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Refining the methodology for geological zoning used in resource evaluation, through the application of sedimentary characteristics of deposition at Kloof Gold Mine

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DECLARATION

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ABSTRACT

Mineral Resource estimation within geologically homogenous zones increases the likelihood of achieving stationarity; a requirement for geostatistical estimation; which consequently increases grade estimation confidence. The relationship between the spatial distribution of gold grade and geological controls is confirmed through simulated drainage models, and exaggerated channel width plots, allowing for an investigation of the existing methodology based on sedimentological attributes including channel width and gold values and to establish whether homogenous zones based on geological characteristics of deposition could be identified and incorporated to refine the geozone modelling methodology.

As a starting point, an initial geozone model based on the existing mine methodology was utilised. This methodology is based on solving for the individual sedimentological attribute weightings which is used to group the sedimentological data into distinct facies types. By considering the spatial position and geological similarities, the facies model is then further refined by grouping similar geological processes.

In the refined methodology presented facies boundaries are then identified and digitised by contouring of the delineated facies types (codes), through an Inverse Distance Weighting process, resulting in nine distinct sedimentological domains being identified. Each sedimentological domain is then assigned a unique set of geological “fingerprints” based on the sedimentological weightings of each domain. The weights have a cumulative sum of one hundred, and the larger the weighting, the more relevant the sedimentological attribute is to its associated sedimentological domain and its resulting grade.

Utilising the assigned geological fingerprints of the domains, a macroscopic, qualitative assessment tool of the reef was developed. To establish the effectiveness of the qualitative assessment tool validations within known and unknown facies were carried out. First, underground mappings and a borehole drilling programme were carried out into an area of known facies and grade. The qualitative assessment tools showed that a

facies and grade range could be established ahead of the mining face where grade information is scarce. As a second and final validation of the qualitative assessment tool as well as the refined sedimentological model boundaries, a borehole was drilled into an unmined reef pillar of an unknown sedimentological domain and grade. Utilising only the borehole assay results, the unmined pillar showed to be uneconomic for extraction, however introducing the qualitative assessment tool and the refined sedimentological domains, the pillar proved to be economically viable, and was subsequently successfully mined. The qualitative orebody delineation methodology as employed in this research, was observed to be a powerful tool for refining geologically homogeneous zones and consequently leading to better informed economic decisions of future mining projects and thereby preventing value destruction.

In conclusion, through the analyses and interpretation of the sedimentological data, it was observed that the depositional environment of the reef has control over the spatial grade distribution, allowing for homogenous geozones to be delineated and refined based on sedimentological attributes, consequently leading to the identification of unique geological facies, each with a unique set of sedimentological attributes.

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LIST OF ABBREVIATIONS

ANOVA	-	Analysis of Variance
BH	-	Borehole
cmg/t		centimetre grams per tonne
CW	-	Channel Width
EDA	-	Exploratory Data Analysis
IDW	-	Inverse Distance Weighting
kg		kilogram
LPC	-	Large Pebble Conglomerate
MPC	-	Medium Pebble Conglomerate
MS		Microsoft
SPC	-	Small Pebble Conglomerate
SW	-	Stoping Width
VCR	-	Ventersdorp Contact Reef

LIST OF SYMBOLS

β	-	Beta
$\sum$	-	Sum

1. Introduction

The relationship between the spatial gold grade distribution and geological controls in the Witwatersrand Basin, having been demonstrated by Dohm (1995), Hall (1997) and Chamberlain (1997), must, as a natural progression of continuous improvement, consider using additional geological attributes to establish homogenous zones for resource estimation based on geological characteristics of deposition. Krige (1990), observed that geological similarities exist between reef horizons, and proposed that by delineating zones of similar geological characteristics there could be a possible improvement in the estimate achieved.

Within this research study, it is shown how geologically homogenous zones were established by utilising sedimentological characteristics of deposition of the Ventersdorp Contact Reef (VCR) and the processes followed to ascertain whether the depositional process of the reef has control over the spatial distribution of the gold value at Kloof Gold Mine and finally concluded that this does have bearing on the gold mineralisation.

1.1 Research Background

This research study was conducted over the lease area of Kloof Gold Mine, on the VCR. The mine is located in the Western Areas Goldfield of the Witwatersrand Basin, South Africa (Figure 1) and is situated approximately 65 km south-west to the city of Johannesburg near the town of Carletonville. Kloof Gold Mine is bound on the west by the Bank fault and the West Rand fault to the east with 1 and 1.5 km up throws, respectively. Normal faults are developed sub-parallel to the West Rand fault with smaller, secondary, north-east trending dykes. Conjugate faulting and dykes occur in a south-west trend with displacement between 1 and 50 m (van Eeden & Lindeque, 2012).

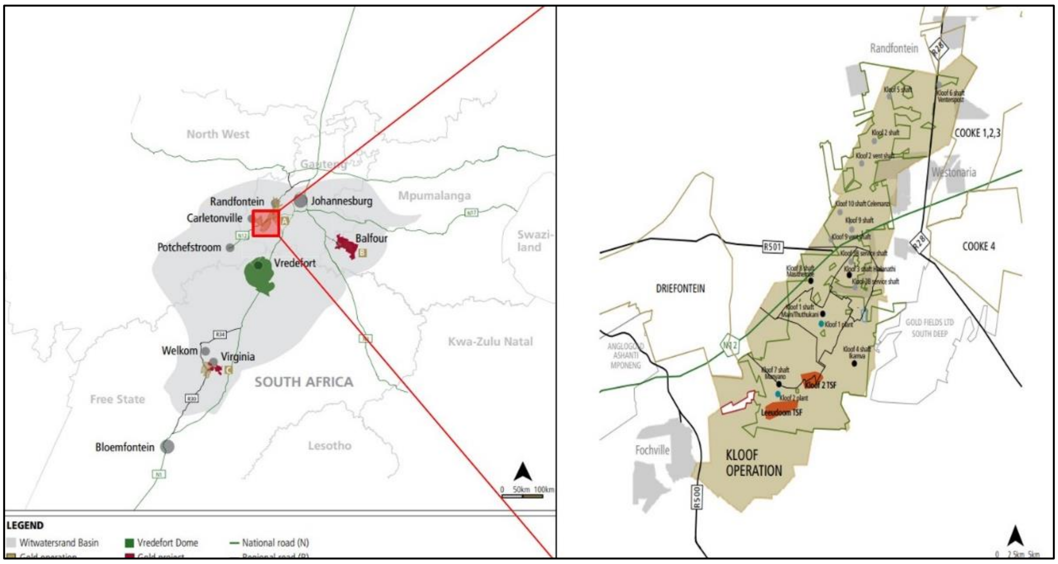

Figure 1: Location map of Kloof Gold Mine modified after SibanyeGold, (2017).

The VCR constitutes over 80% of the underground Mineral Reserve ounces and is the principal reef mined at Kloof Gold Mine (SibanyeGold, 2017). The VCR is accessed via several mature, vertical shafts, with the project area considering several of the shaft areas within the Kloof mining lease (Figure 2).

Due to the depths of mining, and the cost associated with exploration drilling in deep level tabular orebodies in the Witwatersrand Basin, limited data is available to estimate the grade ahead of the face where estimation is primarily of an extrapolative nature (Flitton et al., 2012). With many decisions being based on this extrapolation application, the uncertainty about grade and the associated economic risks in this situation puts many projects in jeopardy, and as such, any relevant and available information should be considered to improve the resource estimation confidence (Dohm, 1995 and Nwaila, et al., 2020).

Hall et al. (1997), observed a close relationship between the gold distribution of economic reef horizons and their sedimentary structures, where Dohm (1995) established a relationship between channel width (CW) and grade. This was fundamental in understanding the relationship between geological setting and gold grade distribution. Shango Solutions (2013), with lesser success, incorporated maximum pebble size and matrix colour as defining characteristics of geological domains at Kloof Gold Mine.

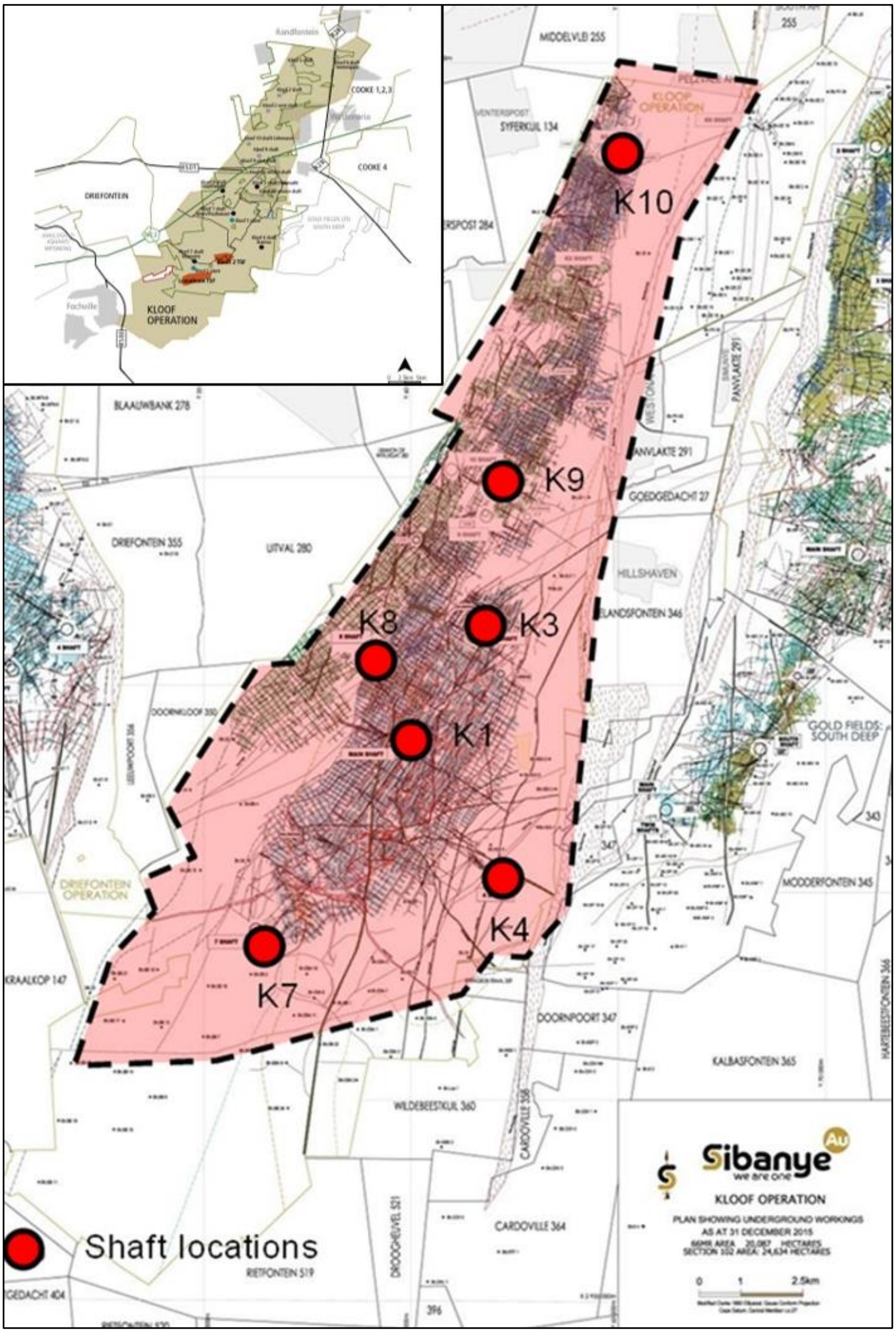

Figure 2: Project area (outlined by black stippled line) across Kloof Gold Mine and shaft locations adapted from van Eeden & Lindeque, (2012).

1.2 Research Hypothesis and Aim

Resource estimation is outside the scope of this research, however for the resource estimation to be effective and reliable the kriging techniques in place on the mine at the time of this research is carried out within defined geozones. Having better geozones definition will have a positive effect on the Mineral Resource estimation in that the assumption of stationarity, inherent in the Kriging methodology applied on the mine, will be better achieved.

The research hypothesis is that: Observable (macroscopic) geological attributes describing the characteristics of the deposition of the VCR can be utilised to refine the homogeneous geozones, to be used to predict the spatial grade distribution and consequently providing improved grade estimates.

The research aim is to show that the geozones defined by the current automated methodology based on sedimentological attributes including grade and channel width can be refined further. Therefore, the focus of this research is on the identification and delineation of refined homogeneous geozones to aid the improvement of the geostatistical estimation and consequent decision making.

1.3 Research Objectives

Previous research by McWha (1994), Dohm (1995) and Hall et al. (1997) established the relationship between gold distribution, geological setting and depositional history of reef horizons in the Witwatersrand Basin. By using all of the available data from the sedimentological characteristics of deposition of the VCR, it is expected that there will be an improvement in resource estimation and confidence of the area, with a reduced grade estimation error. To validate this expectation, the research project had to achieve several objectives namely:

- Ascertain if the deposition of the reef has control over the spatial grade distribution.

- Develop geologically homogenous zones, utilising geological characteristics of a sedimentary gold deposit. In anticipation that this would increase the confidence of achieving grade stationarity in the homogeneous zones; a requirement for geostatistical grade estimation and consequently improve the Mineral Resource estimation confidence of the area.
- Establish relevant depositional (geological) attributes and their associated weighting to be used in delineating homogeneous geozones, and
- To better understand the role of geology in the estimation of a Mineral Resource, leading to improved geological and estimation models and better economic decision making.

