.42	735	3.16	3.76
12	AU	445	2.26	283	2.23	2.4
13	AU	115	1.92	114	1.94	3.6

Table 9 Simple Kriging results of the block model estimated using the Au g/t samples from the steep boreholes dataset

Domain	Parameter	Soft boundary		Hard boundary		AUSK Weighted Mean g/t
		Total number of samples	Mean g/t	Total number of samples	Mean g/t	
1	AU	266	7.13	263	7.18	7.30
2	AU	467	10.49	385	10.86	11.16
3	AU	298	7.44	278	7.35	8.00
4	AU	220	7.88	132	8.71	7.65
5	AU	357	6.81	211	6.16	6.18
6	AU	274	8.25	149	8.62	8.46
7	AU	662	5.21	277	4.70	4.20
8	AU	265	5.89	211	6.06	6.41
9	AU	236	5.05	198	4.8	5.3
10	AU	176	7.75	114	7.93	7.76
11	AU	815	3.47	636	3.16	3.7
12	AU	284	2.57	198	2.44	2.41
13	AU	65	2.2	65	2.19	4.1

9.2. Simple Kriging Parameters

The estimated variable is the grade Au (g/t). The block size 30m x 30m x 1m block size is derived from drill hole spacing & sample lengths for all reefs with a discretisation of 5m x 5m x 1m. Discretisation is used to divide the block volume into many points to allow improved block estimates from point data. The block is divided into many points and then individual point estimates are averaged to get an average over the block. Spatial locality of point data relative to the block to be estimated is hence considered (Dohm, 2016b).

Search range – As the range of variogram decreases to approach zero (pure nugget), the required neighbourhood configuration for good estimation will become progressively larger, and vice versa. A limited search range will result in a block estimate that is progressively spatially uncorrelated to the true grade as the variogram range tends to zero. Using the variogram range or slightly larger than variogram range allows the search volume to have a long-range relative to the block dimensions, thereby accessing samples that might be spatially uncorrelated particularly in areas of data scarcity.

The following Search Ranges are used for the selection of the samples during Simple Kriging:

First search volume; full variogram range (m)

- Minimum number of samples 8 in search volume one
- Maximum number of samples 40 in search volume one

Second search volume is 2 times first search volume;

- Minimum number of samples 4
- Maximum number of samples 30

Third search volume 5 times first search volume;

- Minimum number of samples 1
- Maximum number of samples 20

9.4 Discussion of Results

Detailed checks were carried out for kriged estimates by analysing kriging efficiencies and kriging slopes of regression on an individual kriged block basis. The kriging variance, kriging efficiency, and the slope of regression are calculated from the Ordinary Kriging process and are used to interrogate the efficiency of the kriged estimates.

Adding the flatly inclined dataset increase the confidence in the kriged blocks. There are now more samples utilised during kriging in domain 3, 6 and 7 and this is observed from the increase in the Slope of Regression from the OK estimate in Figure 27a and b.

$$Estimation\ Variance = \sigma_\varepsilon^2 = 2\bar{\gamma}(v,V) - \bar{\gamma}(v,v) - \bar{\gamma}(V,V)$$

$$Kriging\ Variance = \sigma_K^2 = \sum_{i=1}^{n} w_i\bar{\gamma}\,(v_i,V) - \bar{\gamma}(V,V) + \mu$$

$$Block\ Variance = \sigma_B^2 = \sigma^2 - \bar{\gamma}(V,V)$$

$$Kriging\ Efficiency = KE = \frac{\sigma_B^2 - \sigma_K^2}{\sigma_B^2}$$

$$Slope\ of\ Regression = SLOR = \frac{\sigma_B^2 - \sigma_K^2 + \mu}{\sigma_B^2 - \sigma_K^2 + 2\mu}$$

$where$

$\mu = la\ Grange\ multiplier\ can\ be\ positive\ or\ negative$

v = sample support

V= block support and

$\bar{\gamma}(.,.) = average\ variogram\ value\ for\ the\ support$

Source: Dohm (2016b)

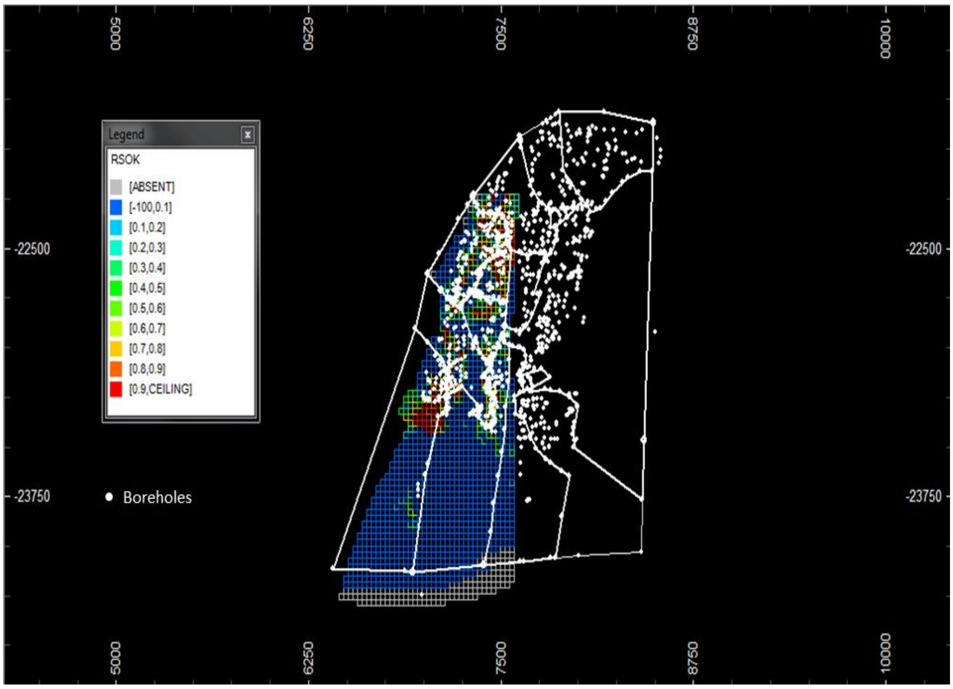

Figure 27a OK Slope of regression for ECT block models from steeply inclined holes

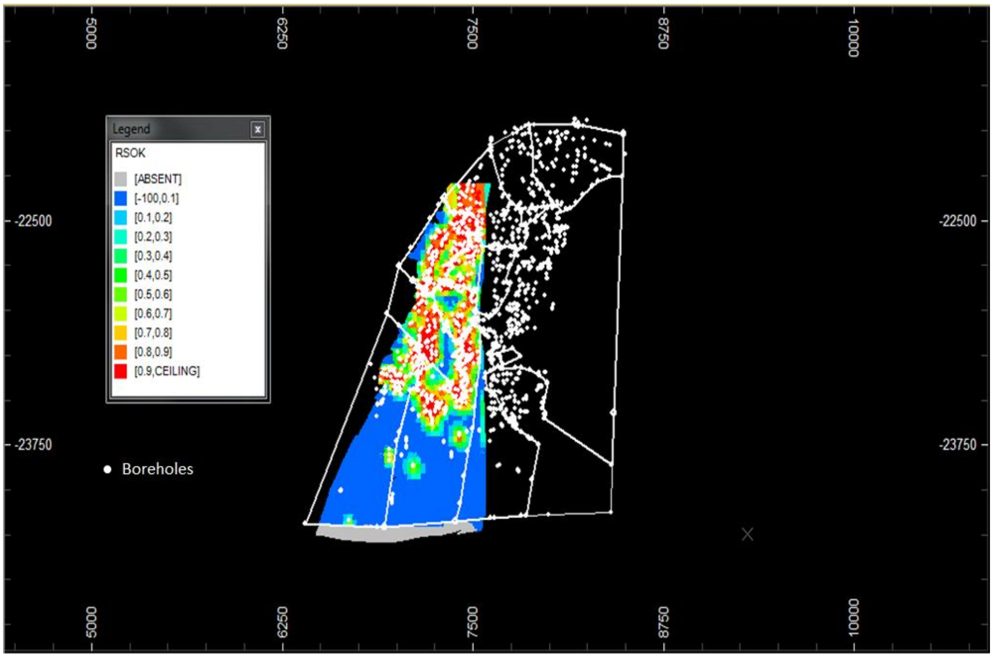

Figure 28b OK Slope of regression for ECT block models from the combined dataset

In addition, checks for the mean are conducted by comparing kriged estimate mean against reef per domain point data mean. Furthermore, the values in the block estimate are visually compared to the values from the sample data that is within that block. (See Figure 28 a and b below)

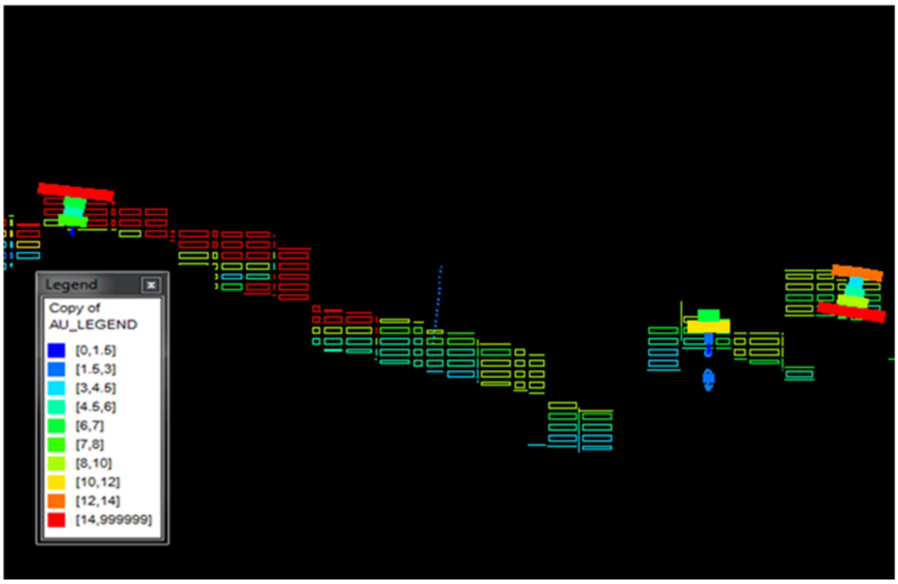

Figure 28a A comparison of the estimated block model with the borehole composites for a model from the combined dataset.

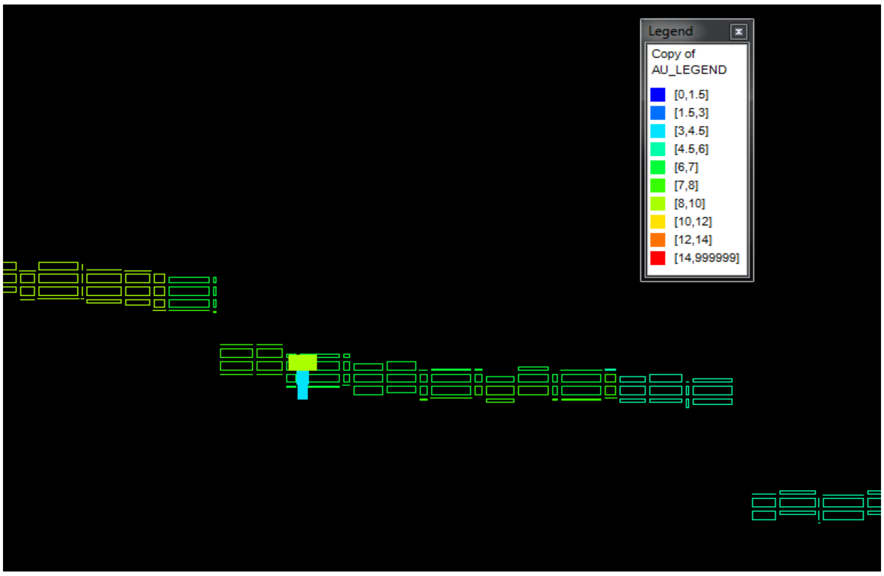

Figure 28b A comparison of the estimated block model with the borehole composites for a model from the steeply inclined dataset.

9.5 Post Processing (Local Direct Conditioning)

This section is mainly informed by Assibey- Bonsu et al (2014) and Assibey-Bonsu, W. and Krige, D.G. (1999). In the area where the data density is low the kriged grade can be smoothed over a vast distance. The local direct conditioning (LDC) allows the correction of the inherent smoothing of the kriged estimates due to information effect. There are various other techniques that are developed to address the smoothing during estimation such as spectral processor and conditional simulation. This approach is based on deriving the unknown distribution from the observed distribution of the kriged blocks estimated from the area with high borehole density.

The estimates from LDC results from the kriged grade estimate. The direct conditioning is achieved by superimposing a lognormal distribution and variance from the actual block values (values from the area with high data density) to the smoothed block values using information effect (See figure 29 below).

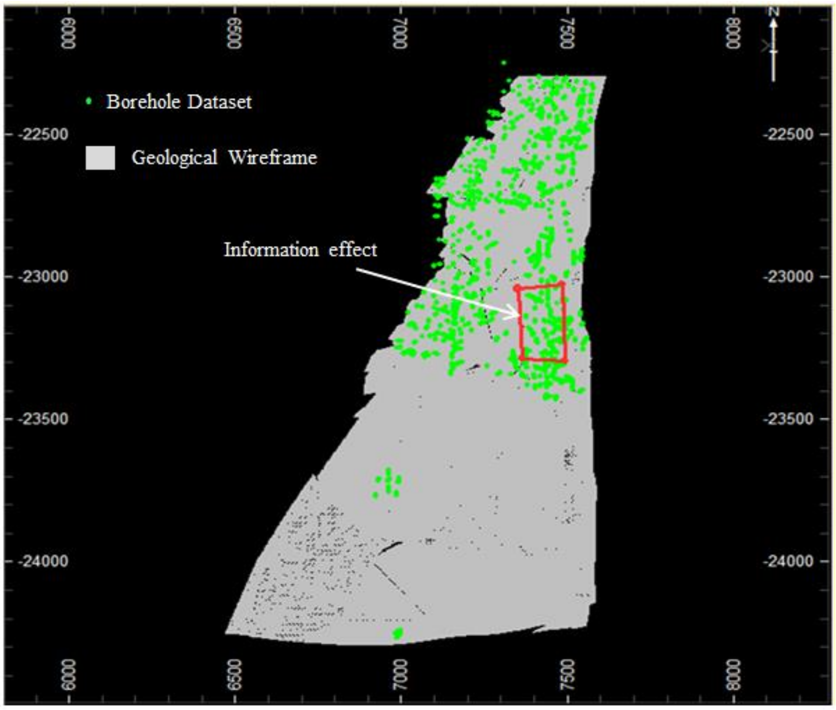

Figure 29 Information effect in the high borehole data density area

In this process one tries to mimic the variation seen in sample grades in a high data density over the low sample density data area. Typically, in the medium term and long-term planning areas of the mine ahead of the current mining faces.

According to Assibey-Bonsu (2014) the LDC process consist of the following steps

- Derive Simple Kriging estimates,
- Estimate the local conditioning distribution using the mean from the smoothed kriged estimates of the selective mining units (SMU) and its variance.
- Translate individual SMU grade tonnage results into a large panel (120m X 120m was used)
- Decompose the panel grade tonnage results into an unsmoothed panel

The Simple Kriging model is post processed from a 30m x 30m x 1m parent block to 10m x 10m x 1m selective mining units (SMU). The post-processing portion of an SMU block that will contain a specific grade and tonnage above different cut-off grades is calculated. This is due to the fact that the estimated grade is the average grade for the block, but higher as well as lower grades will be mined throughout this block, in the end yielding the same average grade. This results in Tonnage and Grade Parcels at different cut-off grades within the block which is referred as the TPGP model.

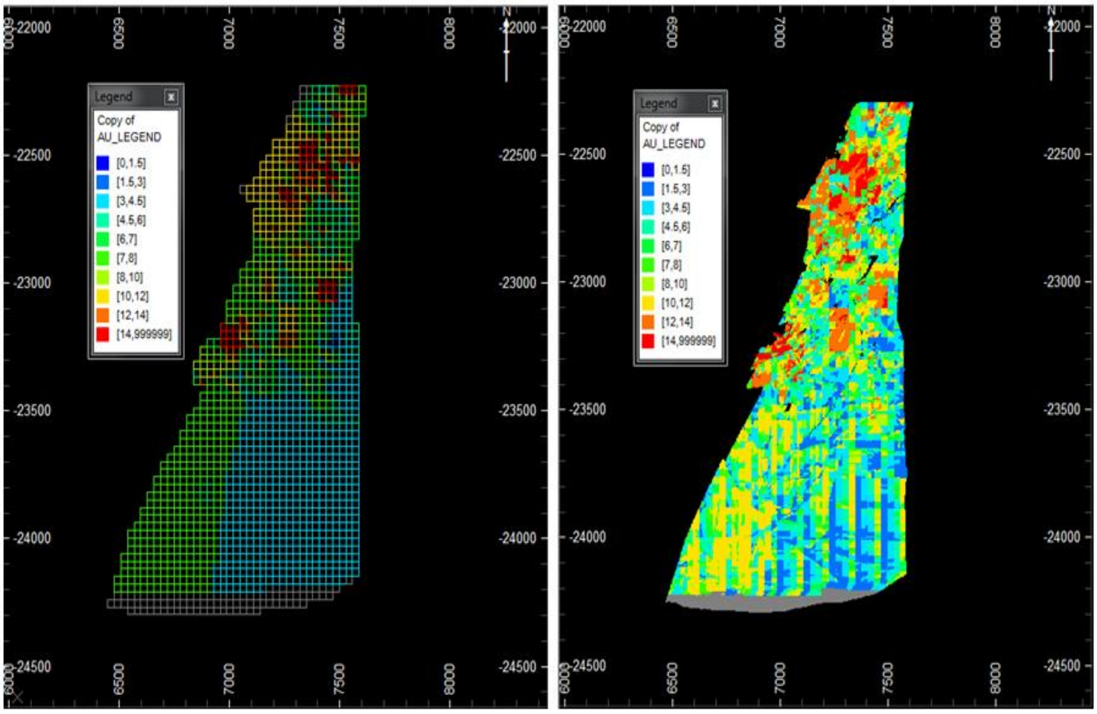

Figure 30 a plan view of the block model for the Steep inclined holes before LDC i.e. with the smoothed estimates and next to it a plan view of the block model for the Steep inclined holes after LDC i.e. with the SMU grade estimates

At South Deep, in the current mine area, the parent block size (Grade Model Block Size) is a 30m x 30m x 1m. The SMU at South Deep is calculated at a block size of 10m x 10m x 1m, and the grade control drilling grid is planned at 30m x 30m x 1m. The discretization during post-processing is kept the same as per the estimation process (5, 5, 1). Localised Direct Conditioning (LDC) utilises the confidence limits, change of support as well as the TPGP's to redistribute the grade within a 120, 120, 1 area (16 parent kriged blocks) to mimic the variation in grade as seen in the grade-controlled areas. (See the Simple Kriging and post processed models in Figure 32).