1.4 Research Methodology

The evolution of the geozone delineation in the Witwatersrand Basin is based on research knowledge obtained through a comprehensive literature review combined with an assessment of historic attempts of incorporating sedimentological attributes in geozone delineation at Kloof Gold Mine specifically. Historic bulk chip sampling and production drilling data were utilised where sedimentological attribute information had been captured to ascertain if the deposition of the reef has control over the spatial grade distribution at Kloof Gold Mine. This relationship was tested by plotting the bulk chip sampling data spatially; an exaggerated channel width plot overlain by a kriged grid and a terraflow simulation. From these plots, geological correlations with respect to value could be observed, thereby confirming the relationship between the deposition of the reef and the spatial grade deposition, enabling the possibility to explore geozone refinement through sedimentological attributes of deposition. The sedimentological attributes were then analysed, and all converted to quantitative scales. The gold (cmg/t) and CW (cm) values were statistically and spatially studied through an exploratory data analysis both individually and combined

At Kloof Gold Mine the existing automated geozone delineation, is influenced by a geozone delineation process developed on mine and which is captured as an Excel script. Within the script, optimised sedimentological weightings are calculated and applied, estimates are calculated for samples, and compared to lognormal block estimates. The estimates within a specified error percentage, are used to identify several homogenous geozones based on observable sedimentological attributes of deposition. In order to refine these initial geozones, tentative boundaries between the geozones were delineated using an Inverse Distance Weighting. Additional refinement of the geozones was achieved by the author developing and applying an underground mapping and drilling programme resulting in an overall model validity where geological observations and correlations could be made.

This allowed for the differentiation of nine distinct, sedimentological domains. Basic statistics were carried out on these domains which proved grade homogeneity. An observable definition of each domain was assigned in combination with two, supplementary qualitative assessment tools that were developed by the researcher, for quick underground classification and mining extraction decisions to be made. A methodology validation was performed by the researcher by drilling a borehole into a pillar and the results were compared to the kriging estimation and the mined value of the area, allowing for sound conclusions to be deduced.

1.5 Chapter Overview

Chapter 1: An introductory chapter that provides background to the research project, including the project location, research hypothesis, aim, objectives, and the research methodology.

Chapter 2: Contains a comprehensive literature review, with suggestions to the geological deposition of the project area, and further reviews on the evolution of the geozones and estimation methods through time, in Witwatersrand gold mines. Details of previous attempts of utilising sedimentological data are also considered. Current geozones in place at Kloof Gold Mine and their current application are also presented.

Chapter 3: The relationship and correlation between geological attributes and gold distribution through relative depth differential simulations and modelling the drainage patterns of the orebody is confirmed. Once geological correlations are made, the original data sets were then assessed. Conversion of qualitative data to quantitative attribute data is discussed followed by a process of data validation and the selection of the final data set utilised for the research project. The Exploratory Data Analysis (EDA) process is performed, wherein a non-linear relationship between sedimentological attributes is discovered and explored further, and individual weighs for each sedimentological attribute are calculated and sedimentological geozones are identified.

Chapter 4: After plotting the data points spatially, according to their geozones, visually distinct boundaries could be observed. These boundaries are further refined by utilising an Inverse Distance Weighting to facies codes to tentatively assign boundaries between geozones. An analysis of these tentative geozone boundaries is then carried out. Observing similar geological processes, as well as the spatial plot of the data, a final interpretation of the geozones boundaries is presented, which created nine larger sedimentological domains. The sedimentological domains are then analysed for homogeneity. The analysis of the identified geozones is then discussed, where each is assigned a unique, observable (macroscopic) set of identifying attributes with accompanying weightings. Two qualitative assessment tools are developed which will further aid in assisting geologists to identify core or stope faces according to the delineated geozones.

Chapter 5: From the assigned, unique set of identifiable sedimentological attributes, graphical representations of the different geozones are created and their spatial context is presented. The sedimentological geozones, in conjunction with their macroscopic definitions, are compared against underground control points through in stope mapping. The results are tabulated, and an overall model validity is calculated. To further test the geozone model and their macroscopic definitions, three boreholes were drilled underground and input into the qualitative assessment tools. The results are tabulated and combined with the underground control points to provide an overall model soundness. A final validation of the geozone model is performed by drilling a borehole into an unmined area, of an unknown geozone. The drilling results are analysed using the developed qualitative assessment tools and compared to the borehole reef intersection.

The results are tabulated and an expected content of the block was calculated based on the identified geozone. This estimate was compared to the kriged estimate, borehole value estimate and final mined content.

Chapter 6: A summary of the research project is presented, and it includes consideration of the refined geozone identification and validation thereof. The chapter concludes the research report with recommendations for future research work.

2. Literature Review

2.1 Geological Setting

The Witwatersrand Basin is situated in a central position on the Archaean Kaapvaal Craton and has undergone a series of metamorphic events through subduction related magmatism associated with massive hydrothermal alteration (Phillips & Law, 1990). Through this subduction, intracontinental basins were formed with siliclastic sedimentary rocks being deposited, where fluctuations between fluvio deltaic and shore face environments indicate an associated eustatic change in sea level (Hall et al., 1997, and Anhaeusser & Button, 1974). These siliclastic sedimentological cycles led to the accumulation of conglomerate units on basal degradation surfaces, normally observed as angular unconformities overlain by conglomerate units of fluvial bar, braided streams and inter-channel bed-forms (Drennan & Robb, 2006 and McCarthy & Rubidge, 2005). These conglomerates were deposited as mature, pebbly arenites with a variety of fluvial lithofacies ranging from clast supported oligomictic conglomerates to loosely packed conglomerates (Phillips & Law, 1990). Due to the distinct control of sediment supply and deposition, a close association between gold distribution and sedimentological characteristics exists (Phillips & Law, 1990 and Smits, 1994).

The VCR at Kloof Gold Mine represents one such conglomerate unit and is characterised as a tabular, steeply dipping (20-45°) orebody, with a general northeast-southwest strike. In addition, the VCR is represented by a predominantly pebble to matrix supported conglomerate that was deposited on an uneven topographic surface of the Elsburg quartzite's units of the Central Rand Group (van Eeden & Lindeque, 2012). A series of fluvial regressions caused by a continuous regional uplift, eroded and reworked the initial sediment deposition. Three major fluvial cycles of the VCR have been identified based on reef architecture, age and terrace elevation (Shango Solutions, 2006, AngloGold Ashanti, 2012 and AngloGold Ashanti, 2014). The oldest, original pulse of conglomerate deposition represents the highest terrace and the youngest, final, reworked conglomerate as the lowest terrace. Fluvial cycles are separated by areas of slope reef, which constitute approximately 10-15% of the VCR surface and are often expressed as a thin veneer of conglomerate preservation (Henning, 1994). Fluvial activity was abruptly halted by the rapid extrusion of lavas and tuffs from the Ventersdorp aged volcanism, which is believed to have preserved the VCR (McCarthy & Rubidge, 2005).The VCR is overlain by the Alberton Porphory Formation (Figure 3).

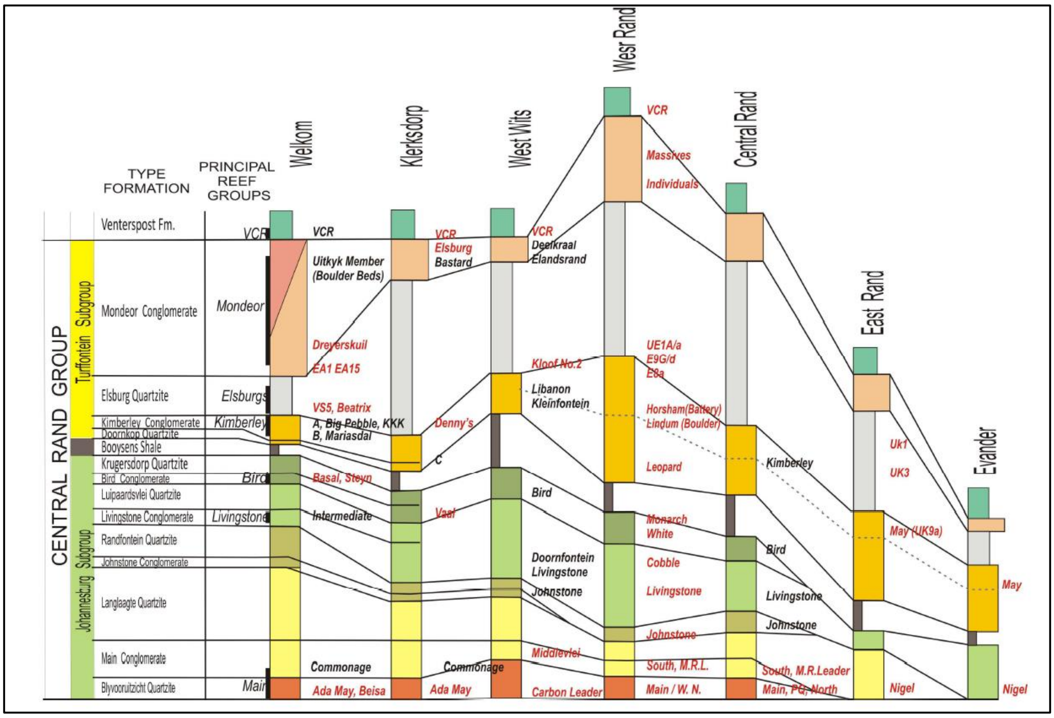

Figure 3: Witwatersrand Basin Stratigraphic column as presented by Tucker, 2018.

2.2 Evolution of the VCR Geozones in the Witwatersrand Basin

Geozones or homogenous zones of similar statistical characteristics were introduced, to achieve best estimations based on similar geological populations (Dohm, 1995). Grade estimations often rely on estimation by extrapolation, and due to sparse data ahead of the mining face, these estimations assume stationarity i.e. no trend in the grades within the geozones. The importance of correct delineation of the geozones is crucial to accuracy of the geostatistical estimation as is the understanding of the geology (Vann et al., 2003 and Rivoirard, 1975).

The variography of point data associated with defined terraces is utilised and the data have been subdivided accordingly in the past. The mine Resource Manager noted that variation in value alone, does not constitute a basis for subdivision, but that the variance within geozones must remain constant. The statistical method of analysis of variance (ANOVA) was then introduced to improve the delineation of geozones and the F-Test for change in variance was employed to test the homogeneity of the delineated geozones.

An F-Test is an analysis of variance (ANOVA) which tests if the means of populations are equal and can be applied to test if the point data belongs to the same population and whether the populations should either be combined or separated. (Draper & Smith, 1966).

As observed by Dean & Illowsky, (2008), the assumptions of the F test are:

- Each population from which a sample is taken is assumed to be normal
- Each sample is randomly selected and independent
- The populations are assumed to have equal standard deviations (or variances).

The theoretical assumptions of the F-test are strictly not met because the underlying gold grade distributions are not normally distributed. However, the application of the ANOVA to test whether the means in the geozones are similar have been found to be practically useful. The F-test is based on the ratio of variances (F-value) of two different populations and is dependent on the number of observations in each population. The ANOVA compares the observed F-value (variation of homogeneity) against F_{crit} (critical variation allowable at a predefined statistical level of confidence). If the observed F-value > F_{crit} then the reef intersections are accepted to be from differing populations (geozones), and they cannot be allocated to the same geozone. The test, although statistical, provides evidence of the geozones to be homoscedastic (similar variability) or heteroscedastic (dissimilar in variability). It was observed by Henning (1994), and later Tomkins (2010) that the fluvial environment of deposition and reef architecture are key determinants of the spatial grade distribution and estimation, yet these have not been fully utilised to delineate homogenous geological zones.

Once the gap between geology and geostatistics is further reduced there can be a possible improvement in estimations, where data will not only be geologically homogenous, but will define the grade distribution in a geozone (Flitton et al., 2012). Dohm (1995) has been a pioneer in applying geological characteristics of the orebody. Sedimentological domains were identified and a relationship between channel width (CW) and grade distribution was established. The CW and grade relationship continues to be applied in some of the larger South African Witwatersrand gold mines. As a consequence of Dohm's (1995) research work and the relationship between geological attributes and grade distribution, it has been established that the geological model, that informs the estimation process, is a crucial input to effective estimation, and that the attributes of deposition play a critical role to the estimation process (Dohm, 1995, Tolmay, 2009, Shango Solutions, 2006 and Rivoirard, 1987). Following the work of Dohm (1995) and Chamberlain (1997) a primitive palaeomorph model illustrating reef deposition as a function of footwall controls, with geozones subdivided across varying footwall lithologies was developed by AngloGold Ashanti’s Mponeng mine (AngloGold Ashanti, 2001). Unfortunately, due to the complexity of the geozone delineation, it was never considered for estimation across the Witwatersrand Basin. In 2001 an attempt was made to re-introduce geological components to model geozones, based on macroscopic identification of the reef. This was a refinement of the palaeomodel of AngloGold Ashanti (2001) in conjunction with the CW model proposed by Dohm (1995) and the work of Chamberlain (1997), which managed for the first time to successfully predict reef channels and terrace elevations ahead of the face (AngloGold Ashanti, 2001). The geozones identified were a combination of statistical techniques, compound lognormal statistics, channel width and boundary analysis (Flitton et al., 2012). At Mponeng Mine, further work in geochemistry and spectral scanning in addition to statistical techniques has been applied but has not yet yielded positive results (Flitton et al., 2012).

Elaborating on Dohm’s (1995) work, a distributional analysis was performed at Kloof Gold Mine which considers CW as an important variable (Tolmay, 2009). Here it was observed that CW within a geozone was not a constraining criterion, but across geozones boundaries became increasingly relevant and could be used as a determinant to identify different geozones boundaries as the variance of the CW increased. Later, Shango Solutions (2013), introduced a lithofacies delineation at Kloof Gold Mine utilising colour and maximum pebble size, where a good correlation to grade distribution was observed. Pebble rounding was observed as a constraining criterion where the more rounded pebbles were said to be associated with a better grade (to an extent) which then suddenly dropped off. This was interpreted to be the transportation distance from the source and recommended that the proximal and distal relationship be further explored. The delineated geozones based on lithofacies were however not adopted at Kloof Gold Mine, as the sedimentological attributes were deemed to be too subjective and the geozones were still largely defined according to geostatistical domaining. Through the evolution of the geozone delineation on Kloof Gold Mine, sedimentological data has not been fully utilised or understood. However, several studies have shown (Dohm, 1995 and Shango Solutions, 2013) that sedimentological data exists in describing the spatial grade distribution.