Assibey- Bonsu et al (2014) specify that the Localised Direct Condition (LDC) methodology is an extension of the Local Uniform Conditioning (LUC) technique proposed by Abzalov (2006) and further applied in Abzalov (2014). The Local Uniform Condition in Abzalov (2014) is described as a technique developed to overcome the limitations of the conventional Uniform conditioning. The methodology is the same as that of LDC where the panels are split on sub cells with sizes equal to the SMUs. These SMUs blocks are distributed in the panel and therefore ranked in order of increasing grade. Based on the ranking, a single grade value is deduced for each block from the uniform conditioning model of the grade tonnage relationships of the corresponding panel. The LUC method is common in grade estimation of the areas with broad data spacing.

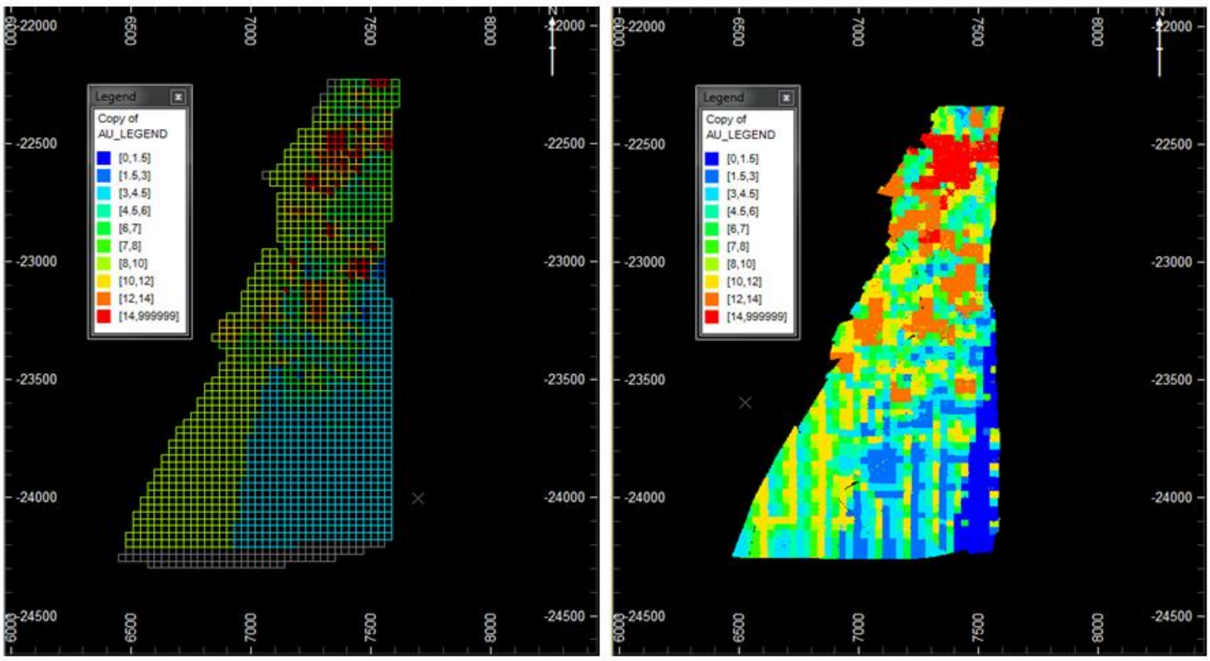

Figure 31 A plan view of the block model for the combined holes before LDC i.e. with the smoothed estimates next to it a plan view of the block model for the combined holes after LDC i.e. with the SMU grade estimates

10 RECONCILIATION

Table 9 summarises, the grades and tonnages above cut-off at different cut-off grades for both the LDC models, this data was used to generate the grade tonnage curve, shown in Figure 32. The addition of flat boreholes into the database results in a slight decrease of the grade estimate by a maximum of 3% at 0g/t cut-off. The tonnage at this cut-off remains unchanged.

The resource estimate for Au content based on Steep inclined holes only at 0 g/t cut-off is 40908197 g which is 40908 kg of gold which is 1442987.2 oz. Using the combined data set this is the resource estimate for Au content based on the total boreholes at 0 g/t cut-off is 39810379 g which is 39810 kg which is 1404256.4 oz. The metal above 0g/t cut off is 3% less than the gold in the combined data at 0 g/t cut off.

Table 10 Grade tonnage table calculated from the 3m x 2m x 1m LDC models

	Steep Boreholes		Difference		Combined boreholes	
Cut-Off (g/t)	AU_LDC (g/t)	Content (g)	LDC	Content	AU_LDC (g/t)	Content (g)
0	7.08	40908197	-3%	-3%	6.89	39810379
3	8.01	38614824	-1%	-1%	7.89	38083870
4	8.59	36319190	-1%	-1%	8.5	35938663
5	9.36	33593938	-2%	-2%	9.21	33055574
6	10.1	29726320	-1%	-1%	10.03	29520296
7	10.78	25733649	1%	1%	10.85	25900751
8	11.28	22865158	2%	2%	11.47	23250298

The observation of changes at the cut-off of from 3g/t to 4 g/t is important, the Mineral Resource and Mineral Reserve reporting occur at these cut-offs.

Negligible deviations were observed in the Grade-Tonnage curve indicating that the model remains stable following the addition of flat boreholes in the estimate. (See Figure 32)

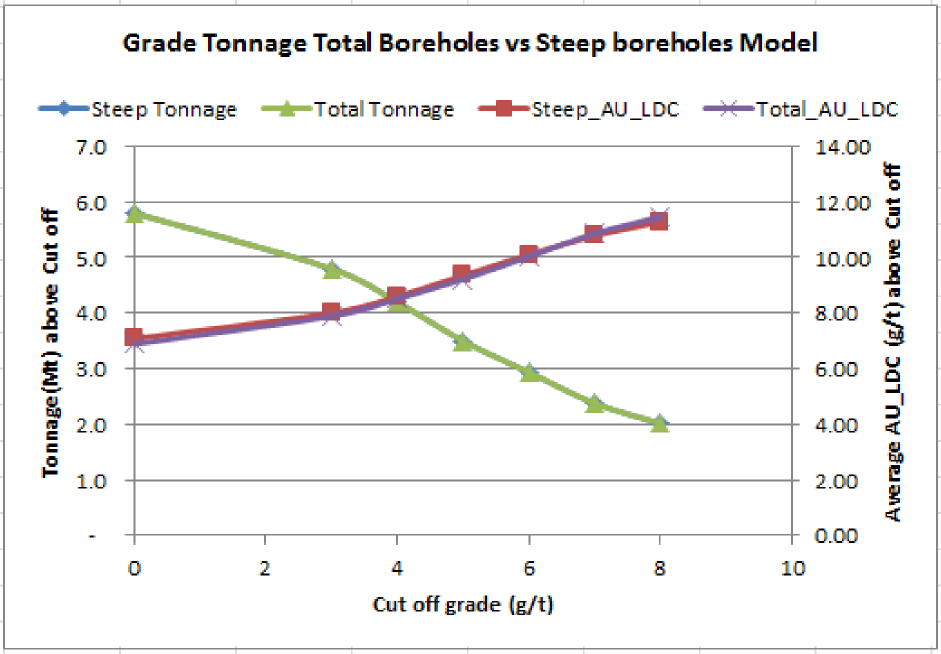

Figure 32 Grade and Tonnage curve of two model results.

11 CONCLUSIONS & RECOMMENDATIONS

The research has been successful in that the research questions have been answered and the objective of improving the modelling of the variography for the ECT reef has been achieved.

This research project highlighted the importance of information from flatly inclined boreholes (boreholes with a dip greater -55^0 or less than 55^0) in the Mineral Resource estimation and evaluation process at South Deep mine. It has been found that adding the flatly inclined boreholes in the Mineral Resource estimation increases the confidence in Kriging and improves variogram models. The distribution of the gold grades from the composites of the flatly inclined boreholes has similar characteristics as to that of the steeply inclined holes boreholes.

This additional information improves variography in all domains in that additional close spaced data is effectively added, the impact is more pronounced in domains with few steeply inclined data. More data in general results in closely spaced drilling information which improves the nugget effect modelling and the reduction of variability in the experimental variogram values leading to improved modelling in a succinct way.

More Ordinary Kriged blocks have a slope of regression that is closer to 1 following the addition of FIBs in estimation. With this it can be concluded that the grade confidence has increased with the inclusion of these boreholes in the estimation process.

The model reconciliation where the model derived from the samples from steep boreholes was compared with the model from the combined boreholes, the results indicate that the model remains stable with 1% changes at the current Mineral Resource and Mineral Reserve cut–off grade. Adding the FIBs in the estimation reduced the ECT reef by 1.4 million ounces which is less than 1% of the estimated ounces from this reef.

All the boreholes (with FIBS included) at South Deep mine are assayed. The flatly inclined boreholes are assayed for Facies modelling only, which adds a significant cost, monetary, time and capturing effort of the assay data. Inclusion of these boreholes in variography and mineral resource estimation ensures a better optimisation of the money spent in assaying, since these boreholes improve the estimation confidence and resulted in improved variogram modelling.

It is recommended that this study is extended to other Elsburg reefs, with the focus on checking the sensitivities in the model. It is recommended that the steep boreholes be prioritised when planning the drilling programme since they provide efficient selection of samples in the Mineral Resource estimation process, but where there is lack of drilling platform it is advised that one plans few flat boreholes for geological modelling and sampling.

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Appendix 1: ECT reef Domain 1 Graphical presentation of Statistics and Geostatistical Analyses

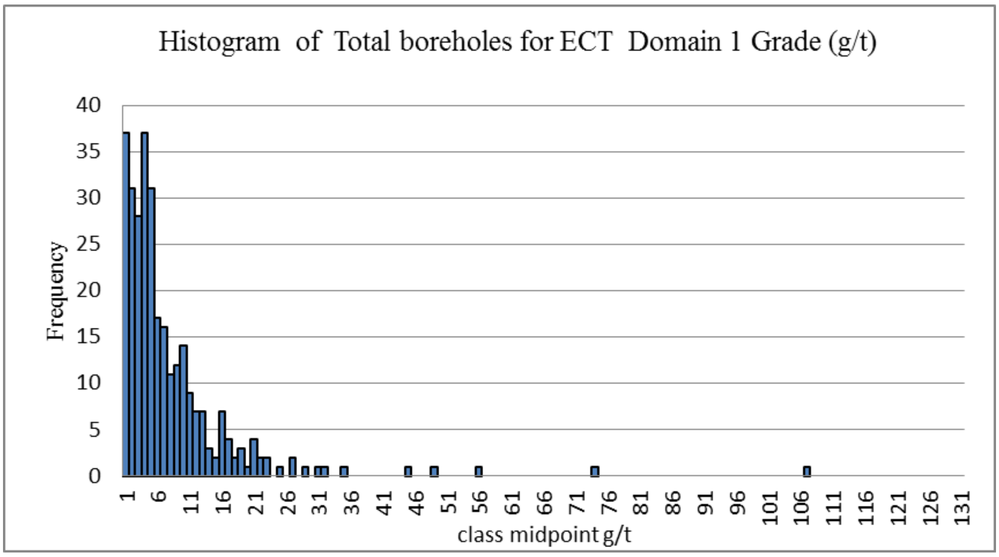

Figure A1 1 Relative Histogram Au (g/t) grade ECT Domain 1

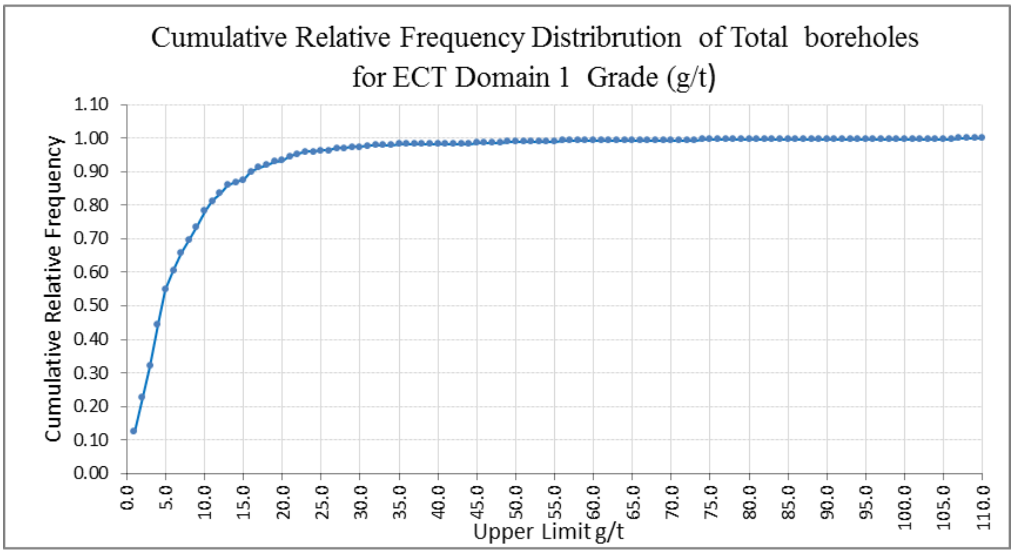

Figure A1 2 Cumulative Relative Frequency Au(g/t) grade ECT Domain 1

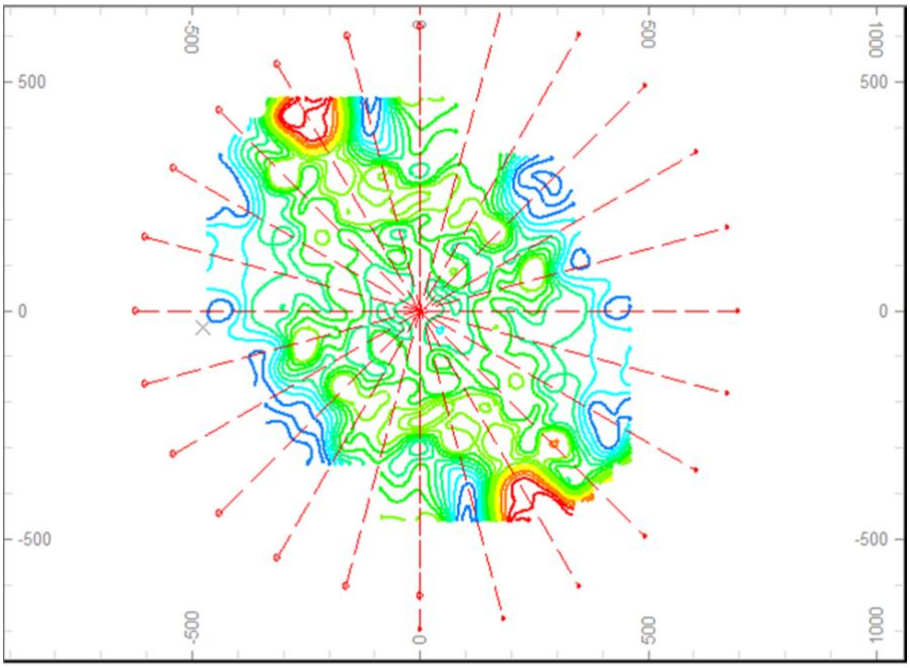

Figure A1 3 Varmap ECT Au(g/t) grade Domain1

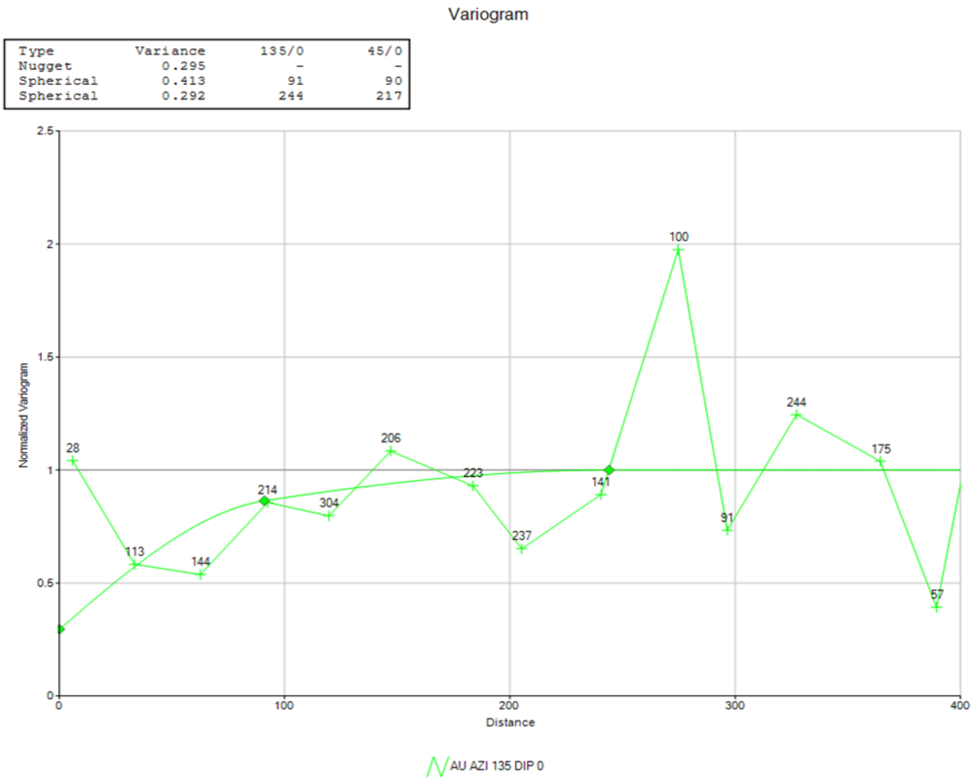

Figure A1 4 Variogram models ECT Au(g/t) grade Domain1

Appendix 2- ECT reef Domain 2 Graphical presentation of Statistics and Geostatistical Analyses