The understanding of the relationship between the mineral of economic interest and sedimentological attributes, required further understanding, and in doing so could optimise the utilisation of scarce data ahead of the face when constraining on sedimentological attributes. This could lead to improved estimates, well defined geologically controlled geozones and an associated reduction in estimation risk. It was observed that to define geozones according to sedimentological characteristics, each sedimentological attribute must be treated as being mutually exclusive. In union of the attributes, the combined probability of achieving the average grade is improved. This practice will allow for the weighting of the sedimentological attributes in each geozone, defining the constraining criteria. The constraining criteria can then be utilised to define geological boundaries and areas of similar geological populations used for estimations (Tolmay, 2009).

This chapter provided a literature review of the evolution of geozone delineation in the Witwatersrand Basin and specifically on Kloof Gold Mine. The need for geozone delineation was highlighted and the benefits of including of sedimentological attributes in the delineation process were discussed.

2.3 Current Geozones

At Kloof Gold Mine, the VCR geozones which were based primarily on lithofacies, were not incorporated into the geozoning process due to being considered as too subjective (Shango Solutions, 2013). Without the addition of the lithofacies, the geozones were solely defined according to geostatistical domaining parameters. However, a previous study of the reef architecture (van Eeden & Lindeque, 2012), showed a relationship to the grade distribution, which led to the grouping of the VCR into three distinct homogenous reef cycles shown in Table 1. The oldest reef cycle is seen as the upper terraces and the lowest terrace conversely being of the youngest cycle.

Table 1: VCR terrace subdivision (van Eeden & Lindeque, 2012).

Terraces	**Lithologies**	**Reef Architecture**	**Reworking**
Upper Terraces (>12m above base level)	Poorly sorted, massive conglomerates with pebble lags	Chloritic, dark green, lime green	Slopes
Middle terraces (4 to 12m above base level)	Matrix-supported conglomerates with variable thickness and milky cobbles	Apple green	Fretted terrains of mixed slope and terrace
Lower terraces (0 to 4m above base level)	Fluvial-dominated	Siliceous	Sand bars

The three distinct terrace subdivisions are currently utilised in conjunction with an Analysis of Variance (ANOVA) and a 95% confidence level. Within the ANOVA, the variation of homogeneity within the identified VCR terraces is tested against the critical variation allowed, and from this process it is determined whether the samples can be considered to be representative of the same geozone or not. The geological boundaries are treated as soft boundaries and are subjected to change, through continued statistical analyses as new information is added to the database, to ensure similar variability within the geozones. The terrace subdivision boundaries are mapped underground and provide hard boundaries to the geological zoning (facies) of the VCR. The three major VCR fluvial cycles can be subdivided into nine smaller VCR cycles based only on sedimentological data. The facies are routinely mapped underground or extrapolated from underground borehole drilling by the respective shaft geologists and are represented on a palaeomorphology plan (Figure 4). These smaller subdivisions fall within the larger geozones and are not used to define the geozones.

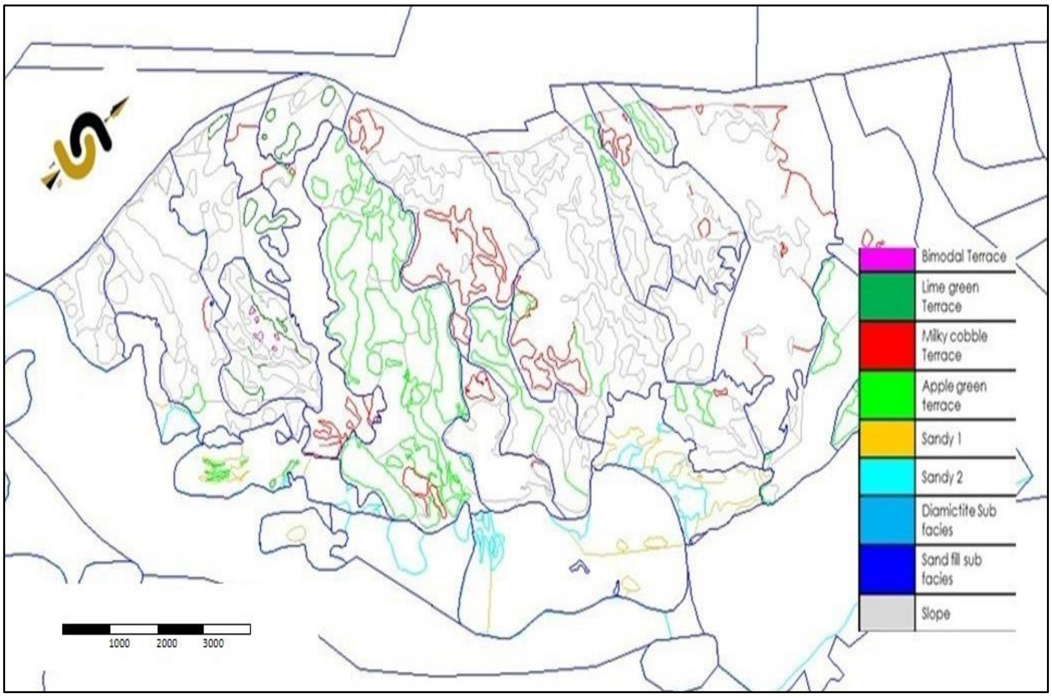

Figure 4: Kloof Gold Mine Geozones currently in use in conjunction with the facies model.

This chapter, records that through routine geological mapping, observable geological attributes are identified and collated to the broader geological setting, their relationship to the spatial grade distribution has however not yet been fully explored.

3. Methodology

3.1 Geological Correlations

To further understand the relationship between grade distribution and geology, an exaggerated channel width with an overlying 60 m x 60 m ordinary kriged cmg/t grid was plotted (kriging was executed and provided by the Resource Manager, guidance with methodology and plotting by Phil Staley), see Figure 5 (Refer to Figure 2 for shaft locations within the mining lease).

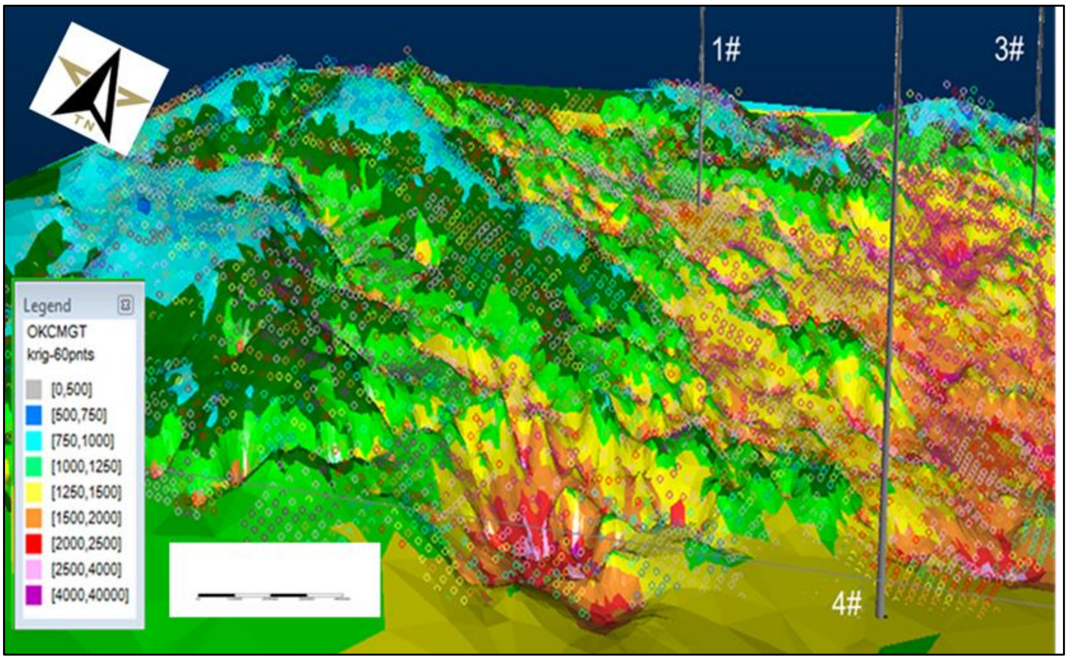

Figure 5: Relative depth differential and 60 m x 60 m kriged cmg/t values.

Studying this graphical representation led to further insight into the VCR deposition in an alluvial fan and braided plain system, where relative depth differential appeared to be critically important for gold concentration. Where deep scours or potholes were formed, generally a high gold concentration, with a well-preserved conglomerate unit is observed. The converse applied to palaeohighs, where poor conglomerate preservation and poor gold concentrations can be observed.

It was concluded that the relative depth differential complemented Dohm's (1995) established channel width and grade relationship.

Comparing the existing facies model with the exaggerated channel width plot, further insights were gained into the unique macroscopic geological characteristics and the spatial grade distribution, see Figure 6. The grade distribution can be explained by the varying observable geological characteristics. The importance between the macroscopic delineation of the reef (reef architecture) is vitally important, and emphasis to remove the subjectivity of sedimentological attributes should be reinforced to further understand the spatial relationship between grade distribution and geological characteristics.

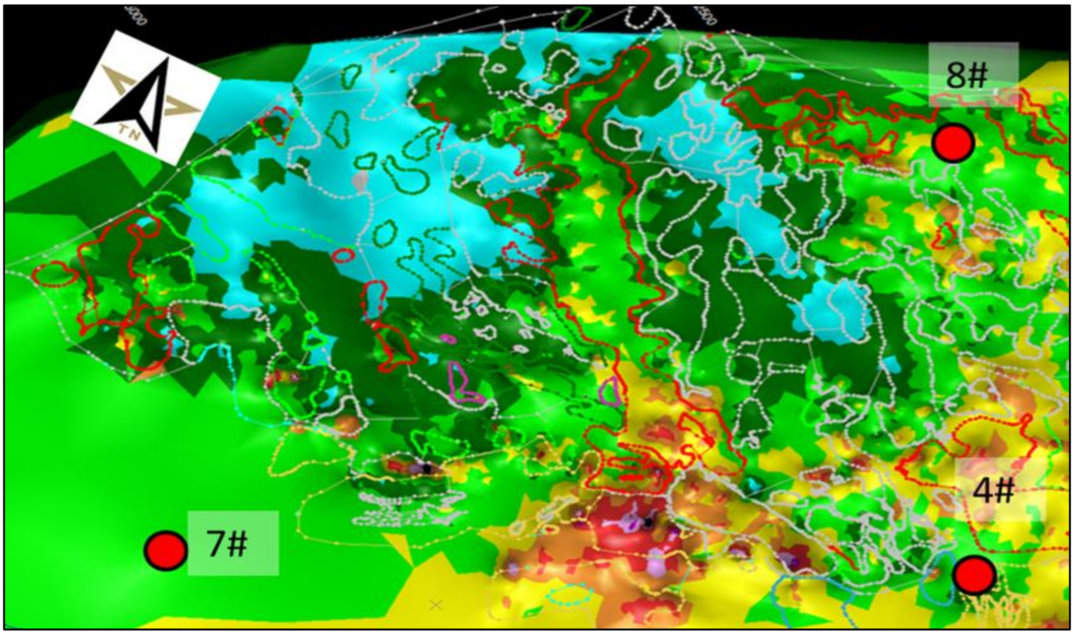

Figure 6: Exaggerated channel width model vs. original facies plan.

As a final geological correlation, the drainage pattern of the area was calculated using terrace elevation differentials (Figure 7) and a dendritic flow between 8 shaft (8#), 7 shaft (7#) and 4 shaft (4#) was identified.

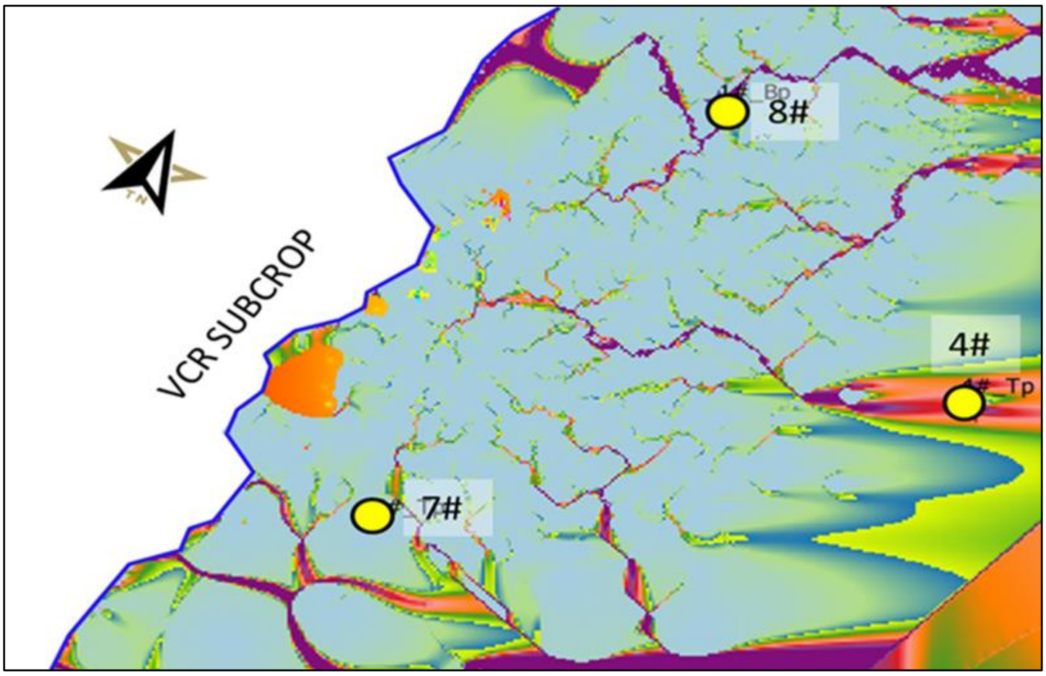

Figure 7: Terraflow model of the VCR.