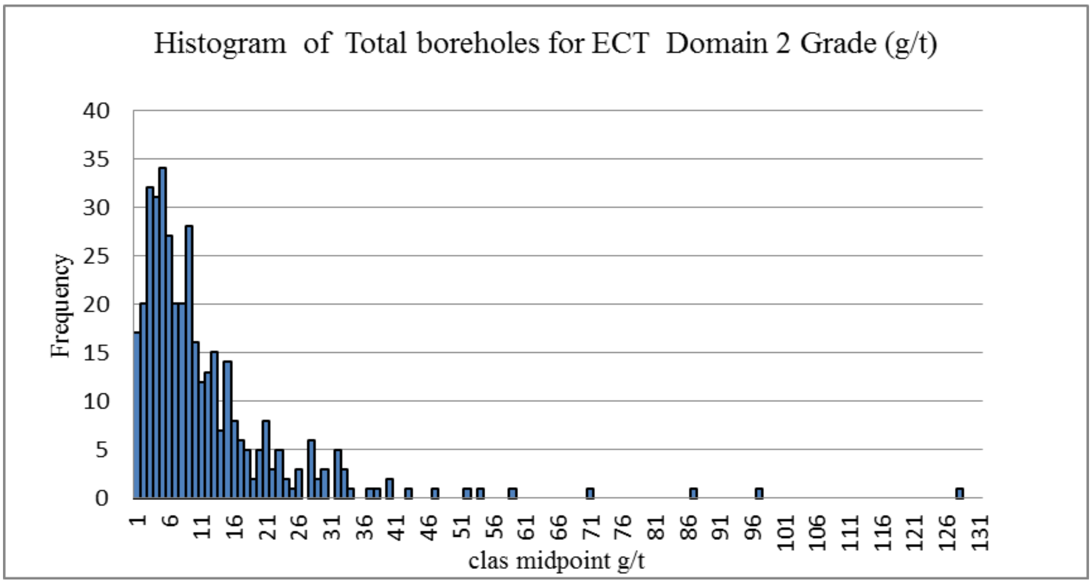

Figure A2 1 Relative Histogram Au (g/t) grade ECT Domain 2

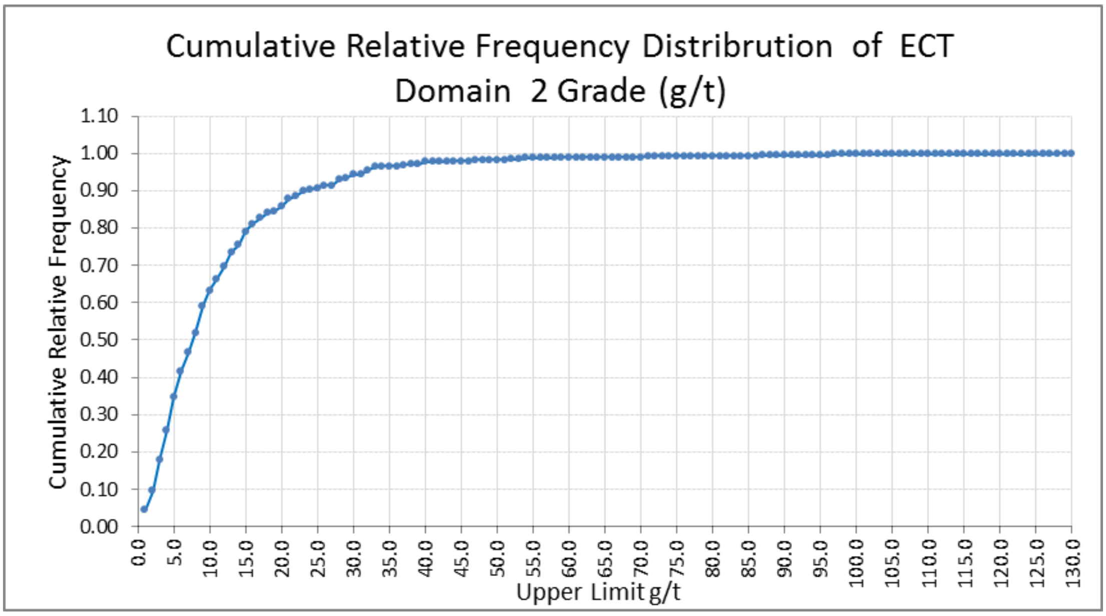

Figure A2 2 Cumulative Relative Frequency Au(g/t) grade ECT Domain 2

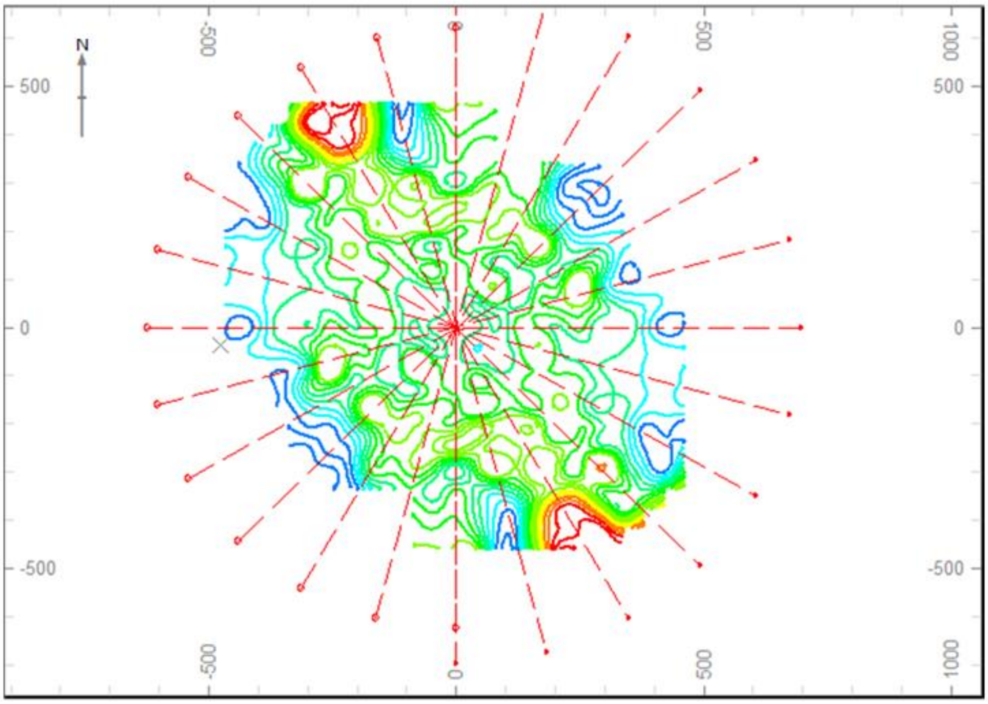

Figure A2 3 Varmap ECT Au(g/t) grade Domain

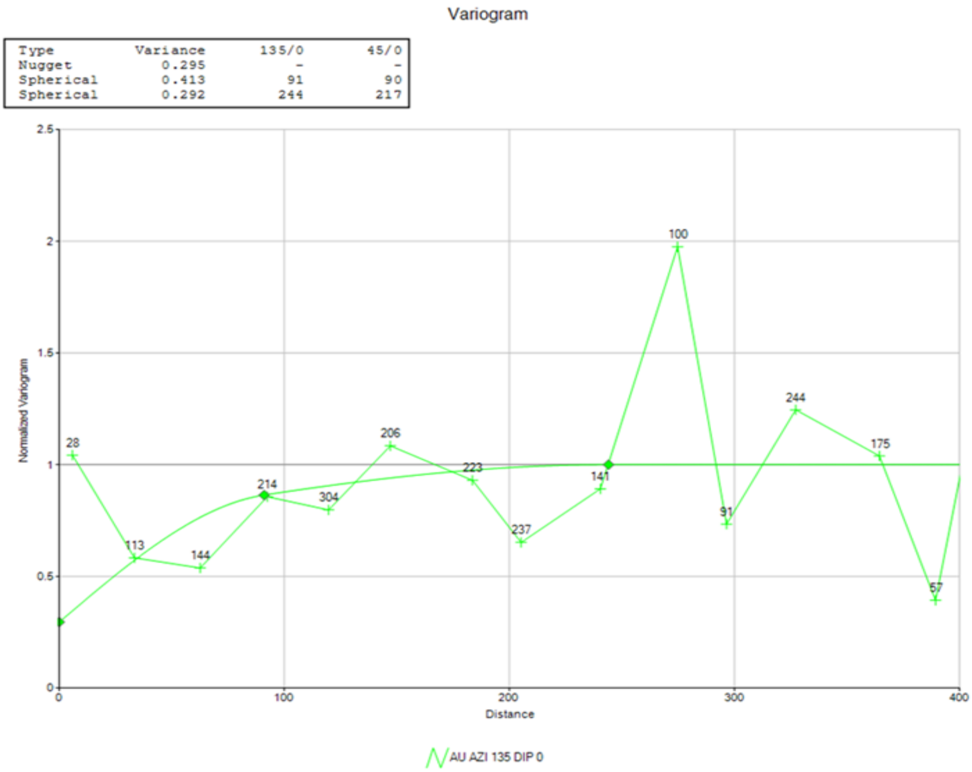

Figure A2 4 Variogram model ECT Au(g/t) grade Domain 2

Appendix 3- ECT reef Domain 3 Graphical presentation of Statistics and Geostatistical Analyses

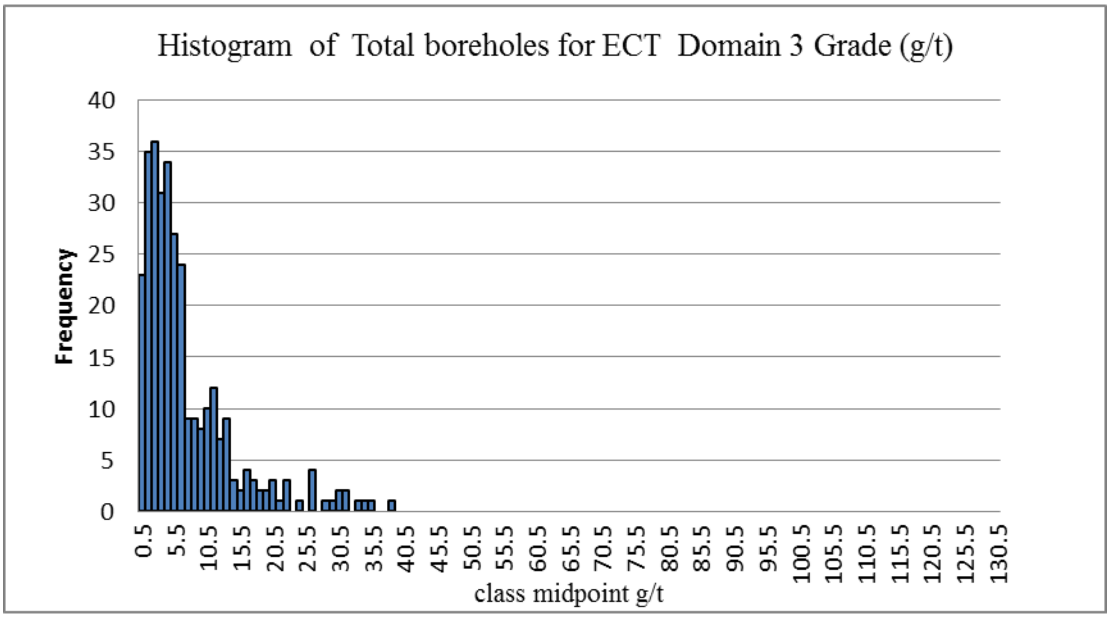

Figure A3 1 Relative Histogram Au (g/t) grade ECT Domain 3

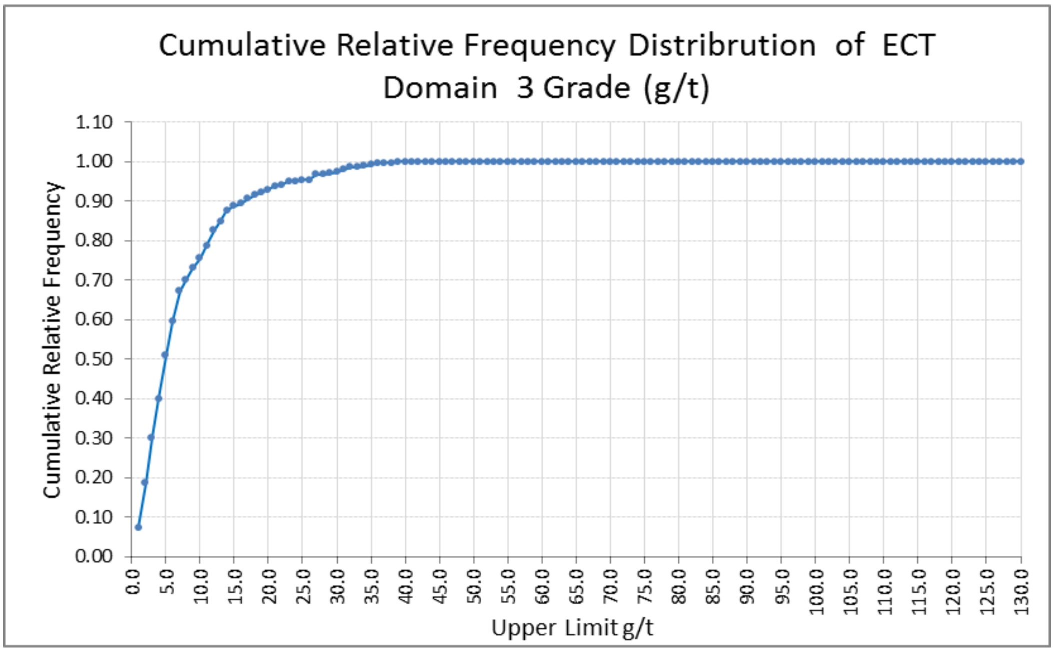

Figure A3 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 3

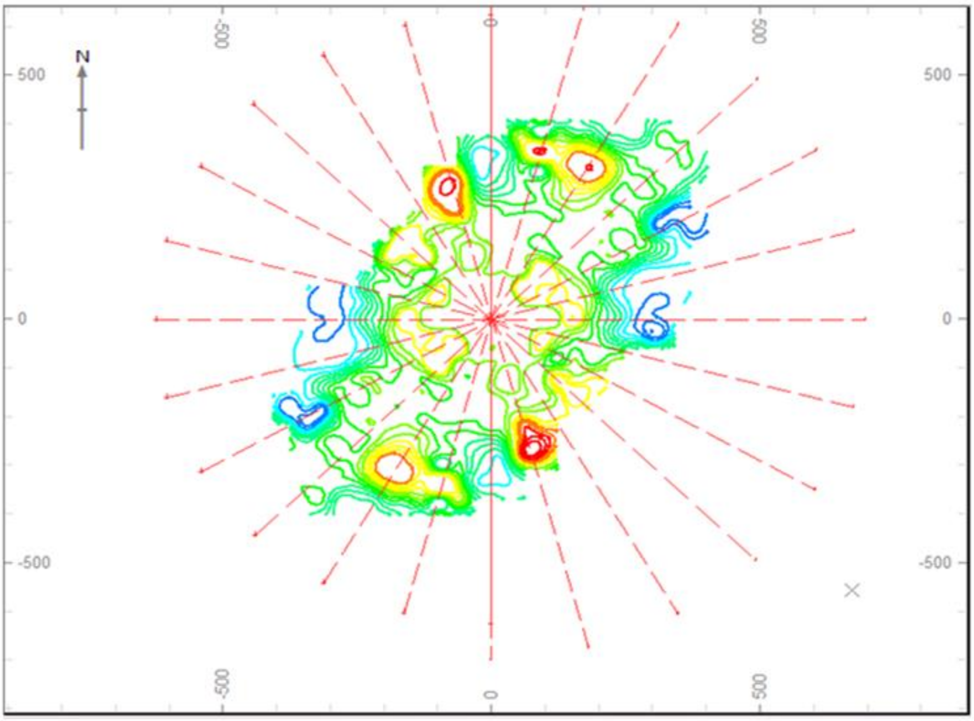

Figure A3 3 Varmap ECT Au(g/t) grade Domain 3

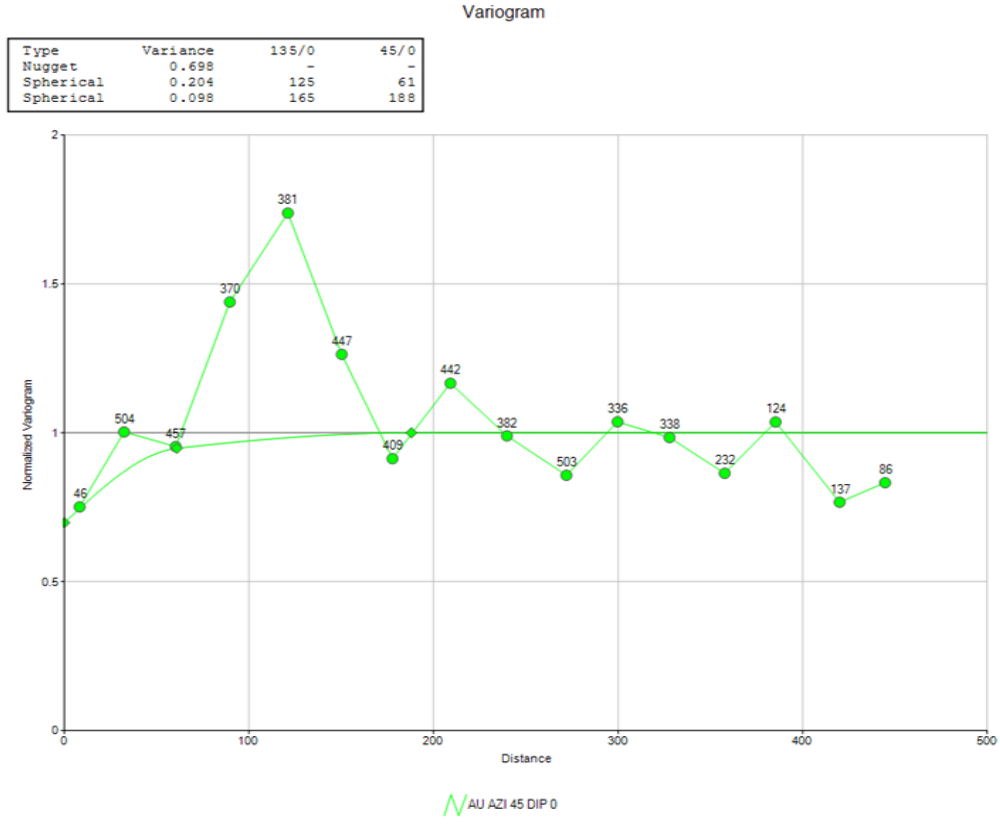

Figure A3 4 Variogram model ECT Au (g/t) grade Domain 3

Appendix 4- ECT reef Domain 4 Graphical presentation of Statistics and Geostatistical Analyses