This correlated well with the existing facies model and explained the deep scours and preserved terraces which were observed in the exaggerated channel width model (Figure 6).

In summary, it is believed that from these plots it was undoubtedly-confirmed that the geological setting can be seen to control the grade distribution, which can be explained by a set of distinct geological characteristics through a unique sediment supply. However, as with most geological models, there are anomalous areas that cannot be explained, and there were occasional exceptions with no apparent geological controls being observed.

3.2 VCR Sedimentological Data

An initial dataset of 783 903 VCR chip samples was accessed. From this data a subset of 37 043 sedimentological data points over the Kloof Gold Mine lease area was available. This sedimentological data was extracted from the original dataset and treated as an independent dataset. With reference to the sedimentological data, eleven sedimentological attributes are considered (Table 2).

Table 2: Sedimentological attributes captured with sampling points.

Pebble maximum size
Packing
Rounding
Sorting
Basal contact
Mineralisation
Buckshot pyrite
Matrix colour
Carbon present
Pebble assemblage
Channel width

The sedimentological attributes are both qualitative (9) and quantitative (2), and where qualitative they had to be converted into a quantitative nature for statistical analysis. A twelfth sedimentological attribute (percent conglomerate) was calculated from channel width and sampling width and was included into the dataset. As part of the geozone characterisation, the channel width and sample values were also considered as observed geological characteristics.

3.3 Qualitative and Quantitative Scales:

Scales are in place to help measure the attributes of the physical world and are either that of a qualitative (observable measurement) or quantitative nature (numerical measurements, also known as categorical measurements). Most measurements are described in terms of distinct numerical relationships (quantitative scales). Although considered to be less scientific, categorical scales can be just as valuable for observing relationships between properties. Categorical scales are used to assign variables with little or no quantitative information and provide a quick tool for assessment and comparisons between observable properties (Bernhard, 2018).

However, due to the inherent nature of categorical measurements (subjectivity) there is a greater uncertainty in definitions. This might create the incorrect impression that categorical scales are less functional.

Categorical scales are of two categories:

- Ordinal (meaningful order of observations)
- Nominal (no meaningful order of observations).

Ordinal scales allow for the difference between measurements but do not consider the magnitude of the observation. Ordinal scales often have an overlap between intervals with no distinct start and end separating intervals on the scale. Sedimentological attributes of deposition are of the ordinal category.

When considering qualitative scales, it must be remembered that the qualitative observations are mostly not linear or mathematical (Bernhard, 2018).

3.4 Conversion of Qualitative Sedimentological Attributes

The nine qualitative attributes (Table 3) were converted into quantitative attributes based on the sedimentology on a scale of increasing maturity.

Table 3: Qualitative sedimentological attributes.

Packing
Rounding
Sorting
Basal contact
Mineralisation
Buckshot pyrite
Matrix colour
Carbon present
Pebble assemblage

The qualitative attributes were then replaced in the database with the converted numerical given below:

Packing:

Nomenclature	Scattered	Pebbly	Well Packed
Converted	1	2	3

Rounding:

Nomenclature	Angular	Sub- Rounded	Rounded
Converted	1	2	3

Sorting:

Nomenclature	Poor	Moderate	Well Sorted
Converted	1	2	3

Basal Contact:

Nomenclature	Faulted	Sharp	Gradational
Converted	1	2	3

Mineralisation:

Nomenclature	None	Low	High
Converted	1	2	3

Buckshot pyrite:

Nomenclature	Absent	Present
Converted	1	2

Carbon present:

Nomenclature	Absent	Present
Converted	1	2

Pebble assemblage:

Nomenclature	Polymictic	Oligomictic
Converted	1	2

Matrix colour:

Nomenclature	Dark green	Light green	Yellow green	Dark grey	Grey	Light grey	White grey	White
Converted	1	2	3	4	5	6	7	8

3.5 Data Validation and Vetting

Both the VCR point sampling dataset (value cmg/t and CW cm) and the converted VCR sedimentological attribute dataset were validated. The VCR point sampling data had previously undergone a vigorous internal cleaning process. However for this research study, all invalid samples (e.g. reef not fully exposed/off –reef) were removed from the dataset (Table 4). Data vetting was also assumed to have been consistent with the on-site mine standard for reef identification and classification, however an element of subjectivity remains.

Table 4: VCR point sampling dataset validation - Number of data.

Original dataset	783 903
Invalid sample data	37 300
Missing co-ordinates	3
Final dataset	746 600

The VCR sedimentological attribute dataset was then cleaned and where any sedimentological information was absent, the data points were removed (Table 5).

Table 5: Validated VCR sedimentological point data - Number of data.

	Number of data
Original dataset	37 043
No Z co-ordinate or duplicate	148
CW absent	1 257
Pebble max absent	1 089
Basal contact absent	37
Mineralisation absent	12
Matrix colour absent	32
Pebble assemblage absent	17
Sorting absent	178
Packing absent	80
Rounding absent	55
Final dataset size	34 135

In this chapter qualitative geological characteristics were converted to quantitative attributes, allowing for a geostatistical approach to analysing the sedimentological attribute data set. Once the data sets were converted, the data set was further cleaned and validated.

3.6 Exploratory Data Analysis (EDA)

The Exploratory Data Analysis (EDA) is a process designed to analyse dataset characteristics by utilising a series of statistical tools both graphical and numeric to analyse the data such as spatial plots, histograms and summary statistics.

3.6.1 Statistical Analysis of the cmg/t Values

The first step in the EDA is to generate a location plot of the data, to understand the spatial distribution. Figure 8 depicts the spatial distribution of cmg/t values considered in this research.

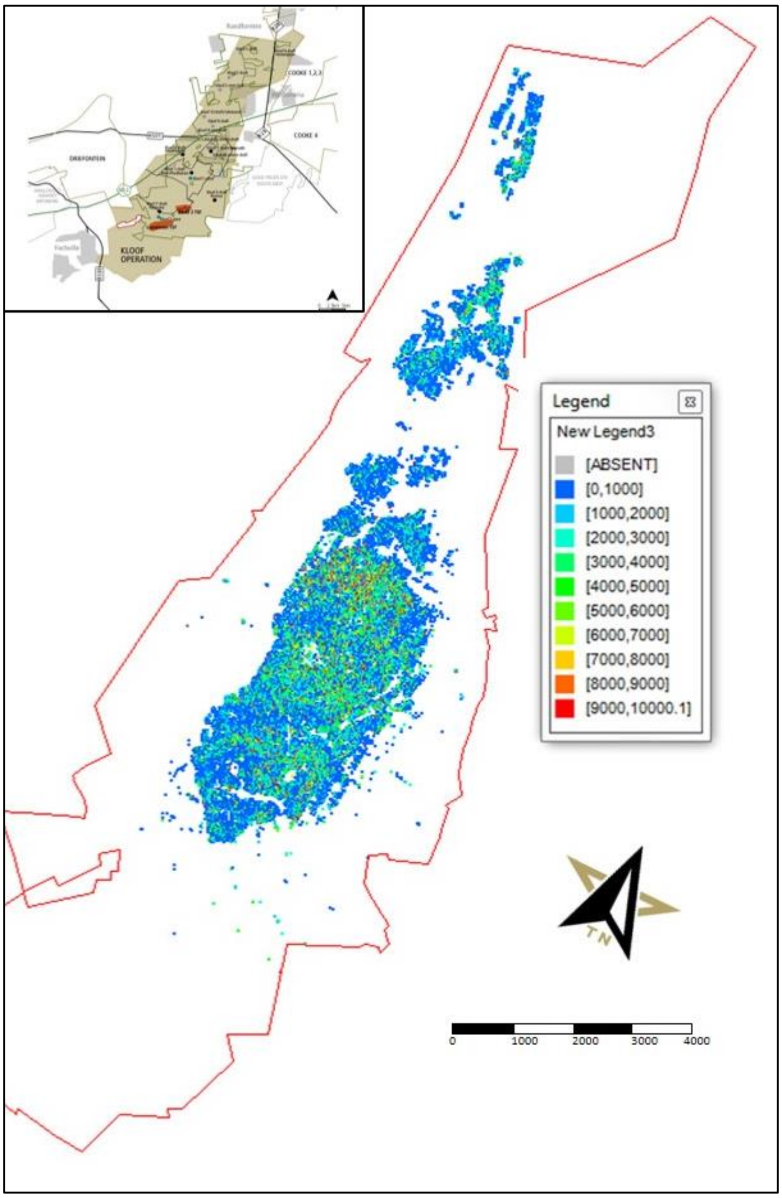

Figure 8: Locality plot of validated data points (SibanyeGold, 2017).

From the locality plot (Figure 8), the value (cmg/t) distribution appears to form in localised, braided channels, which agrees with the deep scours and palaeohighs of the exaggerated channel width plot (Figure 5). Several fluvial entry points could be identified, separated by apparent watershed areas which further agrees with the terraflow, dendritic drainage patterns, highlighting the importance of the geological setting relative to the grade distribution. In addition, the statistics and histogram of the cmg/t values are given in Figure 9. The histogram exhibits a positively skewed distribution, as expected from a Witwatersrand gold deposit, a range of 193 693 cmg/t is observed.

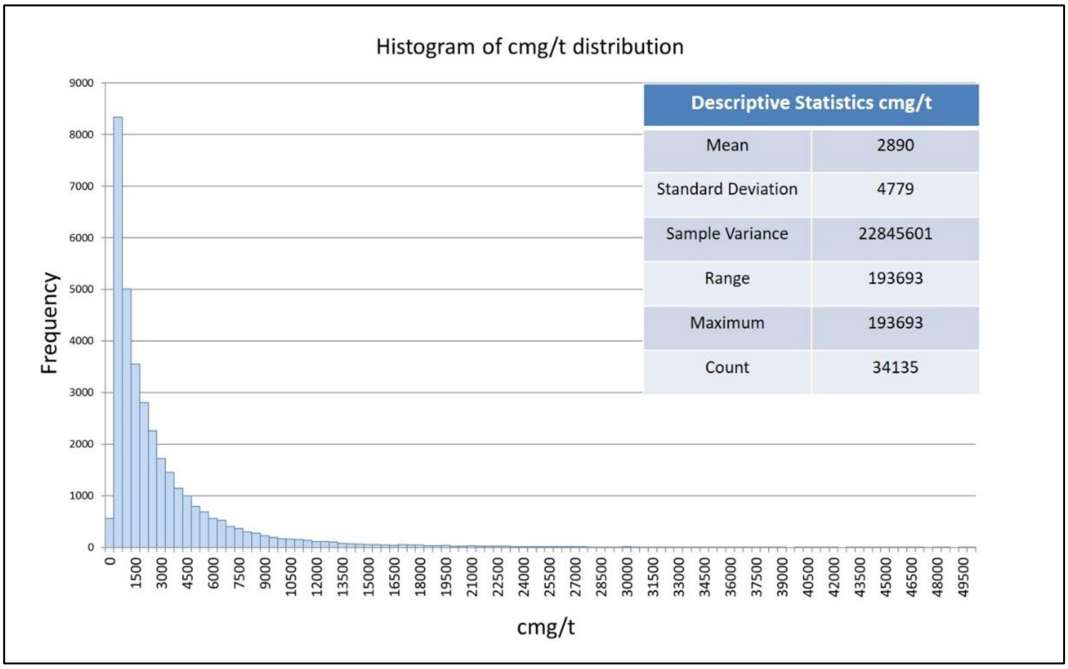

Figure 9: Histogram and Statistics of VCR value (cmg/t).

3.6.2 Channel Width vs. Grade Distribution

The possibility of a linear relationship between the grade (cmg/t) and the CW was explored. For illustrative purposes, the data set was constrained to a subset of the VCR sedimentological dataset of Kloof Mine and specifically the Kloof Manyano shaft area. A graph of CW versus cmg/t was generated (Figure 10). A subset rather than the full data set was chosen so as not to clutter the graphical presentation in this figure.

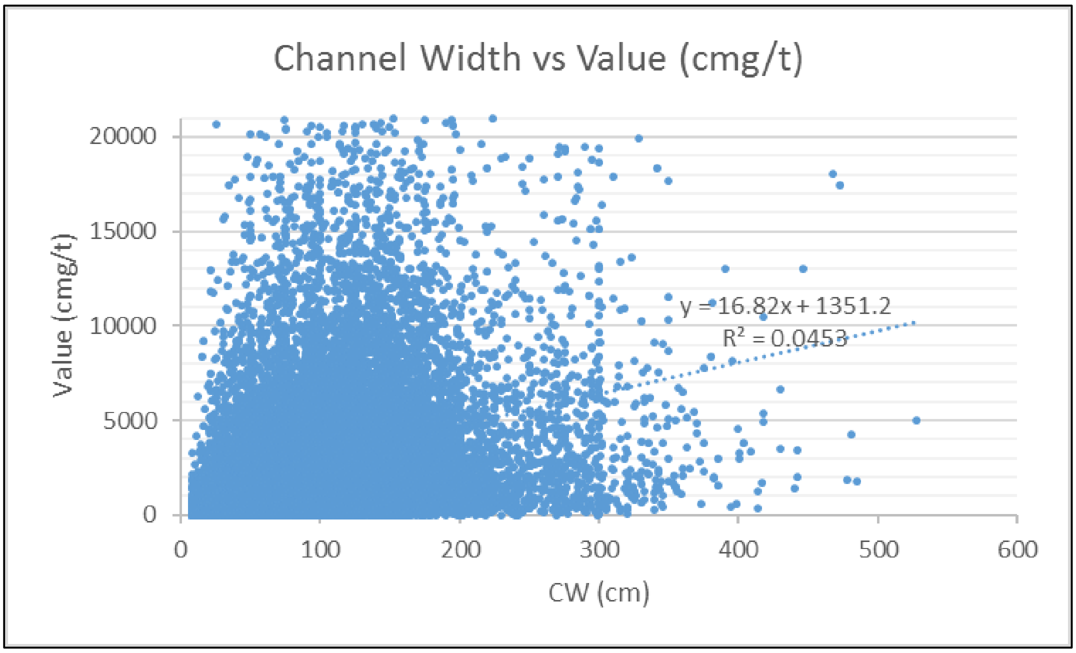

Figure 10: Scatter plot Channel Width vs. cmg/t – Manyano Shaft (K7).