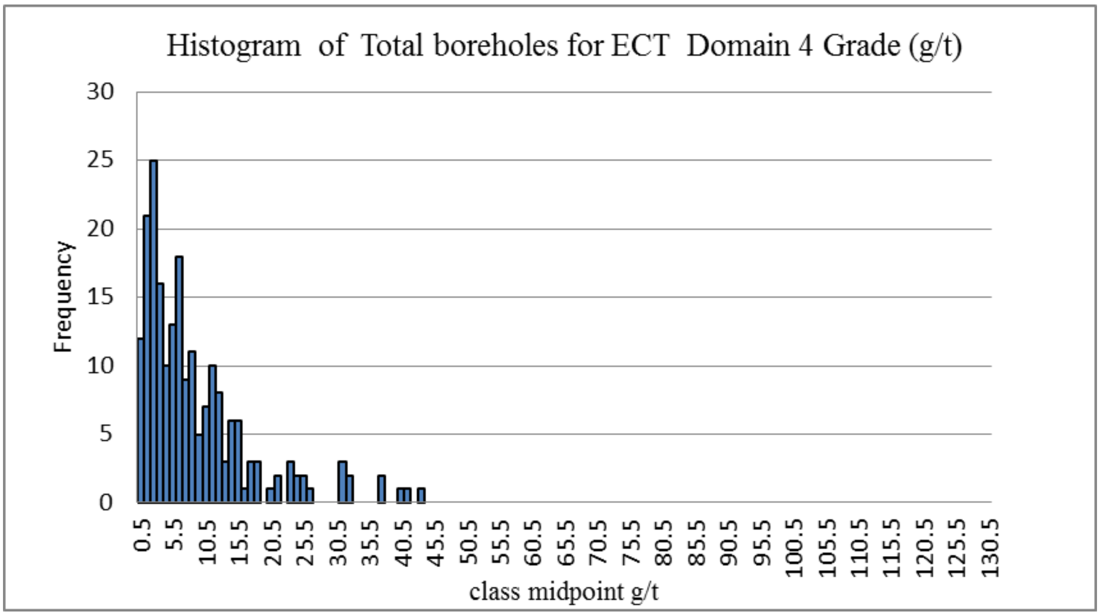

Figure A4 1 **Relative Histogram Au (g/t) grade ECT Domain 4**

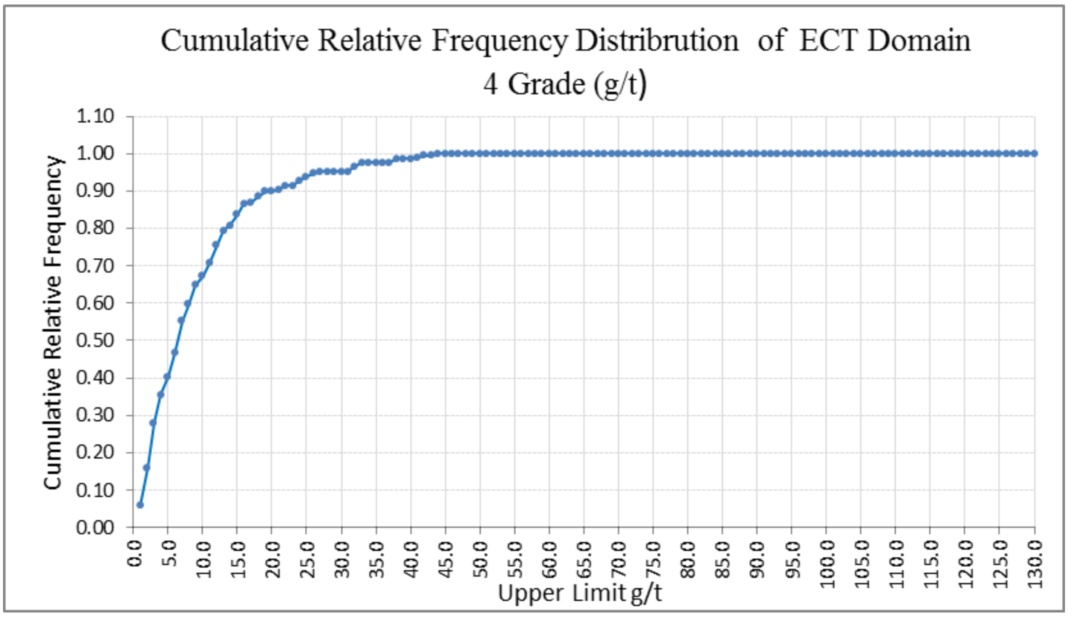

Figure A4 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 4

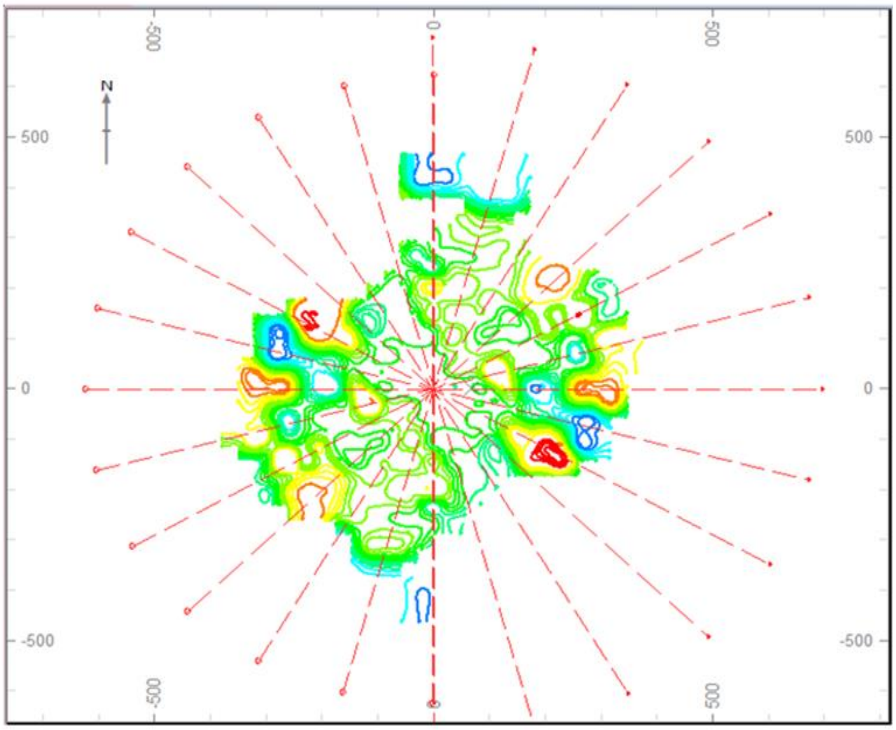

Figure A4 3 Varmap ECT Au (g/t) grade Domain 4

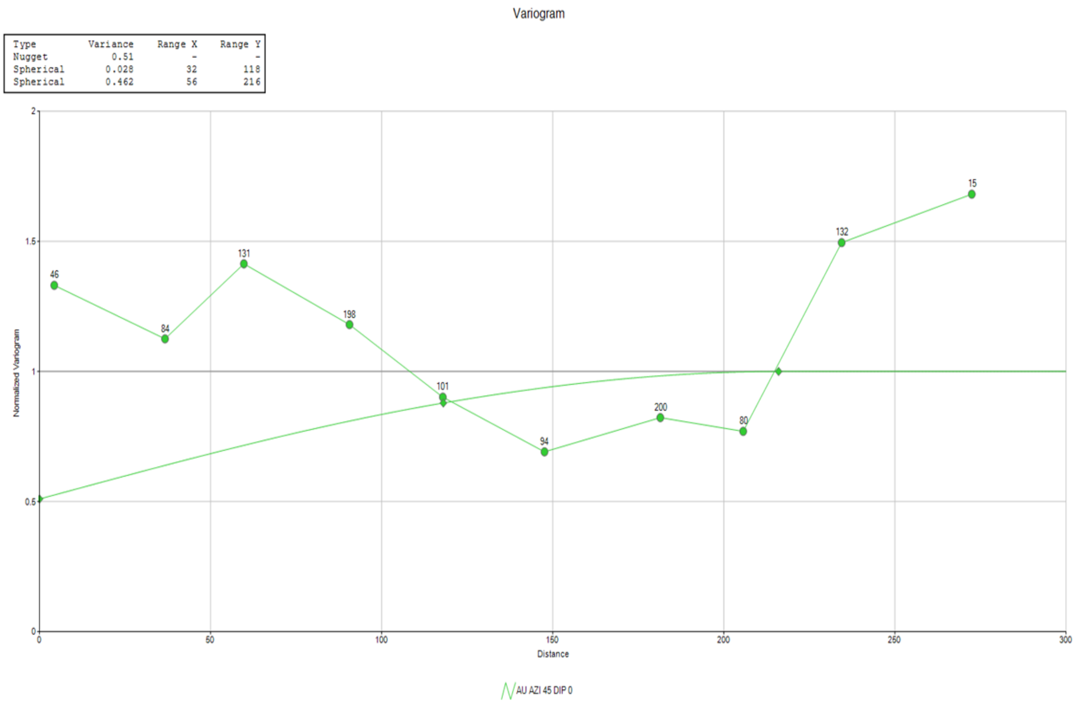

Figure A4 4 Variogram models ECT Au (g/t) grade Domain 4

Appendix 5- ECT reef Domain 5 Graphical presentation of Statistics and Geostatistical Analyses

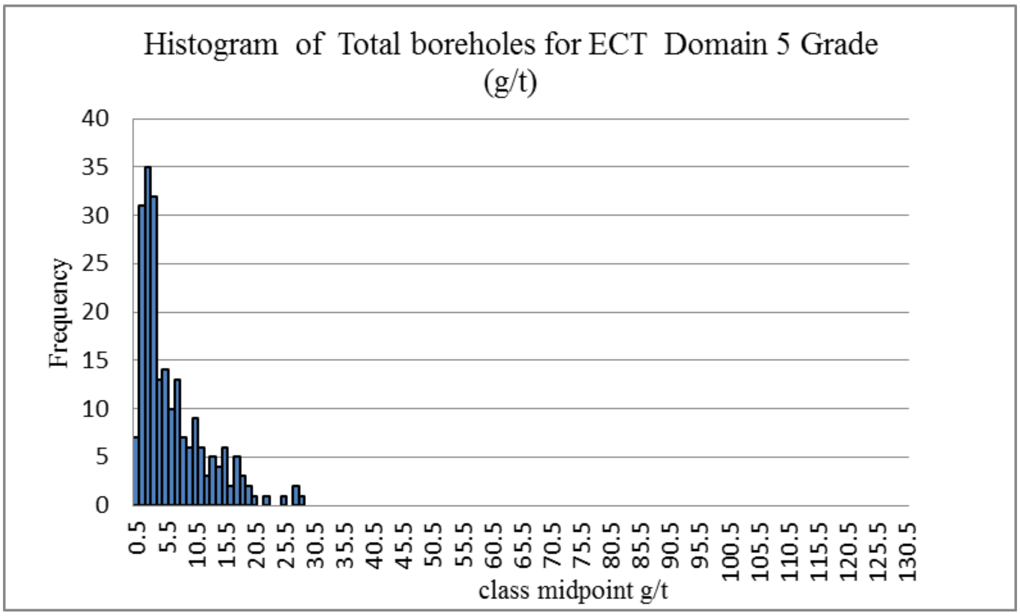

Figure A5 1 Relative Histogram Au (g/t) grade ECT Domain 5

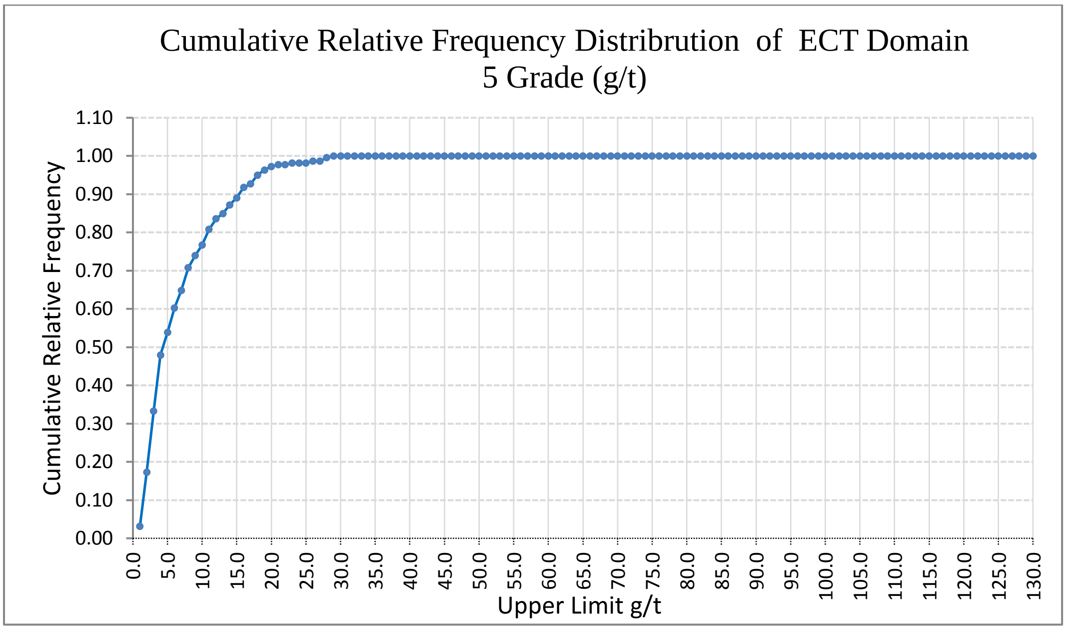

Figure A5 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 5

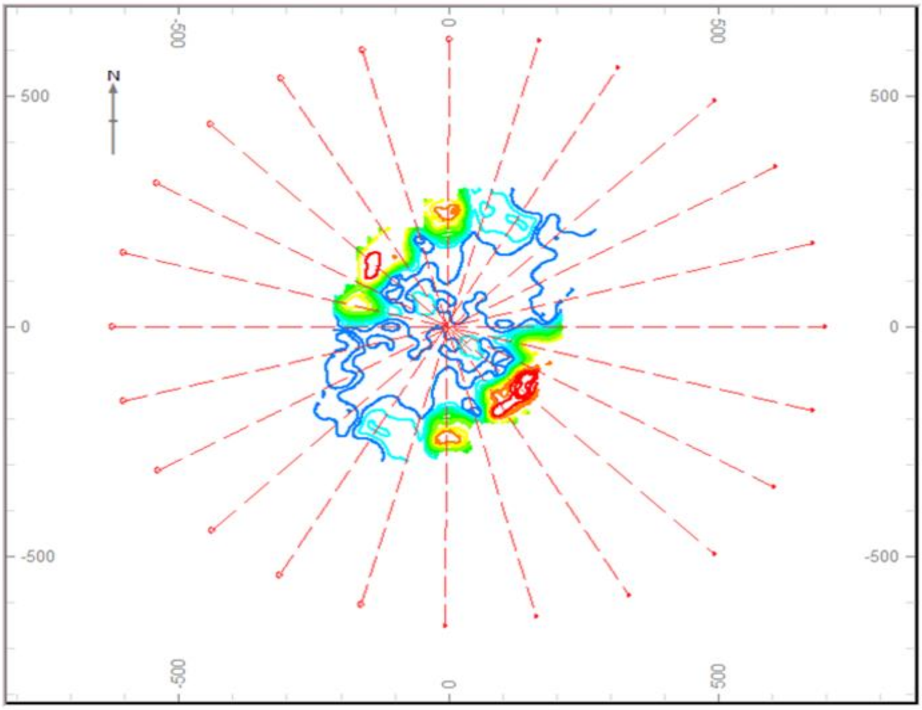

Figure A5 3 Varmap ECT Au(g/t) grade Domain 5

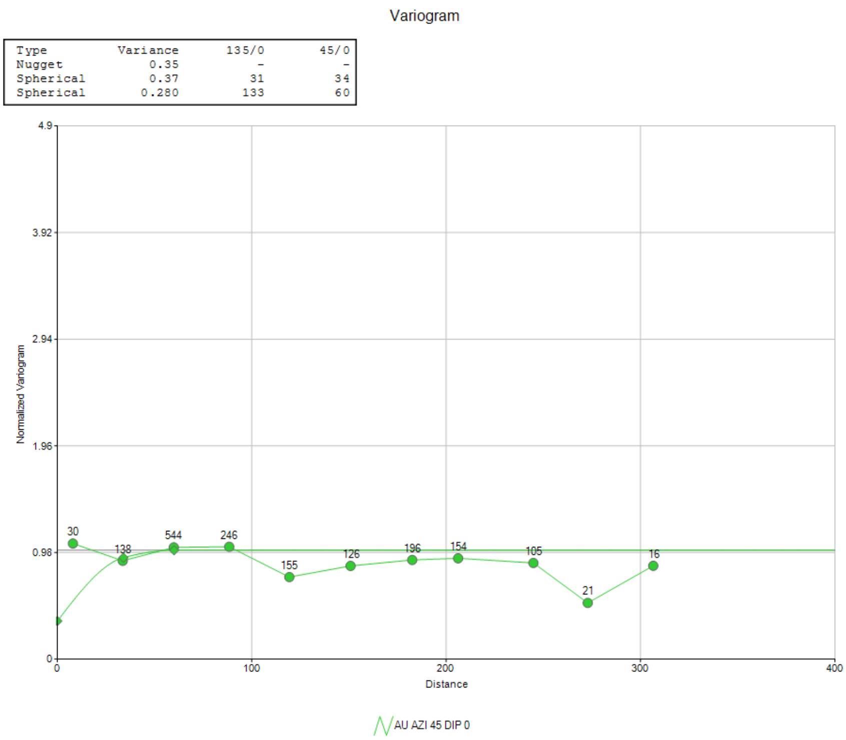

Figure A5 4 Variogram model ECT Au (g/t) grade Domain 5

Appendix 6- ECT reef Domain 6 Graphical presentation of Statistics and Geostatistical Analyses

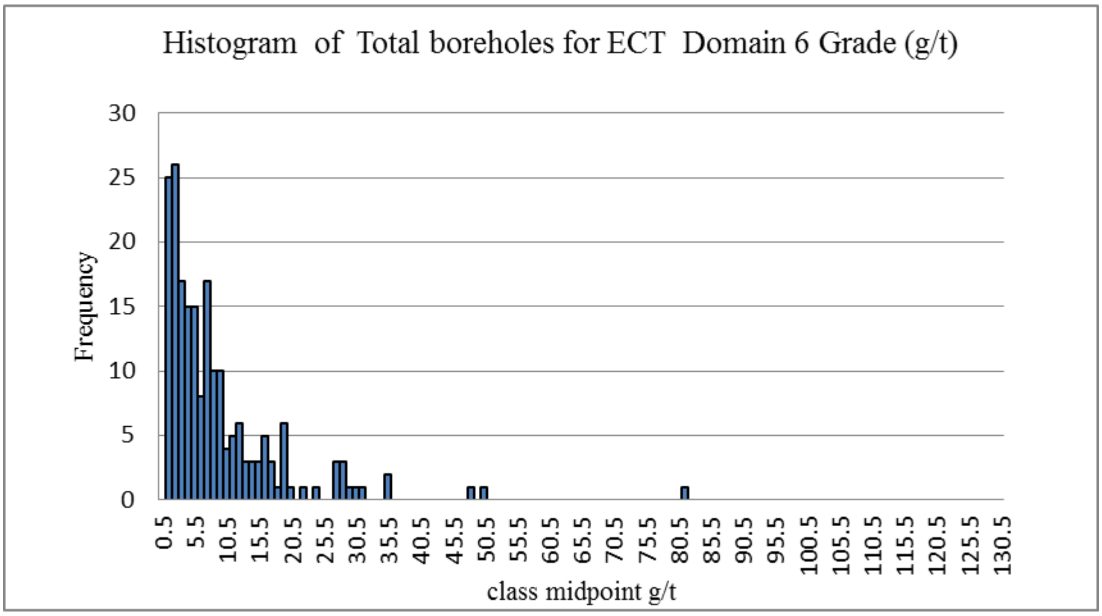

Figure A6 1 Relative Histogram Au (g/t) grade ECT Domain 6

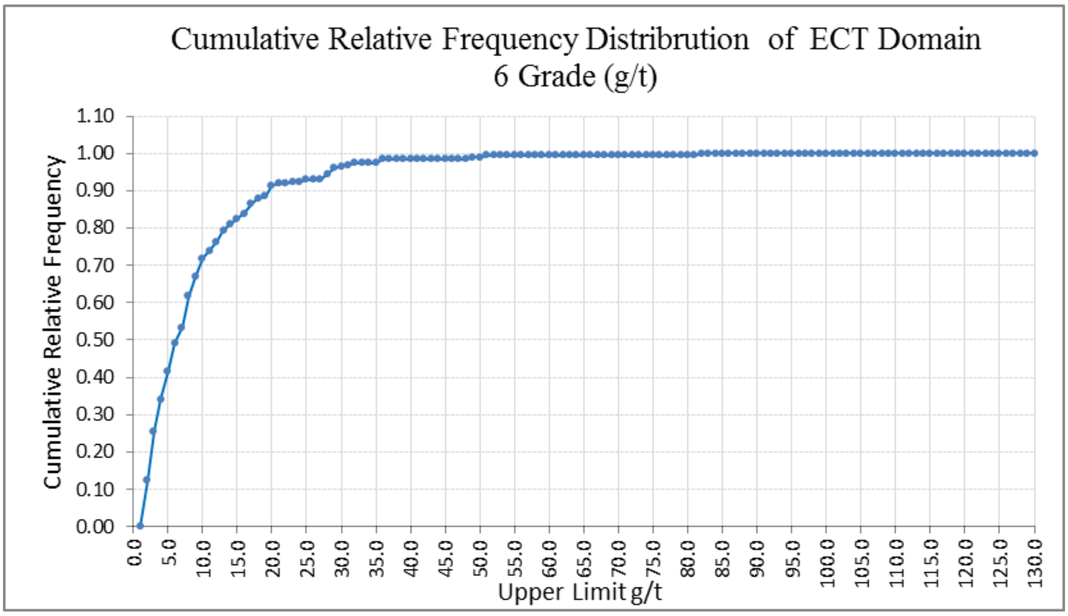

Figure A6 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 6

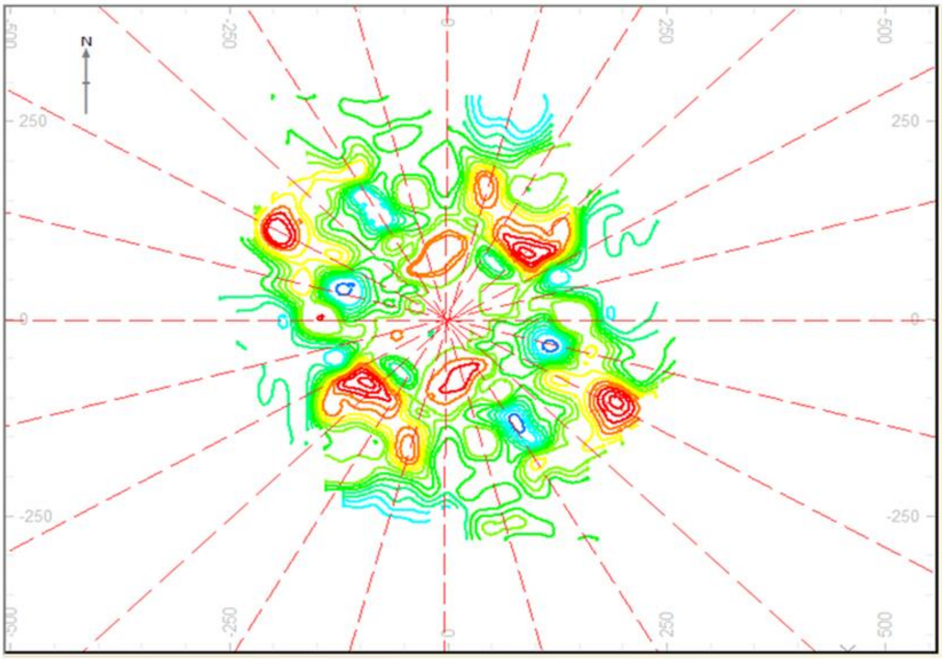

Figure A6 3 Varmap ECT Au (g/t) grade Domain 6

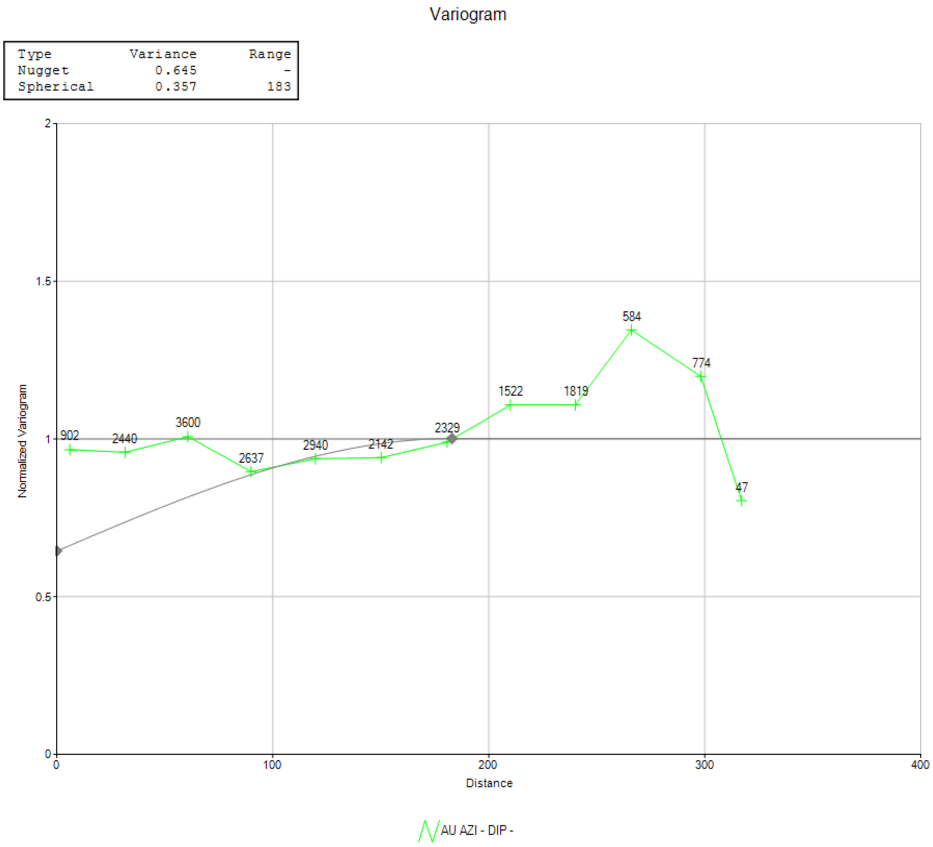

Figure A6 4 Variogram model ECT Au (g/t) grade Domain 6

Appendix 7- ECT reef Domain 7 Graphical presentation of Statistics and Geostatistical Analyses

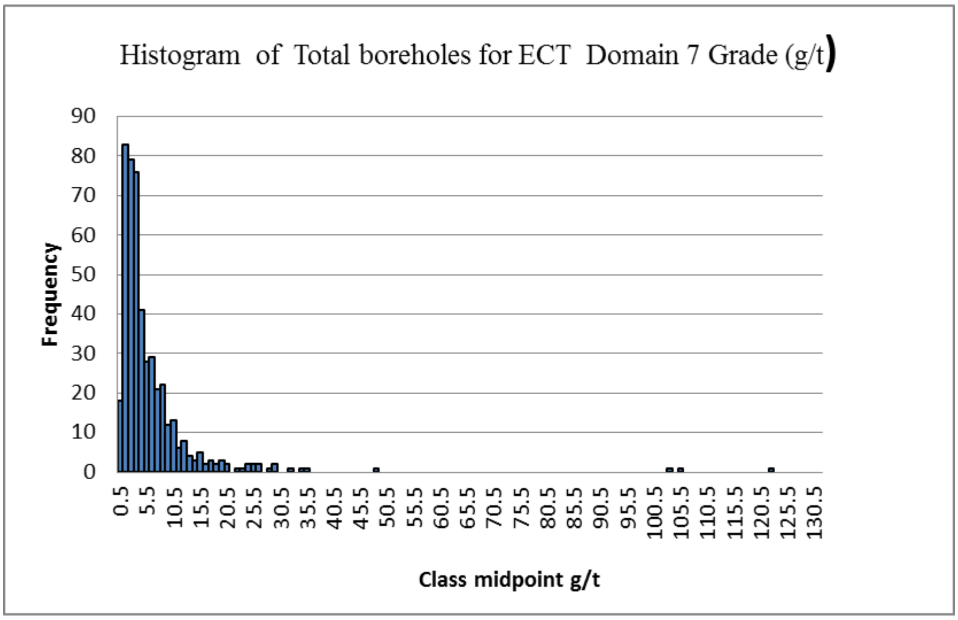

Figure A7 1 Relative Histogram Au (g/t) grade ECT Domain 7

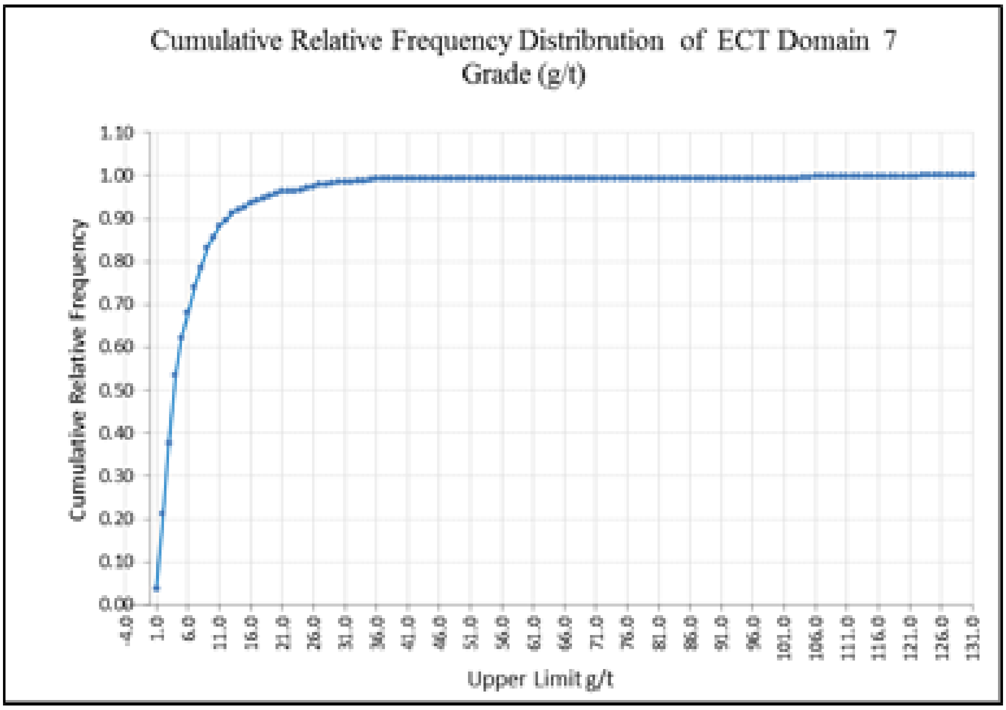

Figure A7 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 7

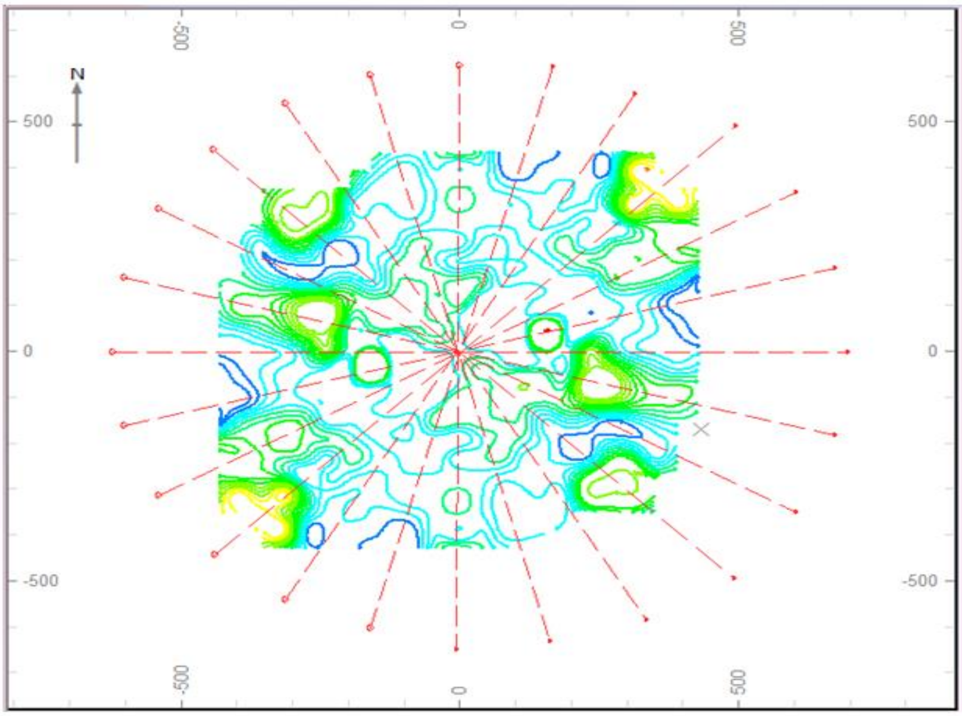

Figure A7 3 Varmap ECT Au (g/t) grade Domain 7

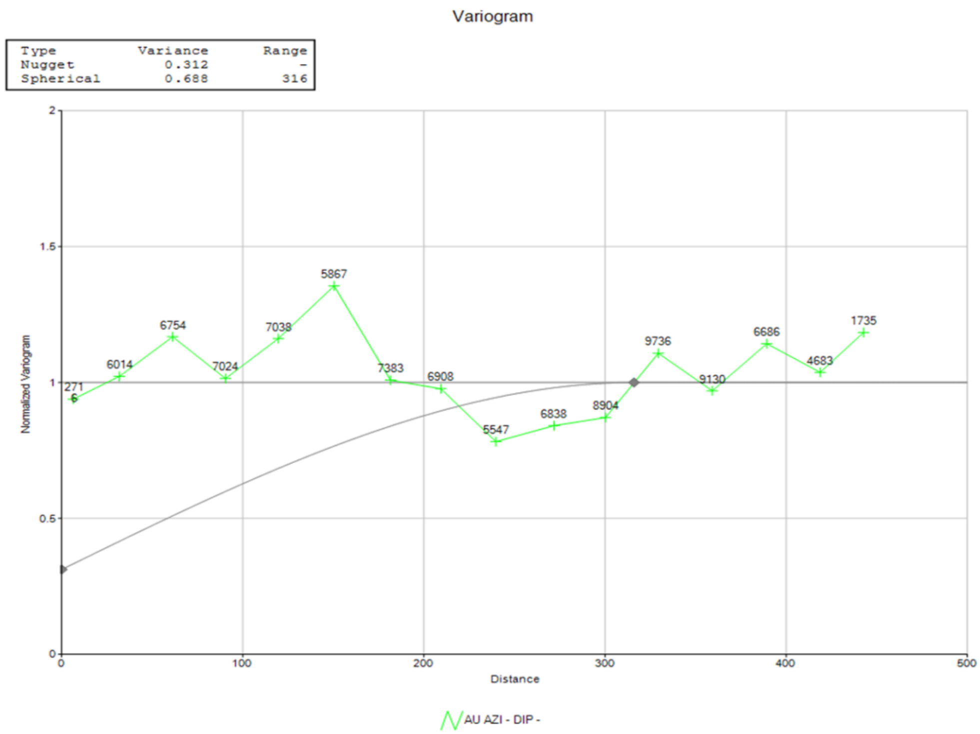

Figure A7 4 Variogram model ECT Au (g/t) grade Domain 7

Appendix 8- ECT reef Domain 8 Graphical presentation of Statistics and Geostatistical Analyses