R^2 is known as the coefficient of determination and is a measure of the total variation in Y (cmg/t) explained by the fitted regression model equation which is (cmg/t (y) = 16.82CW(x)+1 351.2) in this instance. In Figure 10, R^2 is seen to be 0.0453. Generally, if R^2 is greater than 0.8, then one could consider that a significant linear relationship exists. It can therefore be concluded from Figure 10, that no significant linear relationship exists between grade and CW. To further complement this observation, an ANOVA for regression (Draper & Smith, 1966) was performed between the CW and the cmg/t values, within MS Excel. The results for 95% confidence appear in (Table 6). The probably of an F value of 992 is insignificant. Thus at 95% confidence, it can be observed that there is no significant linear relationship between the CW and the grade values. A non-linear relationship between CW (cm) and grade (g/t) was observed as per Dohm (1995).

Table 6: ANOVA cmg/t vs. CW Manyano Shaft (K7)

ANOVA					
Source	*Degrees of freedom df*	*Sum of Squares SS*	*Mean Squares MS*	*F*	*Significance F*
Regression	1	3 677 103.89	3 677 103.89		
Residual	20 929	77 578 215.42	3 706.73	992.0067	0
Total	20 930	81 255 319.3			

To broaden the understanding of the non-linear relationship between CW (cm) and grade (g/t), the conditional expectation of grade was plotted across Kloof and Driefontein Gold mines (Figure 11). Channel width values were grouped into 20 cm intervals: 1st interval CW ≤ 20 cm and the next CW interval 20 cm < CW ≤ 40 cm and so forth until all the channel widths in the data base were grouped. The Au (g/t) grades of samples within each CW interval were averaged as were the CW (cm) values. This effectively constitutes the calculation of the conditional grade expectation per 20 cm channel width interval. The mean gold grades (g/t) of the 20 cm CW intervals were plotted against the mean CW(cm) value of these intervals for both the Kloof and Driefontein datasets.

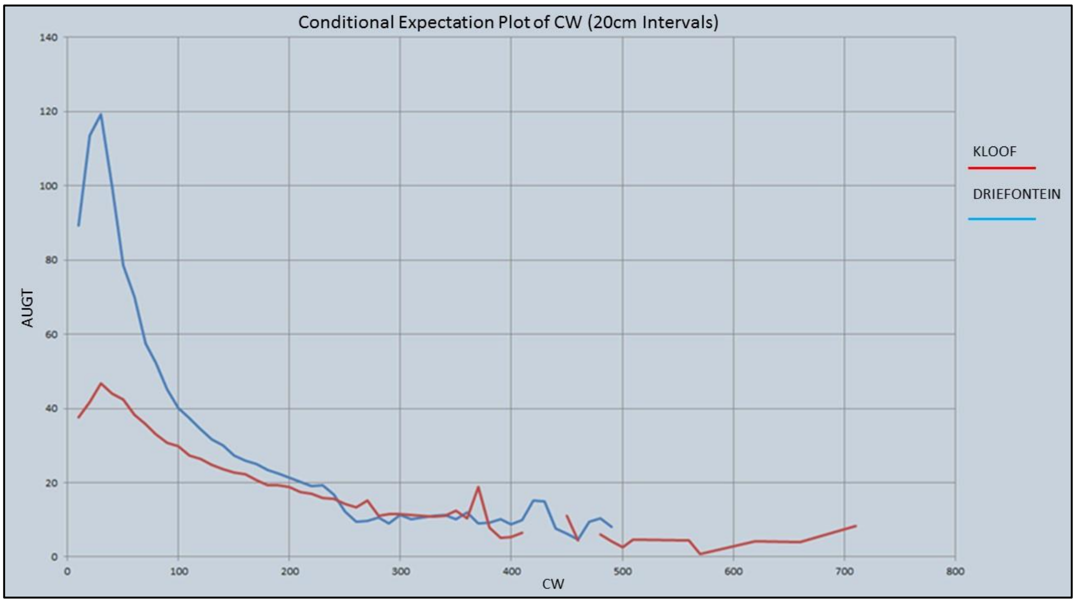

Figure 11: Conditional expectation of CW in 20 cm intervals across Kloof (Red) and Driefontein (Blue) Gold mines.

From the conditional grade expectation plot (Figure 11), it is observed that as CW increased, the associated grade (g/t) decreased. It could be concluded that CW may not play a major role towards grade distribution within geozones (similar CW's), but can be used as a constraining criteria across geozone boundaries, where significant lithological changes in CW and grade are observed on a local scale. This observation can be transferred to a slope (narrow width) and terrace (wider width) environment, typical to Kloof and Driefontein Gold Mines (Figure 11).

To explore in more detail, the non-linear relationship between CW and gold value (cmg/t) distribution, the inflection points on the relative cumulative distribution plot were assessed. The rate of change in the slope of the relative cumulative distribution provide an indication of a change in the inherent distribution of a variable within the orebody (Dohm, 2016). From the relative cumulative frequency distribution plots, seven inherent inflection points were observed with respect to value (cmg/t) (Figure 12) and eight with regards to CW (Figure 13).

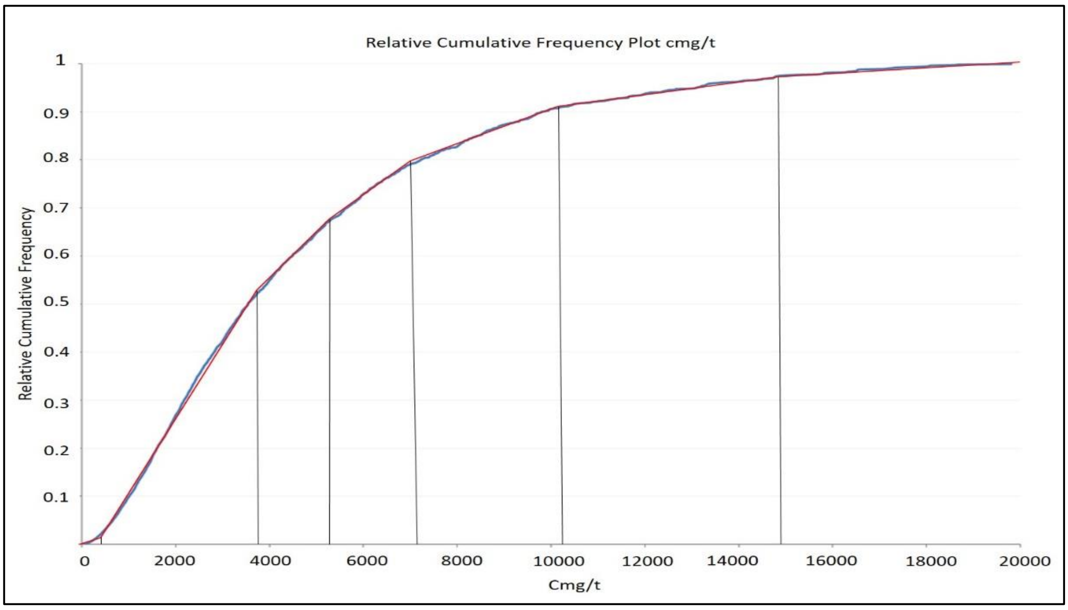

Figure 12: Relative cumulative sum frequency plot cmg/t.

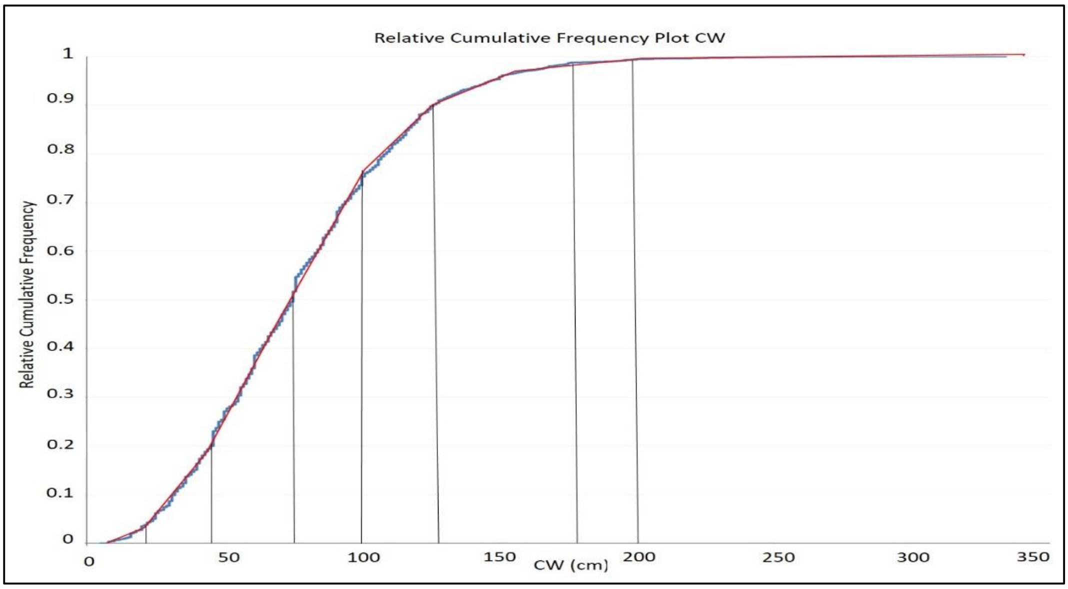

Figure 13: Relative cumulative sum frequency plot CW cm.

The inflection points, once identified graphically from the cumulative frequency plots (Table 7 and Table 8) were colour coded using the inflection points and plotted to observe if any spatial relationship could be visually identified.

Table 7: Coded inflection data value (cmg/t).

Inflection point coding	Value (cmg/t)
1	0-50
2	51-3 000
3	3 001-4 500
4	4 501-6 500
5	6 501-9 250
6	9 251-14 500
7	14 501-50 000

Table 8: Coded inflection data CW (cm).

Inflection point coding	CW (cm)
1	0-20
2	21-45
3	46-70
4	71-100
5	101-125
6	126-175
7	176-200
8	201-500

When plotting the encoded inflection points, due to mixed data near proposed boundary lines, and observing the data spatially, the hard boundaries were considered “tentative”. These tentative, geological boundaries identified were partially in agreement with the underground mappings and facies plan. This further confirms the relationship between grade distribution (Figure 14) and CW (Figure 15) across geological boundaries as well as other geological attributes of deposition. From the relative cumulative frequency plots, it was concluded that geological processes can be utilised to determine gold value (cmg/t) ranges and subsequent concentration of the mineral of economic interest. It was also observed that geological relationships are not linear across geozone boundaries and that geological attributes should not be treated with equal weightings.