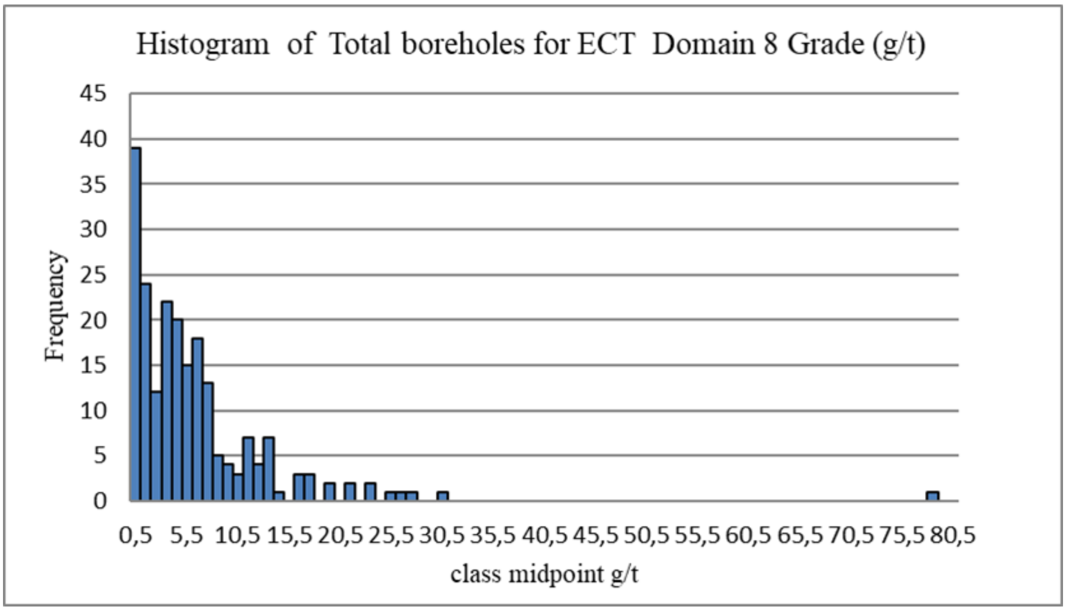

Figure A8 1 Relative Histogram Au (g/t) grade ECT Domain 8

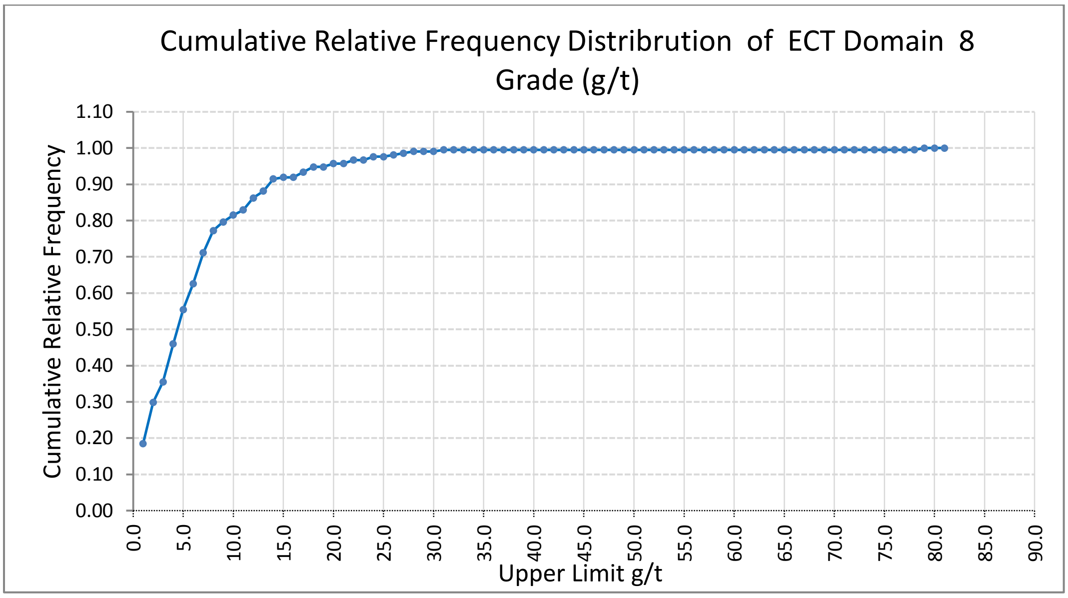

Figure A8 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 8

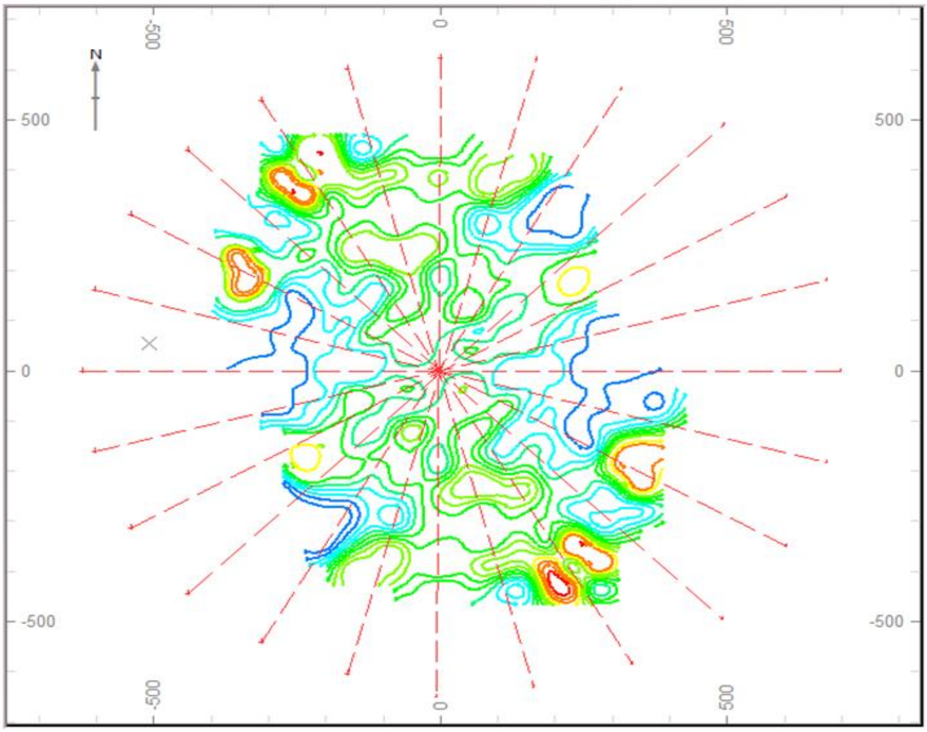

Figure A8 3 Varmap ECT Au (g/t) grade Domain 8

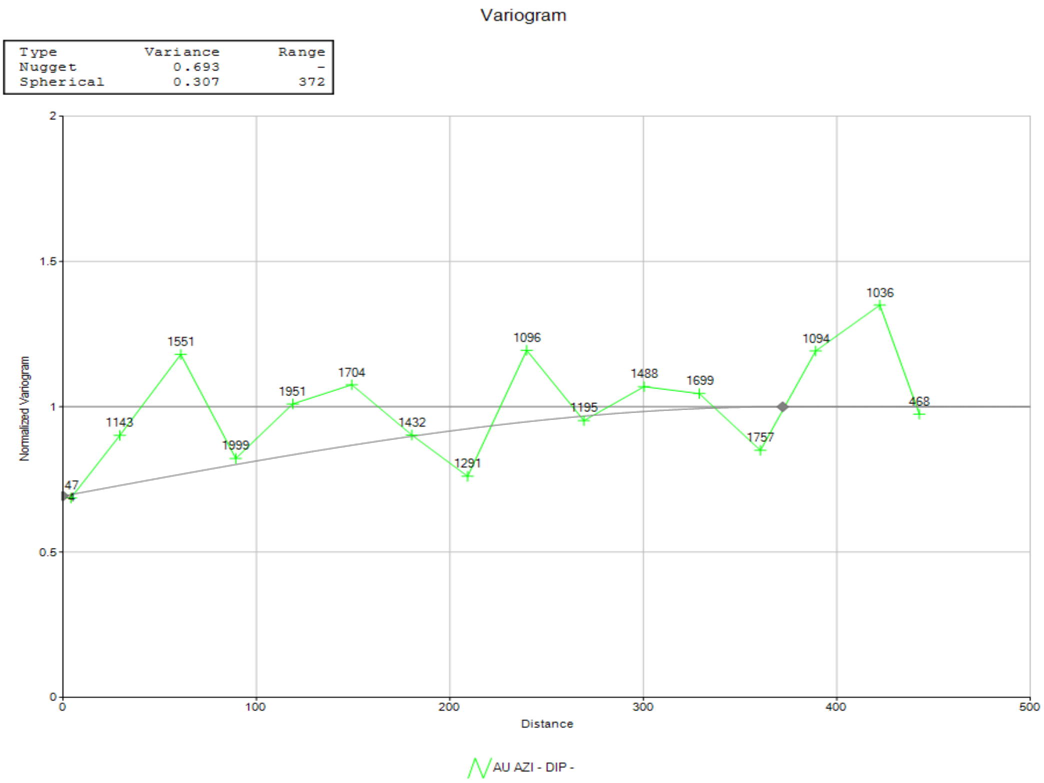

Figure A8 4 Variogram model ECT Au (g/t) grade Domain 8

Appendix 9- ECT reef Domain 9 Graphical presentation of Statistics and Geostatistical Analyses

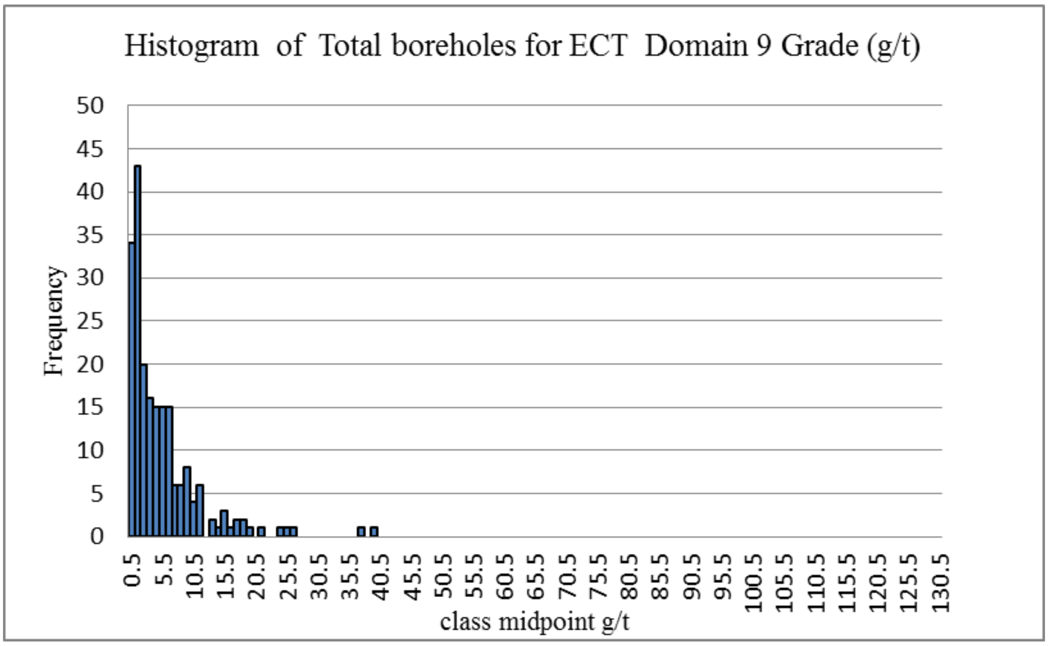

Figure A9 1 Relative Histogram Au (g/t) grade ECT Domain 9

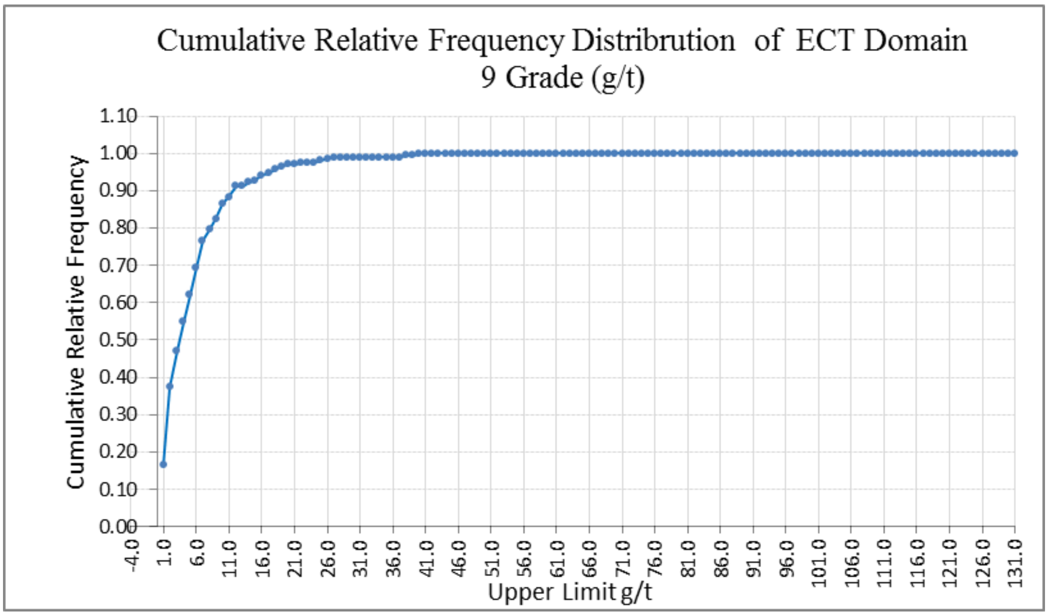

Figure A9 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 9

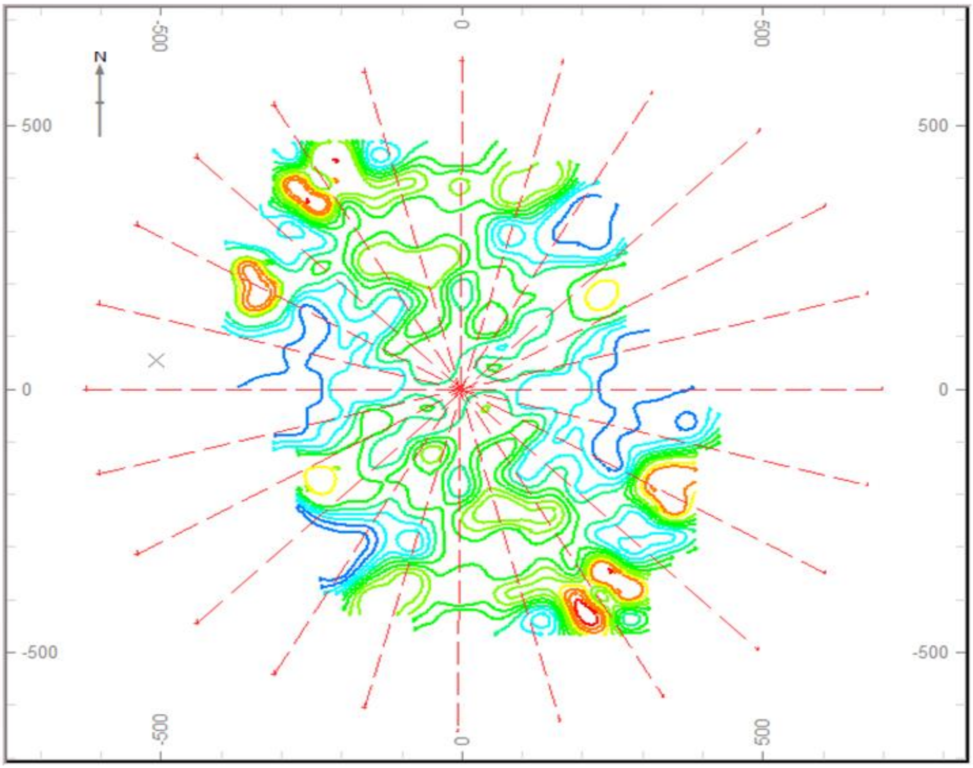

Figure A9 3 Varmap ECT Au (g/t) grade Domain 9

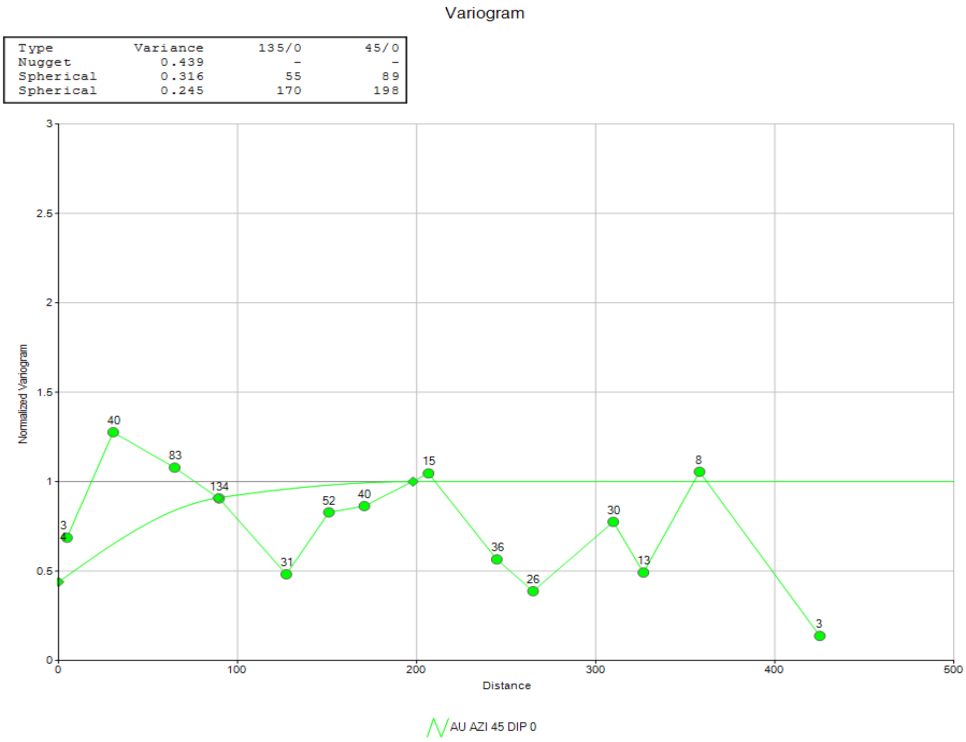

Figure A9 4 Variogram model ECT Au (g/t) grade Domain 9

Appendix 10- ECT reef Domain 10 Graphical presentation of Statistics and Geostatistical Analyses