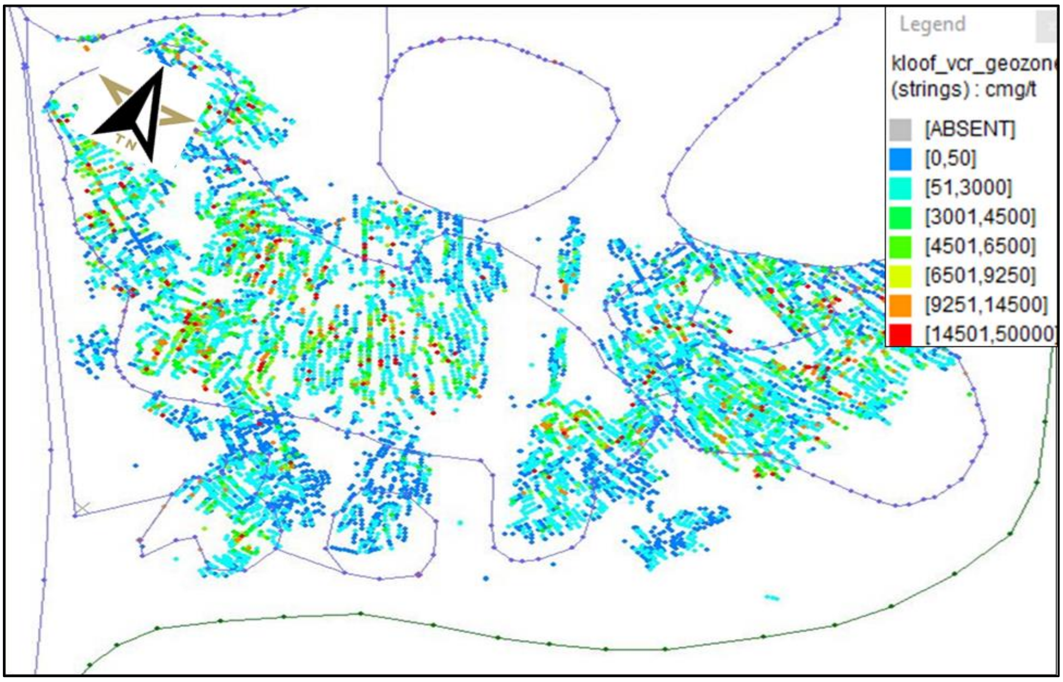

Figure 14: Value (cmg/t) colour coded on inflection points

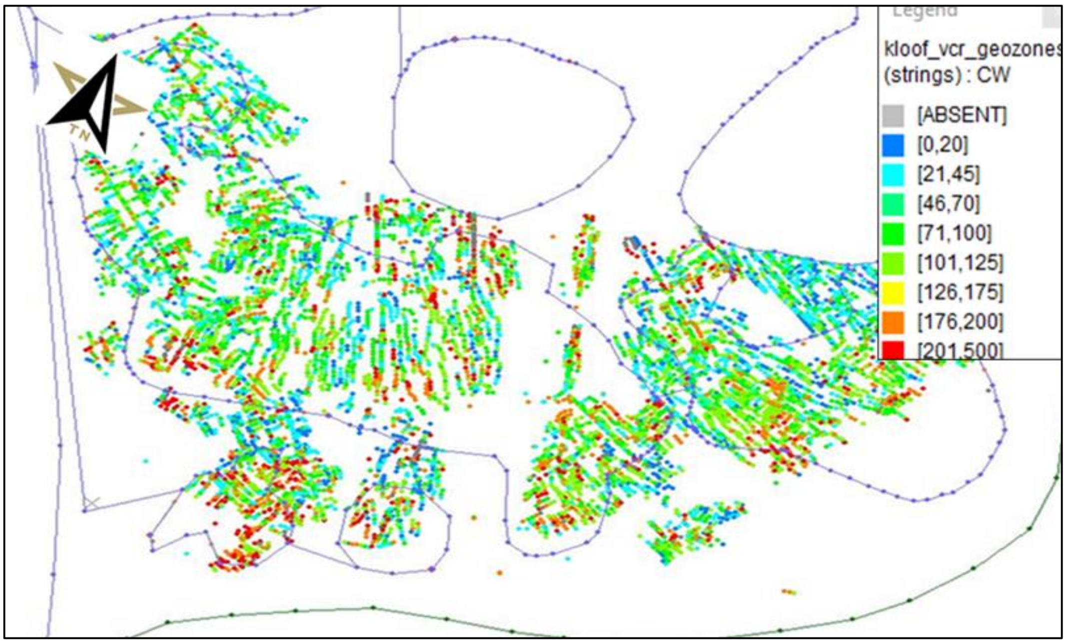

Figure 15: CW(cm) plot of colour coded data.

3.7 Existing geozone identification

From Dohm (1995) and the relative cumulative distribution plots (Figure 12 and Figure 13), it was observed that a non-linear relationship exists between the sedimentological attributes of the VCR. Previous attempts of utilising sedimentological data have assumed a linear relationship with an equal importance weighting. However, due to the non-linear relationship observed, individual weightings of each sedimentological attribute must be considered. To assist with the sedimentological weighting calculations, statistics of each sedimentological attribute were calculated and can be observed in Table 9.

Table 9: Descriptive statistics of the sedimentological attributes.

Sedimentological Attribute	Mode	Min	Max	Range	Sum
Pebble Max	4	0.01	99.00	98.99	187 572
% Conglomerate	1	0.00	2.19	2.19	30 692
Packing	3	1	3	2	76 429
Rounding	2	1	3	2	73 551
Sorting	2	1	3	2	75 361
Mineralisation	3	1	3	2	86 706
Assemblage	2	1	2	1	54 624
Matrix	8	1	8	7	211 295
Basal contact	3	1	3	2	89 348
Carbon	1	1	2	1	38 551
Buckshot	1	1	2	1	35 259

3.8 Refinement and interpretation of the geozones

An initial geozone model based on the existing mine methodology was created. This methodology for identifying the facies is based on solving the individual sedimentological attribute weightings, as originally developed by the mine Resource Manager and is captured in an MS Excel script. The theory underpinning this methodology is out of scope of this research and is considered to be mine Intellectual Property. The principles behind it are discussed and illustration of the application thereof is provided as relevant. This algorithm is an automated sequential process based on statistical knowledge of the probability distributions of the gold values (cm.g/t) and the VCR channel width, and the application of linear programming techniques to determine attribute weights whilst minimising the error between observed block values (3 parameter lognormal cm.g/t estimate) and block values based on a weighted average of the attribute. This is then further refined based on an analysis of variance and a predefined error threshold for a sample to belong to a specific facies or not. Input to this algorithm is all the available validated sample records. Each sample point is represented by a line record in the file and each record contains the following variable fields: Surveyed X, Y, Z co-ordinates, measured channel width, average gold value (cm.g/t) calculated as the width weighted average of the assay grades(g/t) at the sample location. Followed by the observations of the nine sedimentological attributes.

This existing methodology once utilised, established the initial existing geozones, which were then later refined based on the research of the author and cross validated with borehole drilling and underground mapping by the author of this research project.

The existing methodology from Mr L Tolmay (personal communication) can be summarised as follows:

1. A block size is chosen for analysis. As this process is to be utilised for exploration purposes, a block size indicative of the prospective exploration targets should be utilised. In this case, a search radius of 100 m was selected resulting in a block size of 200 by 200 m being

used. At Kloof Gold Mine, the average distance between two adjacent raise lines is one hundred meters (100 m), which allowed for a larger area of geological influence to be considered.

2. In the areas where sampling is more abundant, the averages of the samples within each block is established based on a 3-parameter lognormal distribution, with the optimised third parameter, identified by minimising the skewness of the log transformed cmg/t values in the block using the Goal Seek function in MS Excel. This 3-parameter lognormal estimate of the block is assumed to be the "actual" cmg/t value of the block and is labelled as "Act Value".

3. The minimum number of samples required in order to obtain a representative mean for 200 m x 200 m block size is determined. By utilising an SMU of 100 m, the point data in the block are regularised and the mean of differing sample sizes is plotted against the zonal mean. Where the mean tends towards the zonal mean, this is chosen as the minimum number of samples required. On Kloof Gold Mine, this has been repeatedly calculated to be a minimum of 40 sample points.

4. The blocks that meet the minimum sample requirement are then considered as having a mean representative of the "actual" block value. This representative average value (Act Value) is used as the target value in the optimising the weights to be assigned to the sedimentological attributes for a specific facie or geozone.

5. The numeric rating (quantitative value) of each sedimentological attribute including the cmg/t and CW is then utilised to construct for each observed sample, an equation of the form:

$$Value = \sum_{i=1}^{n} w_i \times \ attribute(i)$$

Equation 1

6. The initial sum of squared deviations of all the estimates for each sample point minus the block means wherein each sample point resides is calculated with Equation 2:

$$Sum\ of\ Errors = \sum(Act\ Value\ -\ block\ mean\ value)^2 \qquad \text{Equation 2}$$

The sum of the squared errors is then assigned as the objective function which is minimised in MS Excel utilising the Solver function in MS Excel.

7. A plot is created of the estimated cmg/t value based on the weighted sedimentological attributes vs the lognormal estimate and an example appears in Figure 16. The straight line represents the case were these two values are equal.

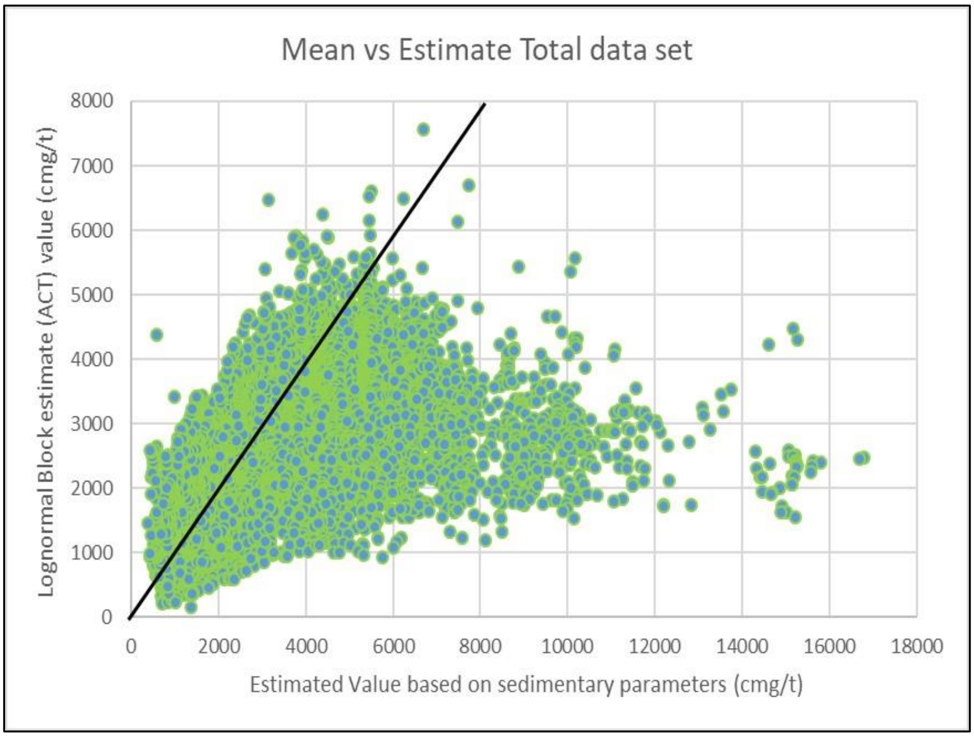

Figure 16: Sedimentological estimate vs. Lognormal Block Estimate.

8. At this point a subjective decision is made, which is: how much of an error one is prepared to accept before one considers the borehole or sample to reside within a different facies type. For this research project, an error of 10% was deemed as acceptable. After identifying the samples for say Facies 1, with 10% difference between the ACT block mean and the estimated value based on a optimally weighted sum of sedimentological attributes including the cmg/t and CW appear in Figure 17. All the boreholes and samples which meet the error

criteria defined above are then removed from the dataset as well as their corresponding weights. This identifies a sedimentological facies type, in this example Facies 1.

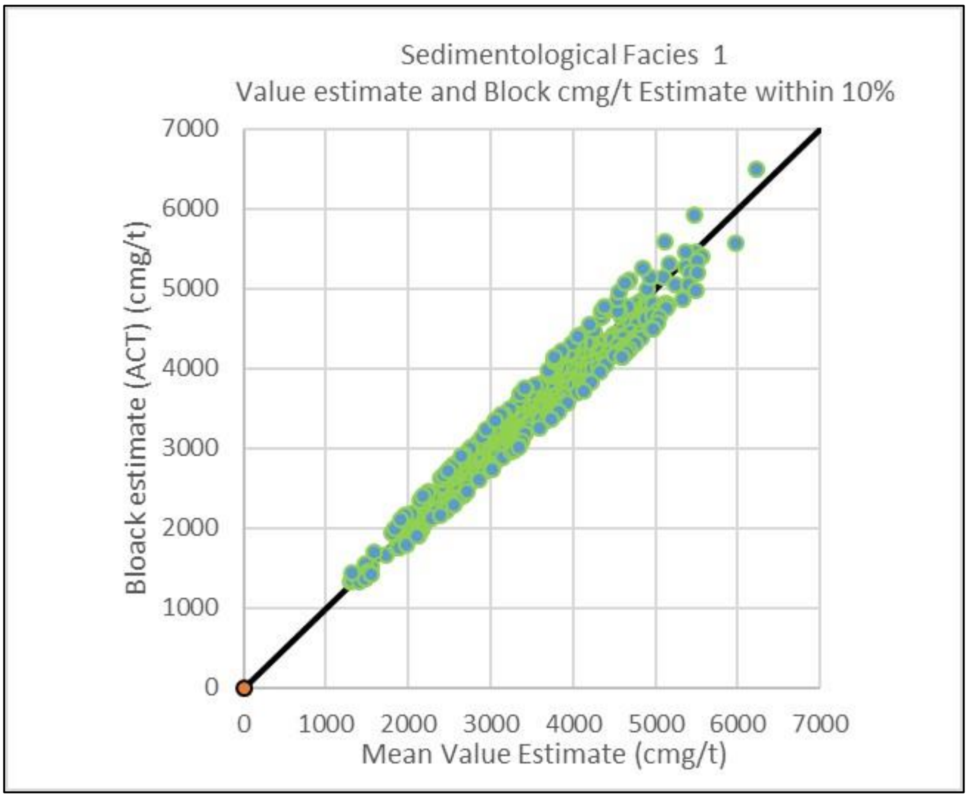

Figure 17: ACT block mean vs. estimated value using optimally weighted attributes for Facies 1.

9. The process is then re-run from step five onwards, on the remaining dataset, to determine the next facies type and its corresponding weights. The process is repeated until no more samples are available or a fit that meets the error cut off is no longer obtained. A total of 39 different geozones were delineated utilising this process is summarised in Figure 18.

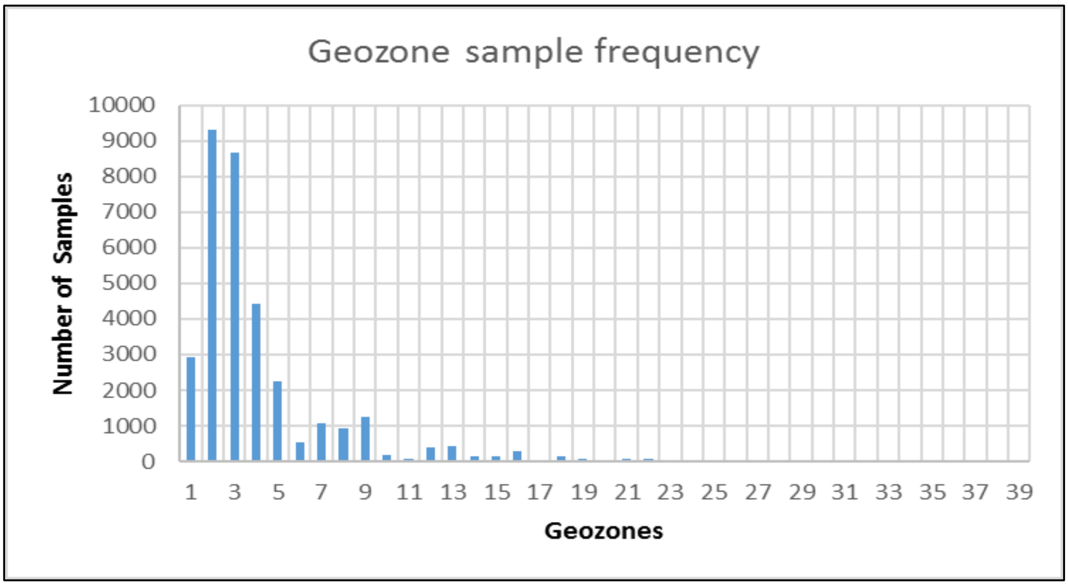

Figure 18: Number of samples per geozones.

However, due to legacy data (subjective or generic sedimentological points), many geozones were assigned less than 50 data points (<2% of the dataset). These geozones are statistically insignificant and are assigned a zero geozone value. Removing the geozones with less than 50 data points, 22 geozones remained (Figure 19).

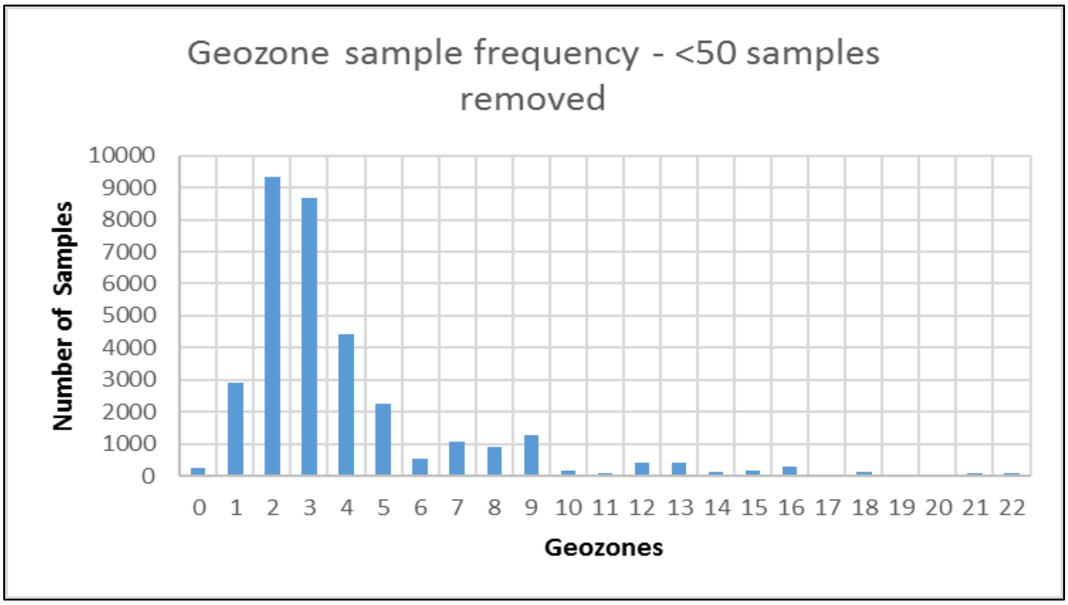

Figure 19: Final geozones numbers with 50 or less data points removed.

10. In the final phase the individual facies are then plotted, and polygons are created to constrain the individual facies.

In analysing the weightings of the geological attributes, it was observed that where an attribute had a positive weighting, there was a direct relationship between the attribute and grade. Where the attribute had a negative weighting, it could be observed that the presence of the sedimentological attribute had a detrimental effect to the grade. A summary of the solved weights for the different facies or geozones established in this research appear in Table 10. The larger the weight proportion of each sedimentological attribute, the more important that attribute is as a constraining criterion for that geozone (facies) under consideration and the greater its impact on the resulting grade, where each sedimentological attribute has a sum of 100 %.

This chapter discussed how the optimised sedimentological weighting could be calculated while reducing the error associated with estimations. It was further observed that the sedimentological attributes have a non-linear relationship between them, which was explored in detail and allowed for homogenous geozones based on sedimentological geological attributes to be identified.

Table 10: Optimised sedimentological attribute weightings per geozone.

Geo Zone	CW	CMGT	Pebble max	Percentage Conglomerate	Packing	Rounding	Pebble sorting	Mineralisation	Assemblage	Matrix	Basal contact	Carbon	Buckshot
1	0.0476	0.0032	2.7782	0.9123	13.7726	-4.7103	60.0560	53.4469	-1.1459	26.5080	-51.9985	0.2377	0.0919
2	0.0081	0.0006	0.6088	0.0239	15.6160	-0.0172	-0.3803	74.7244	-0.0590	8.4323	0.9973	0.0400	0.0049
3	0.0445	0.0032	3.2067	5.3937	-3.5617	4.5182	41.3613	13.7037	-0.2927	27.1075	8.5693	-0.0296	-0.0244
4	-1.8590	-0.0048	-38.8063	3.1674	8.6001	96.0461	19.0461	14.8555	43.5261	-63.1476	12.2737	3.5616	2.7416
5	0.6809	0.0012	11.4514	-1.7797	35.5825	12.4784	33.7259	7.3936	-10.9726	7.0416	8.5020	-2.3459	-1.7597
6	1.4774	0.0030	25.8956	7.6178	7.7500	5.1377	5.9595	5.7825	3.9525	19.3921	7.4710	4.5098	5.0503
7	1.7979	0.0030	22.8187	7.9620	9.9184	5.9723	7.4199	6.3001	4.4077	13.4153	9.9278	4.7147	5.3413
8	0.0043	0.0004	0.3338	4.8453	2.9986	6.5113	13.0584	96.8008	-0.2055	-5.8799	-0.5055	-18.5775	0.6152
9	0.0853	0.0003	1.9749	44.3284	5.3419	5.2352	5.3463	4.7921	7.1256	2.0108	4.2997	9.0852	10.3740
10	-0.0026	-0.0002	-0.2003	-2.3530	-2.3888	-4.3920	-2.7062	112.6290	-0.2058	-0.1995	-0.3662	0.7735	-0.5883
11	0.2492	0.0007	4.7057	23.1105	3.3426	4.0091	3.9686	4.8462	12.6862	4.8977	2.9200	16.6670	18.5962
12	0.5781	0.0015	11.3324	16.5564	10.6108	6.3178	7.3995	5.5756	4.4759	9.4540	9.0775	7.9972	10.6227
13	0.1815	0.0004	3.3531	13.8312	8.2931	7.8375	8.1313	7.7436	10.3248	3.2111	6.9510	14.5670	15.5742
14	0.8969	0.0020	17.0340	-47.9203	20.8140	38.4630	38.3360	106.3688	-27.1266	22.6278	17.3774	-37.2036	-49.6707
15	-0.2419	-0.0004	-3.8535	1.3569	8.0010	50.8799	14.5756	-11.9025	17.5252	-4.2240	24.6104	1.8516	1.4215
16	-0.3173	-0.0007	-6.4127	-41.9150	18.2508	41.4163	30.7862	141.0231	-24.0464	-5.6693	21.9358	-36.1480	-38.9032
17	0.0719	0.0000	1.0326	-5.7218	0.7704	0.7932	0.7846	0.8007	0.9830	1.3758	0.7749	102.8368	-4.5022
18	0.0074	0.0003	0.3214	4.2833	2.7741	5.6926	11.2334	23.6633	82.2008	43.7031	-80.9890	1.4639	5.6450
19	0.1593	0.0001	2.2141	-2.6148	-8.1199	43.0214	-25.6664	89.3300	15.3781	2.3873	-11.0247	-2.5488	-2.5160
20	0.0083	0.0003	0.4440	5.5010	3.7249	8.4407	15.7058	36.1574	-13.2628	25.2505	17.8745	0.0333	0.1219
21	0.0830	0.0001	1.1282	17.1356	3.3599	3.6525	3.7193	5.2479	26.6874	1.3950	3.1040	19.7130	14.7737
22	-0.0142	0.0000	-0.2413	49.6377	-0.5588	-0.5862	-0.5925	-0.5446	-1.2148	-0.2002	-0.4911	23.9703	30.8356

4. Geozone Analysis and Refinement

4.1 Geozone Boundary Refinement – 1st step

The 100 m x 100 m identified sedimentological domains were plotted spatially and coloured according to their assigned geozone. Visually, distinct boundaries between the geozones could be identified (Figure 20).

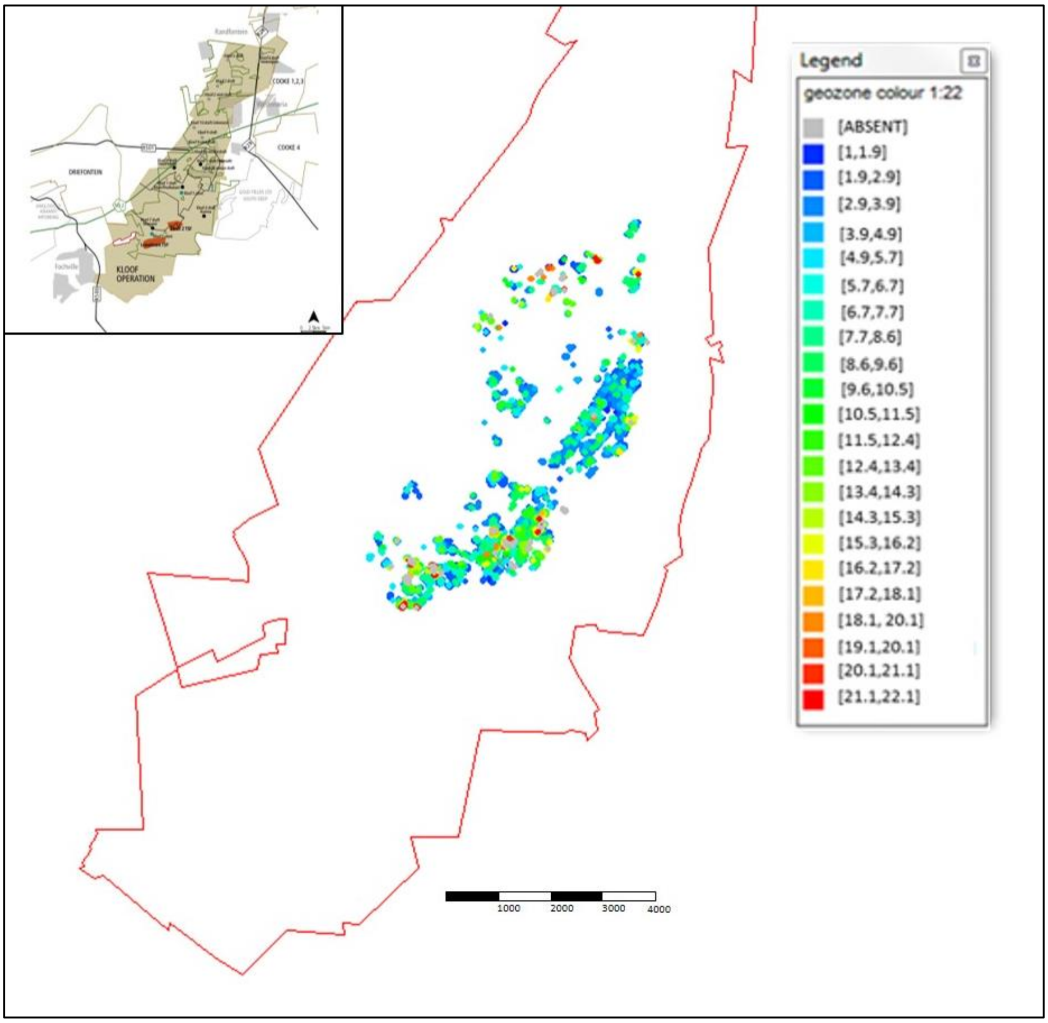

Figure 20: Spatial plot of facies data (SibanyeGold, 2017).

To refine the geozone boundaries further, the facies boundary codes were interpolated using an Inverse Distance Weighting (IDW) methodology. The IDW tentatively indicated boundaries between the geozones as depicted in Figure 21.