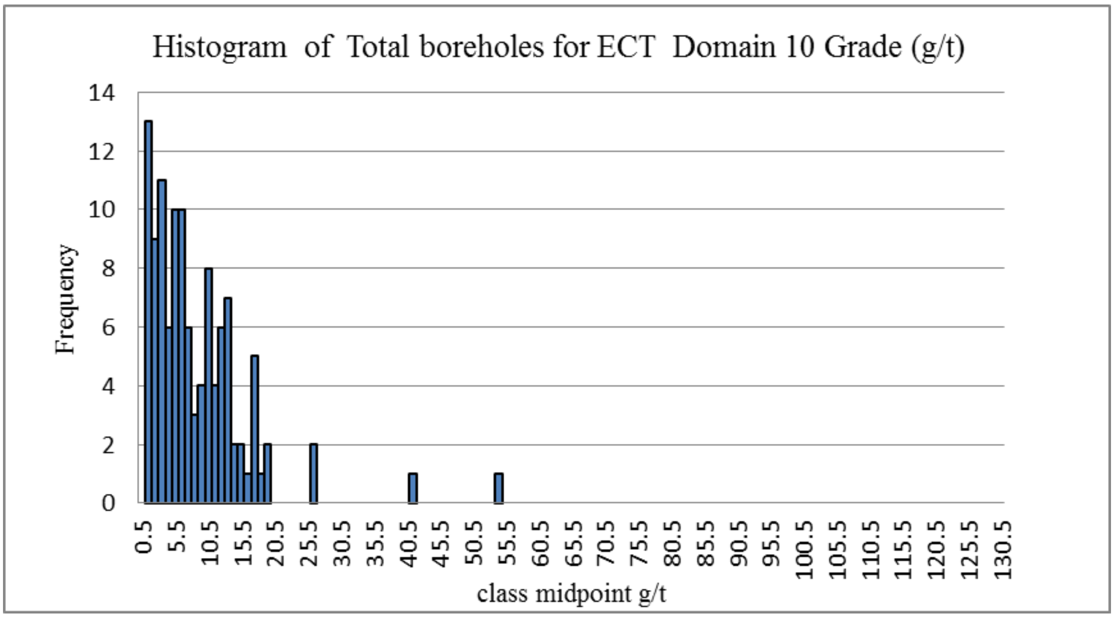

Figure A10 1 Relative Histogram Au (g/t) grade ECT Domain 10

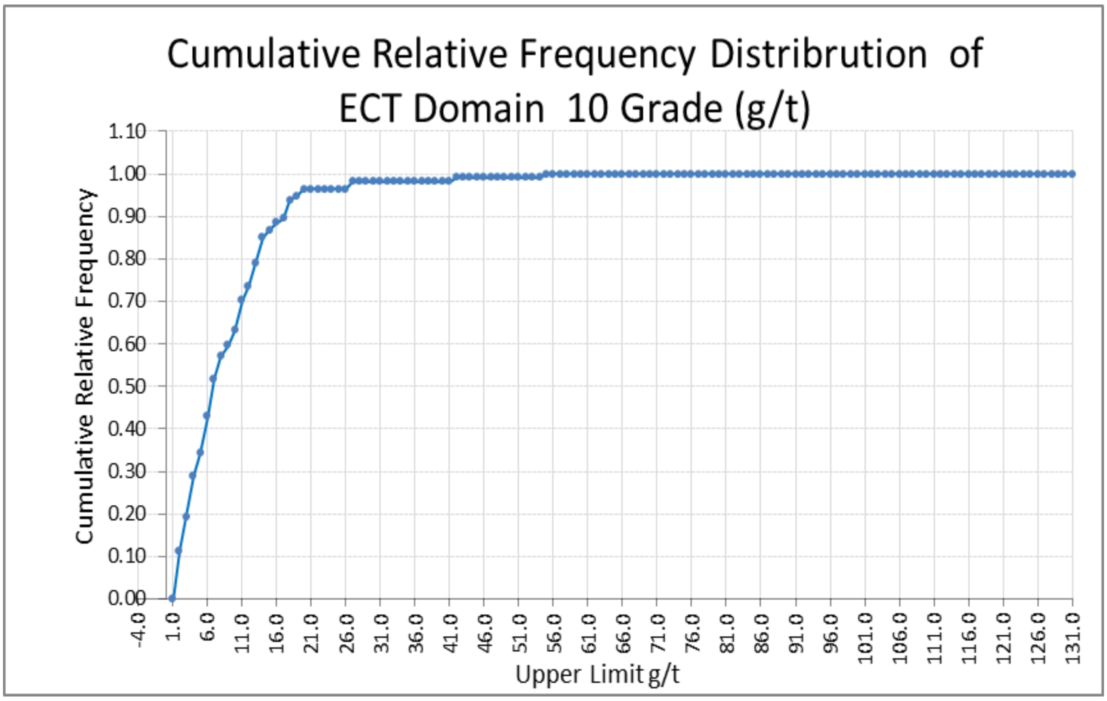

Figure A10 2 Cumulative Relative Frequency Au(g/t) grade ECT Domain 10

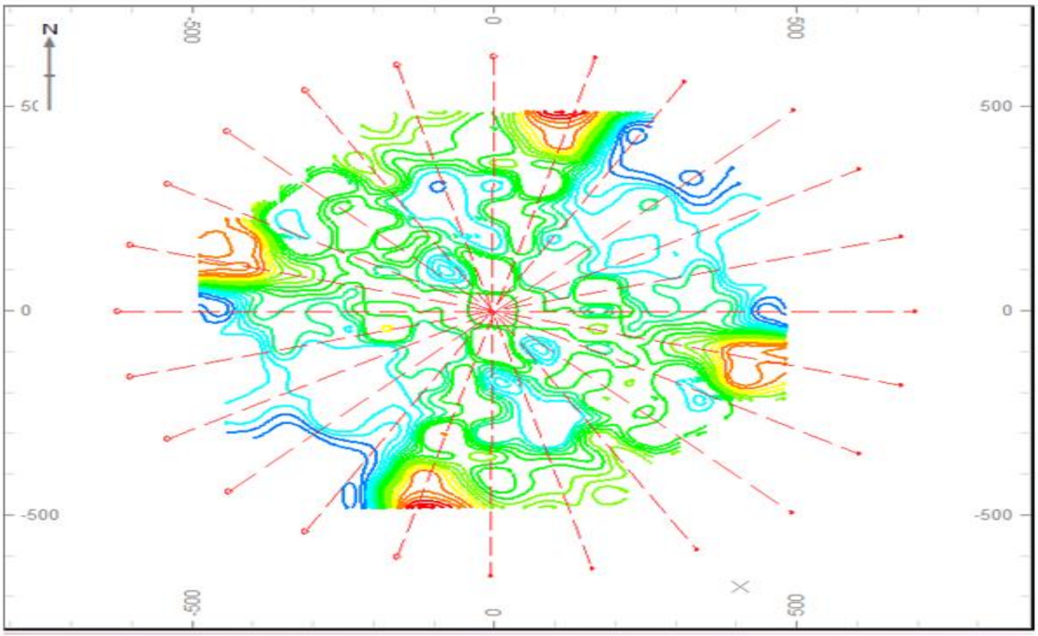

Figure A10 3 Varmap ECT Au (g/t) grade Domain 10

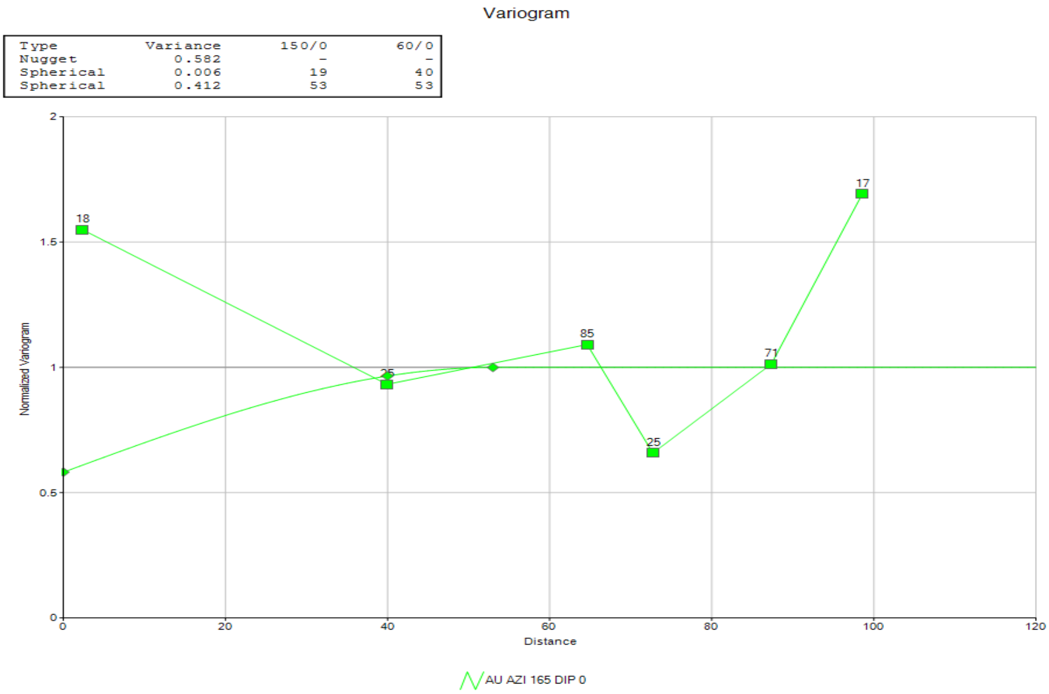

Figure A10 4 Variogram model ECT Au (g/t) grade Domain 10

Appendix 11- ECT reef Domain 11 Graphical presentation of Statistics and Geostatistical Analyses

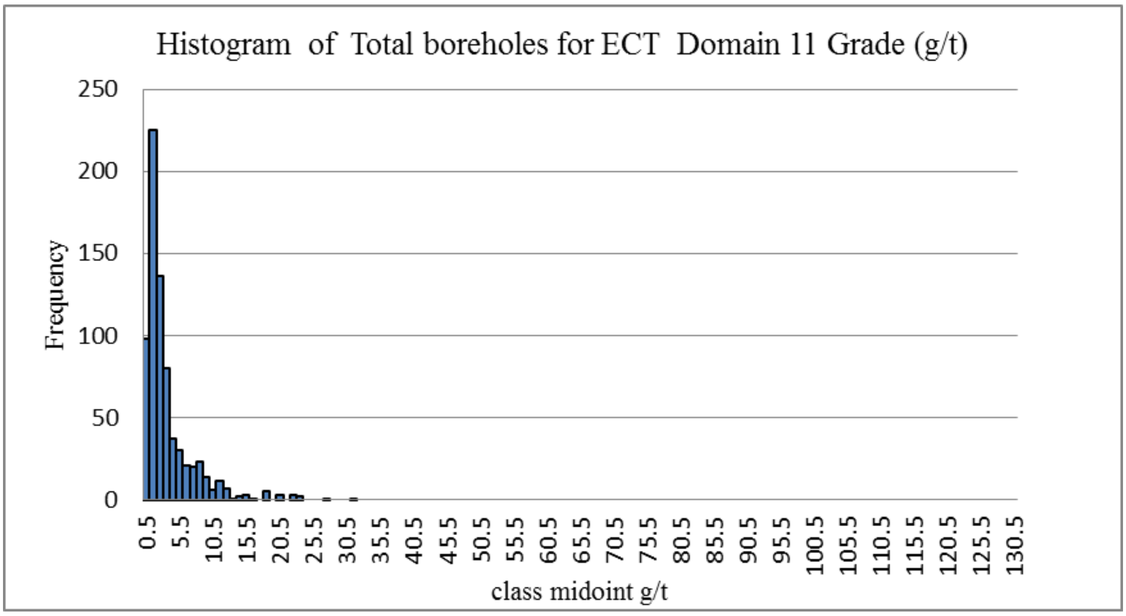

Figure A11 1 Relative Histogram Au (g/t) grade ECT Domain 11

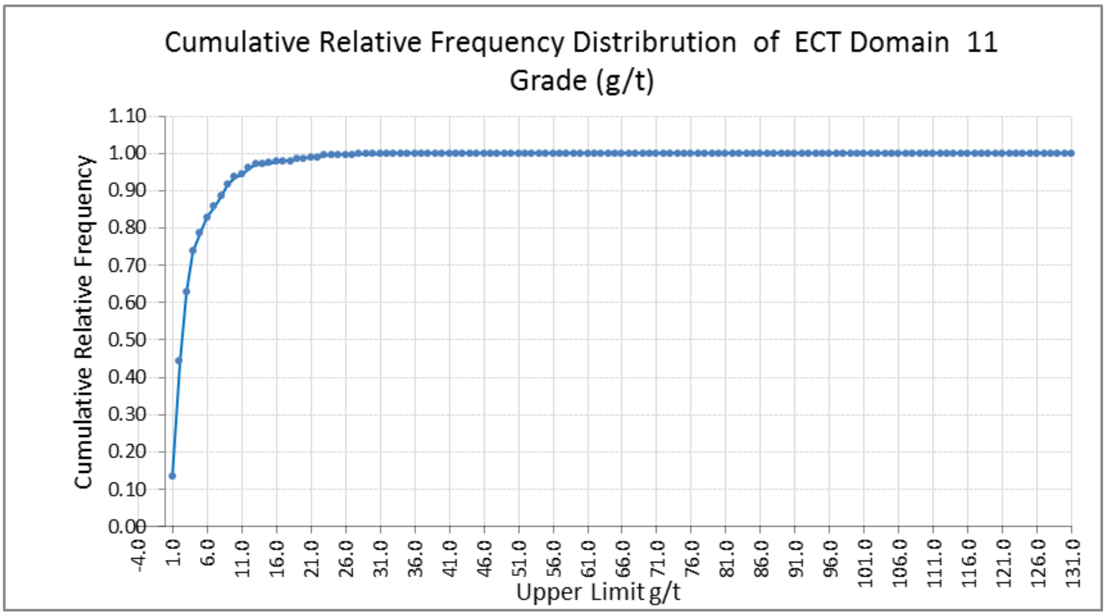

Figure A11 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 11

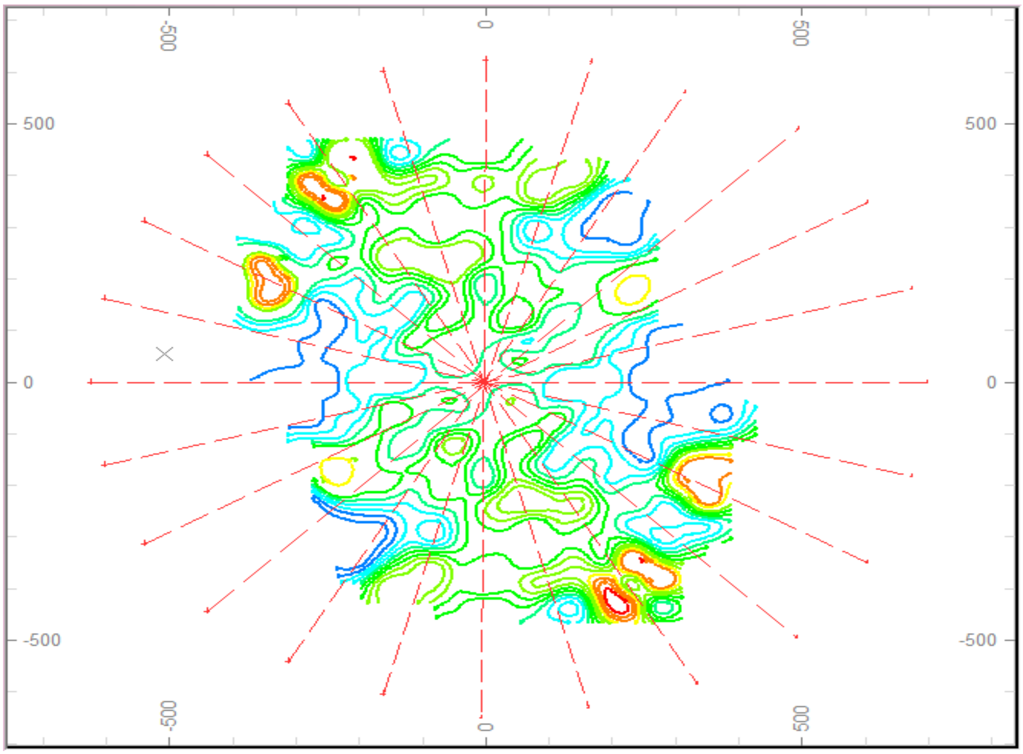

Figure A11 3 Varmap ECT Au (g/t) grade Domain 11

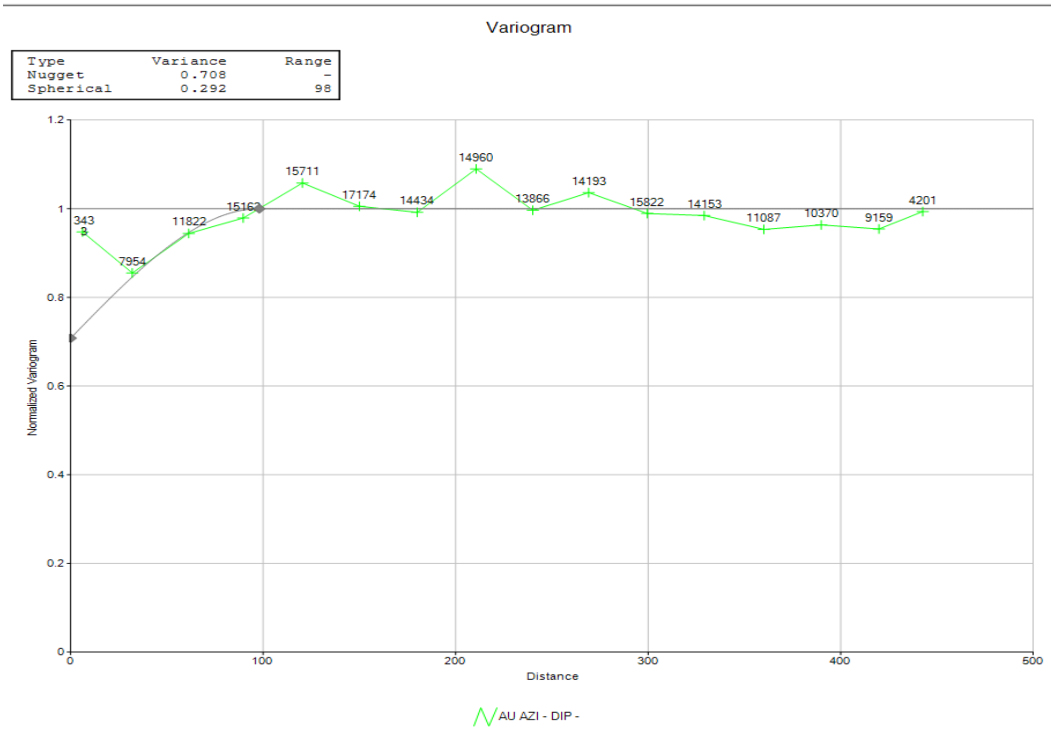

Figure A11 4 Variogram model ECT Au (g/t) grade Domain 11

Appendix 12- ECT reef Domain 12 Graphical presentation of Statistics and Geostatistical Analyses

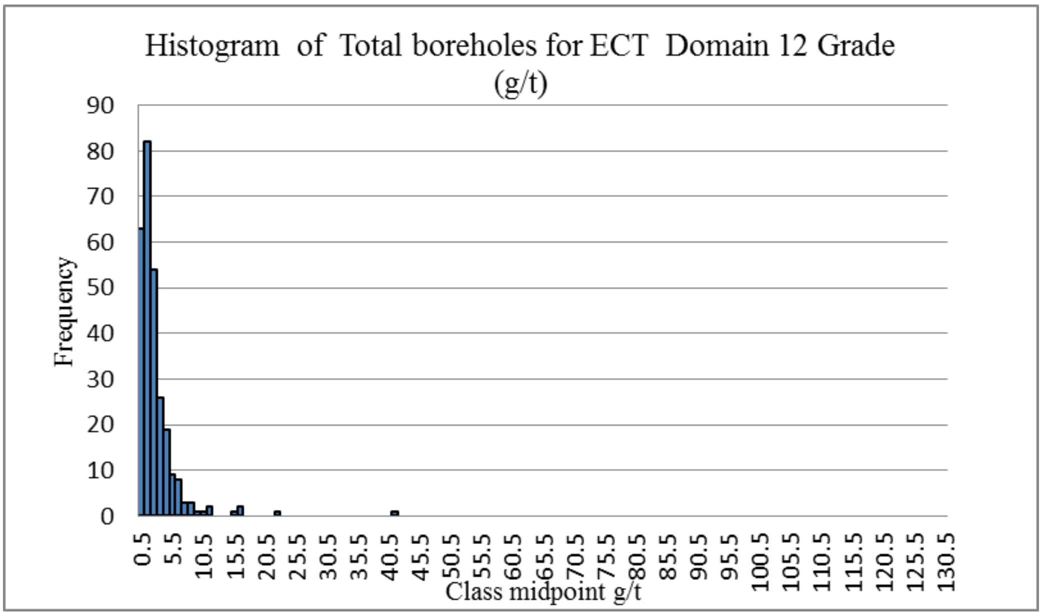

Figure A12 1 Relative Histogram Au (g/t) grade ECT Domain 12

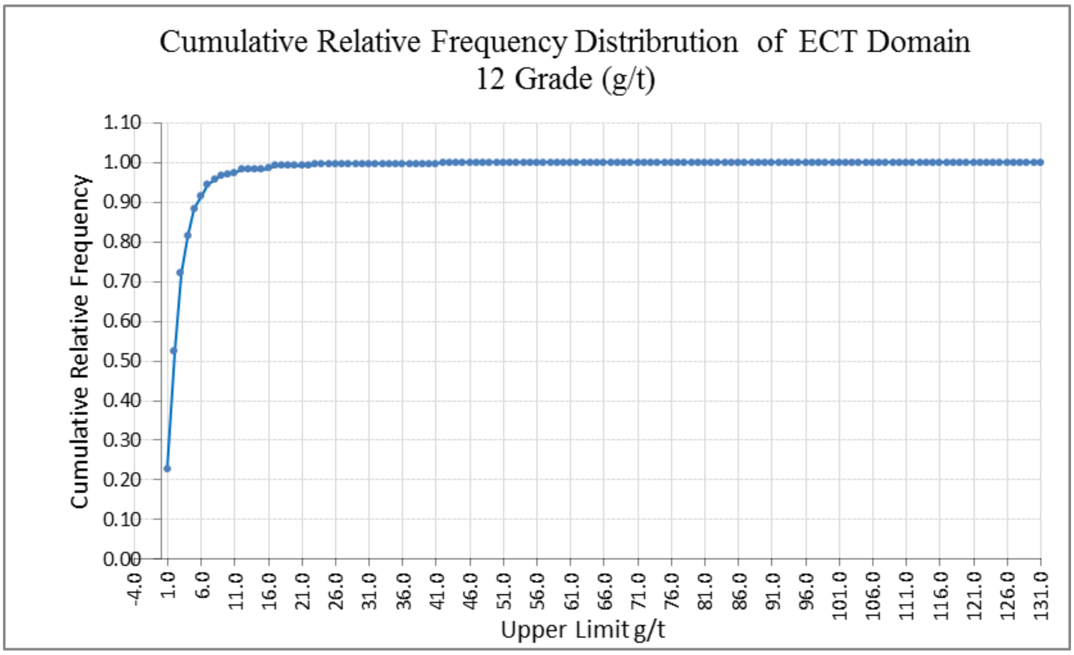

Figure A12 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 12

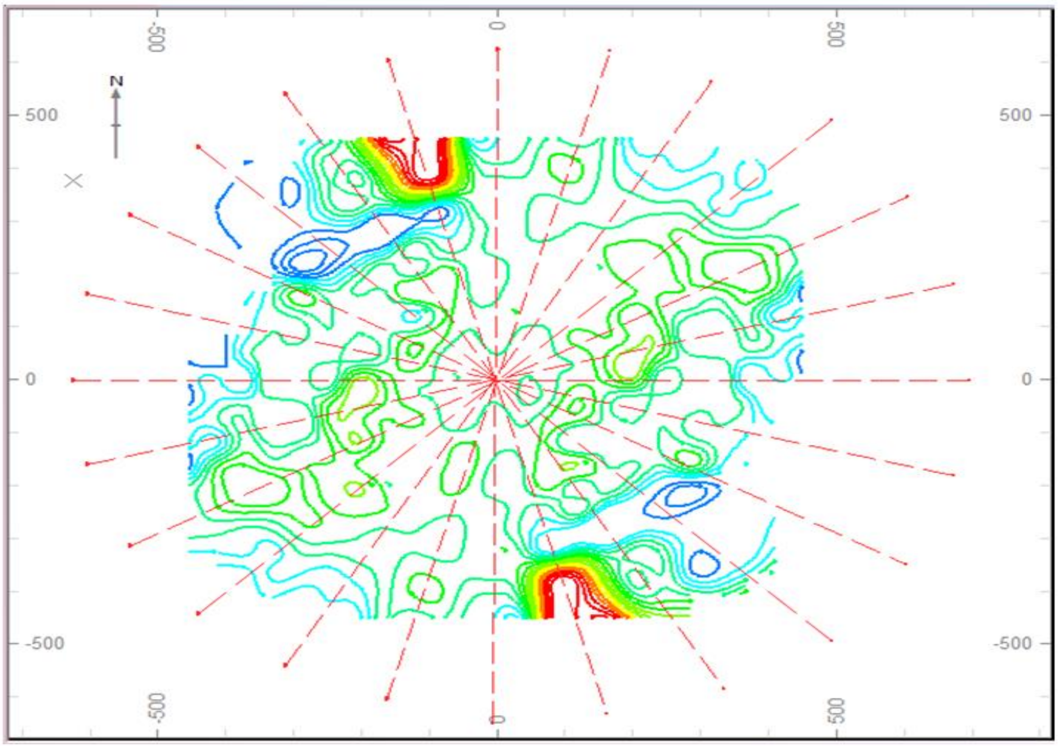

Figure A12 3 Varmap ECT Au (g/t) grade Domain 12

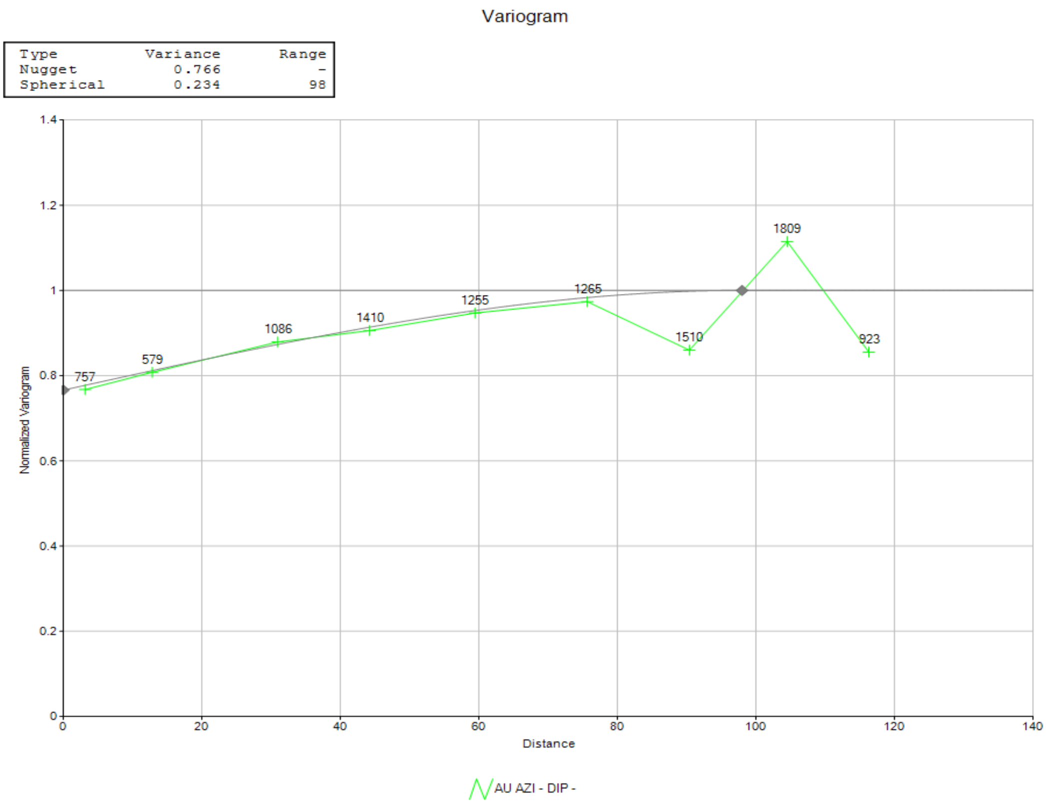

Figure A12 4 Variogram model ECT Au (g/t) grade Domain 12

Appendix 13- ECT reef Domain 13 Graphical presentation of Statistics and Geostatistical Analyses

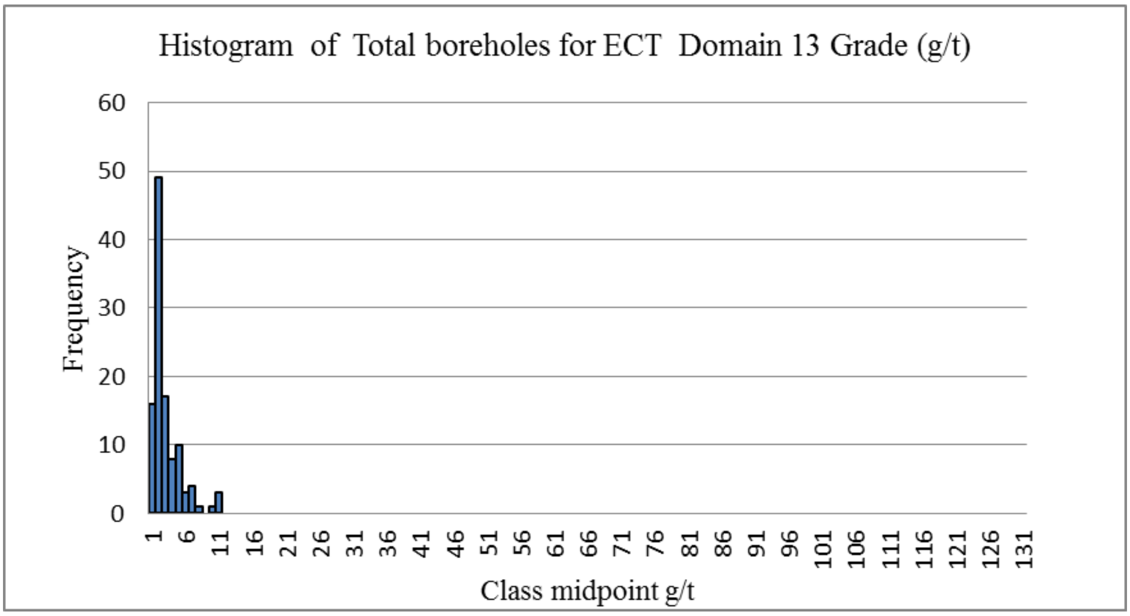

Figure A13 1 Relative Histogram Au (g/t) grade ECT Domain 13

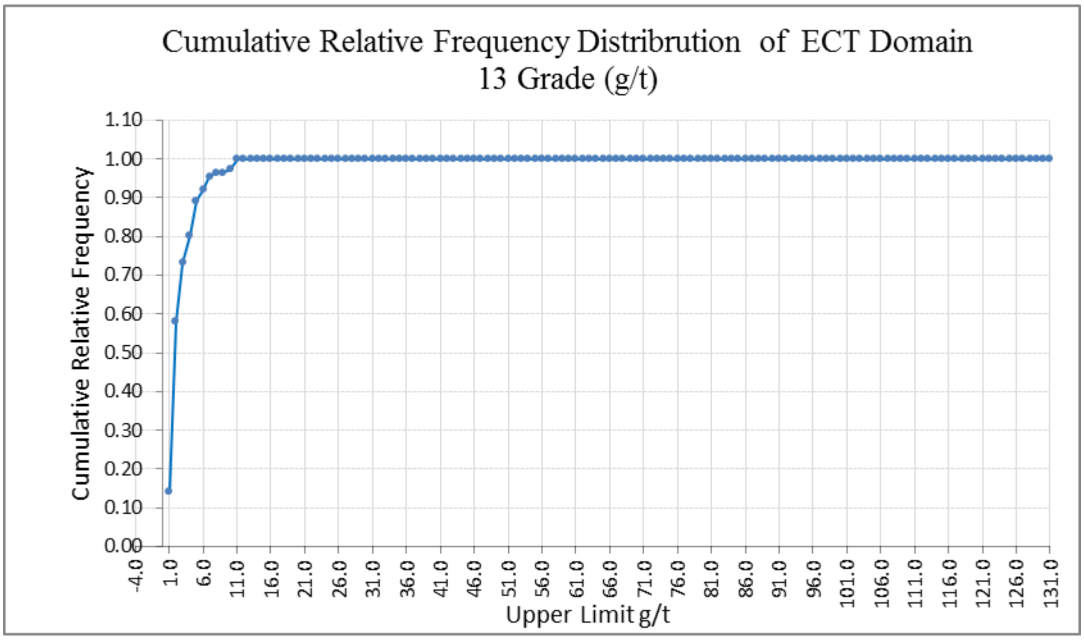

Figure A13 2 Cumulative Relative Frequency Au (g/t) grade ECT Domain 13

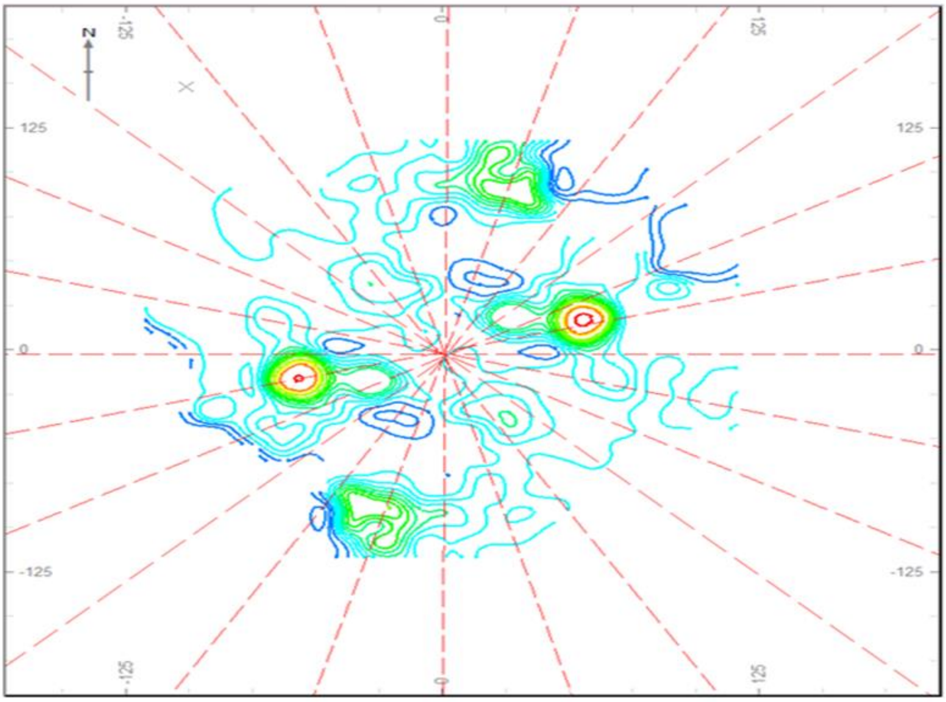

Figure A13 3 Varmap ECT Au (g/t) grade Domain 13

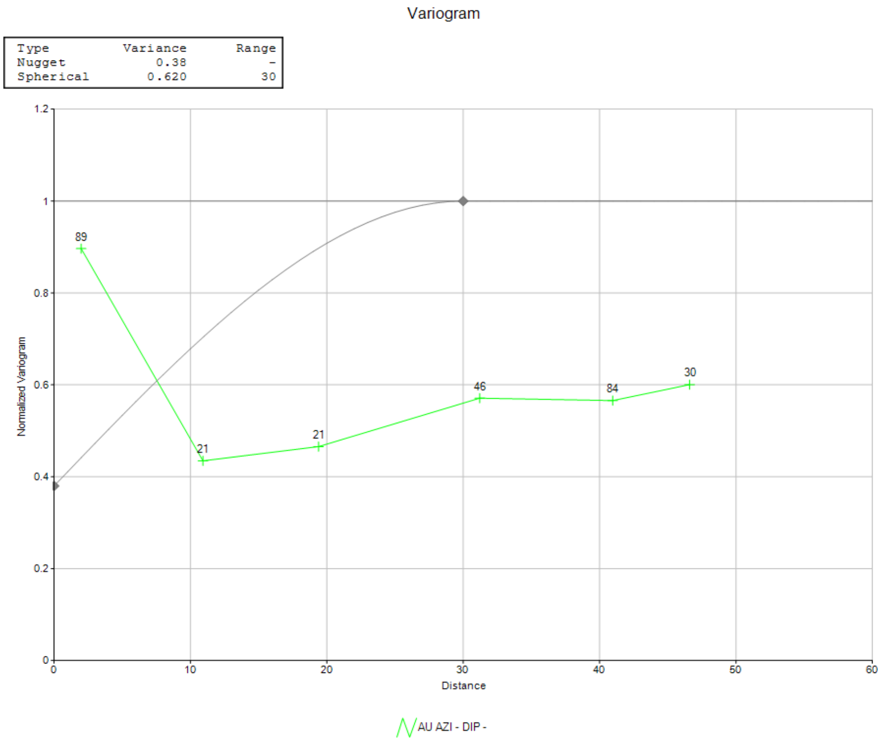

Figure A13 4 Variogram model ECT Au (g/t) grade Domain 13