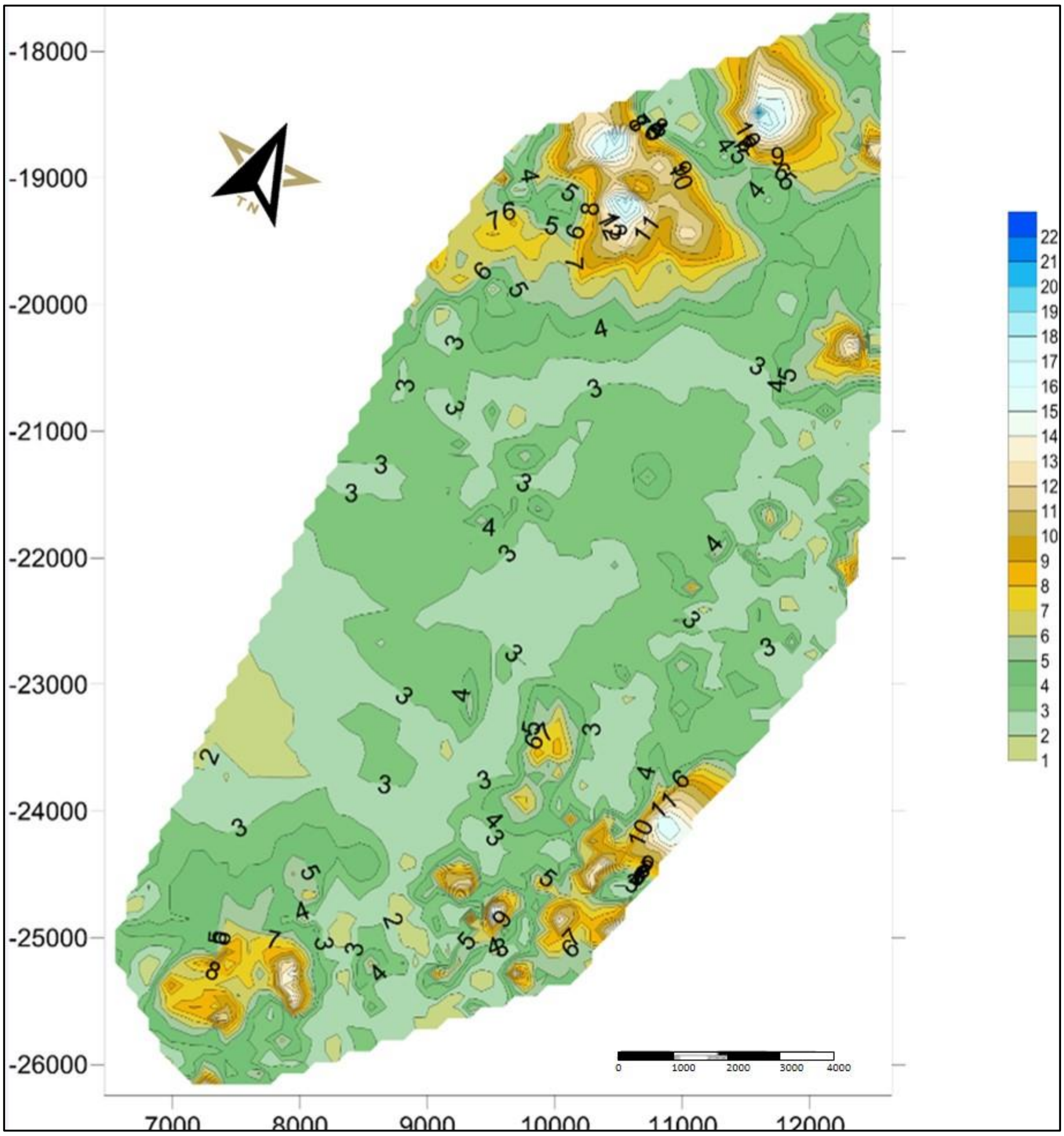

Figure 21: IDW indicating tentative boundaries between geozones.

The geozones boundaries were then digitised and compared to the current underground facies to ascertain the continuity with previous geological mappings (Figure 22). A good correlation between the existing facies model (mapped lithological boundaries), and the observable identification of facies is observed.

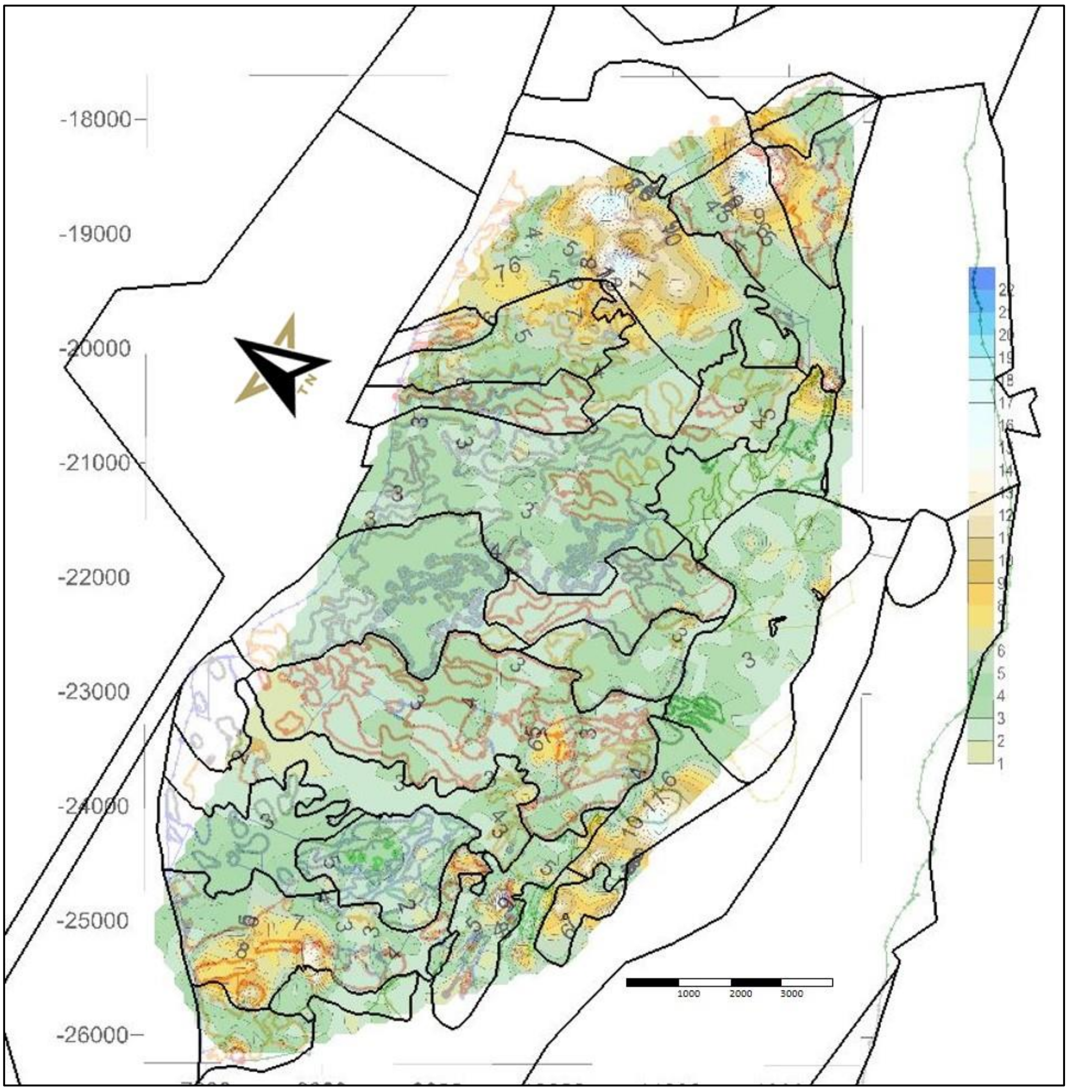

Figure 22: Digitised geozones (black) vs. facies plan (other colours).

Within the twenty-two macroscopic domains (facies), it was observed that the salient geological features were preserved, where palaeo highs and erosion embayment's were identified as prominent geological processes, smaller, localised geological features were however lost due to the large search radius (100 m). It was further also commonly observed that several geologically similar zones clustered closely together, which possibly represented statistically similar, larger zones from the same depositional event with smaller geological subdivisions (Figure 23). This illustrated how geological processes, with similar styles of deposition have similar geological characteristics and can be clustered together as a single homogenous group where each deposition event has a unique geological "fingerprint".

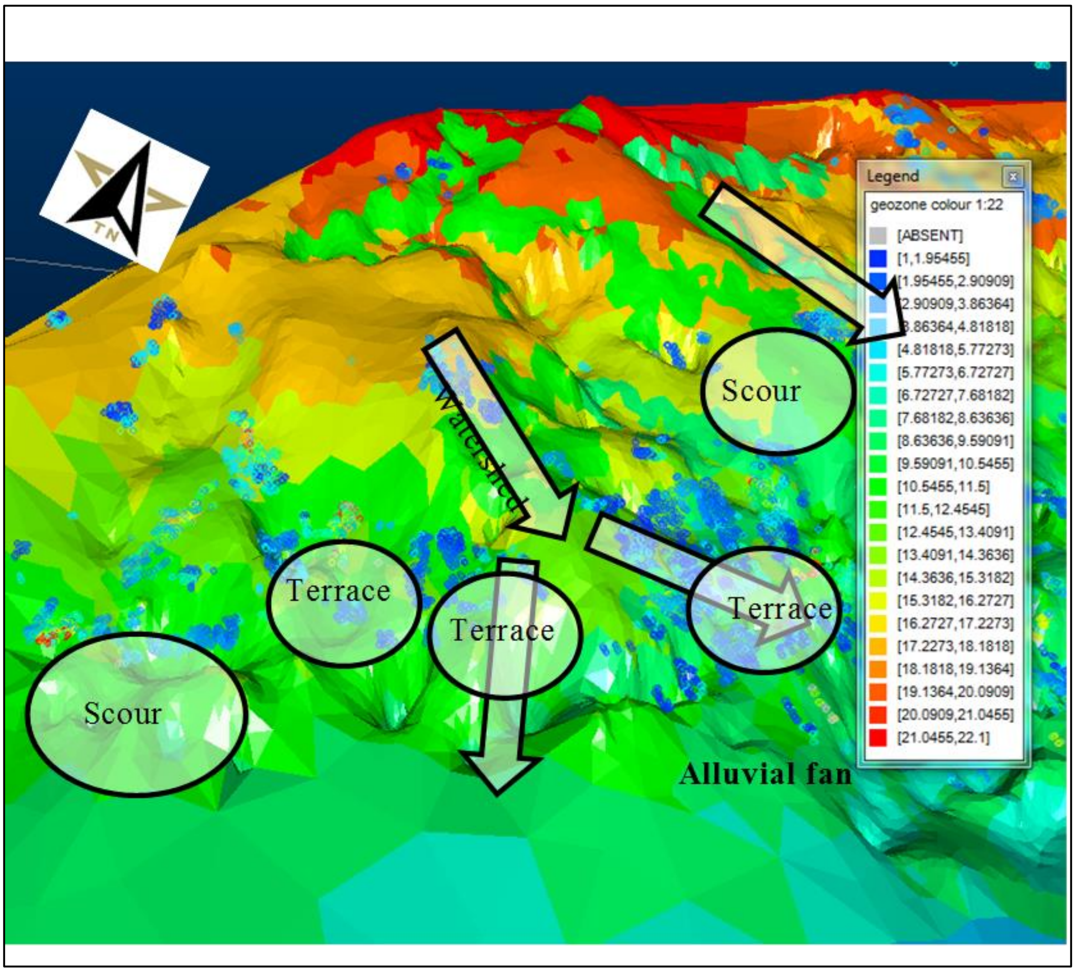

Figure 23: Geozones relative to exaggerated CW showing unique geological characteristics in different geological settings.

Where data points had an unassigned geozone (50 data points or less), the points were often plotting in braided fans, fluvial fans and fretted terraces, all which have inconsistent geological "fingerprints" and erratic deposition. These data points were then assigned to an identified geozone according to their spatial position and reef architecture.

4.2 Interpretation, Analysis and Homogeneity of Geozones

Where similar weightings were observed, in combination with the spatial plot, several facies were thought to be of similar geological processes and combined into one larger "sedimentological domain" (Figure 24), a similar process was independently identified by Nwaila, et al. (2020).

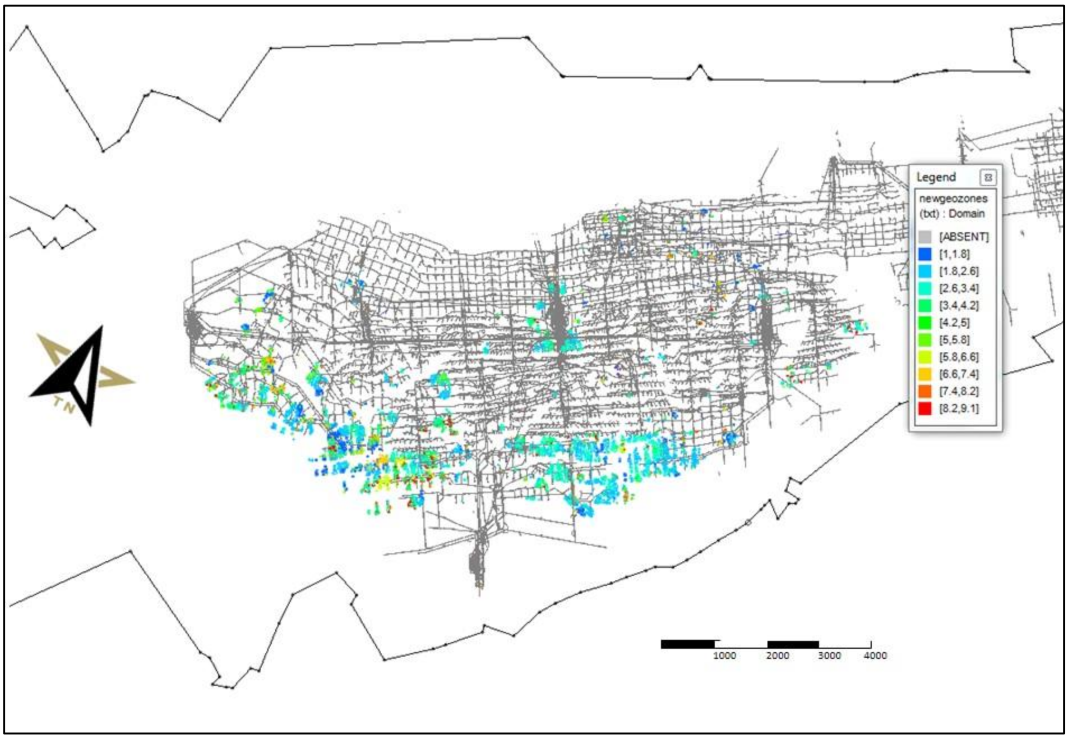

Figure 24: Spatial plot of combined facies.

Nine larger "sedimentological domains" (each with their own unique geological fingerprint) were identified and an IDW (Figure 25) was performed on the new domains giving tentative boundaries between the larger domains. This correlated extremely well with the original cycles based on reef architecture.

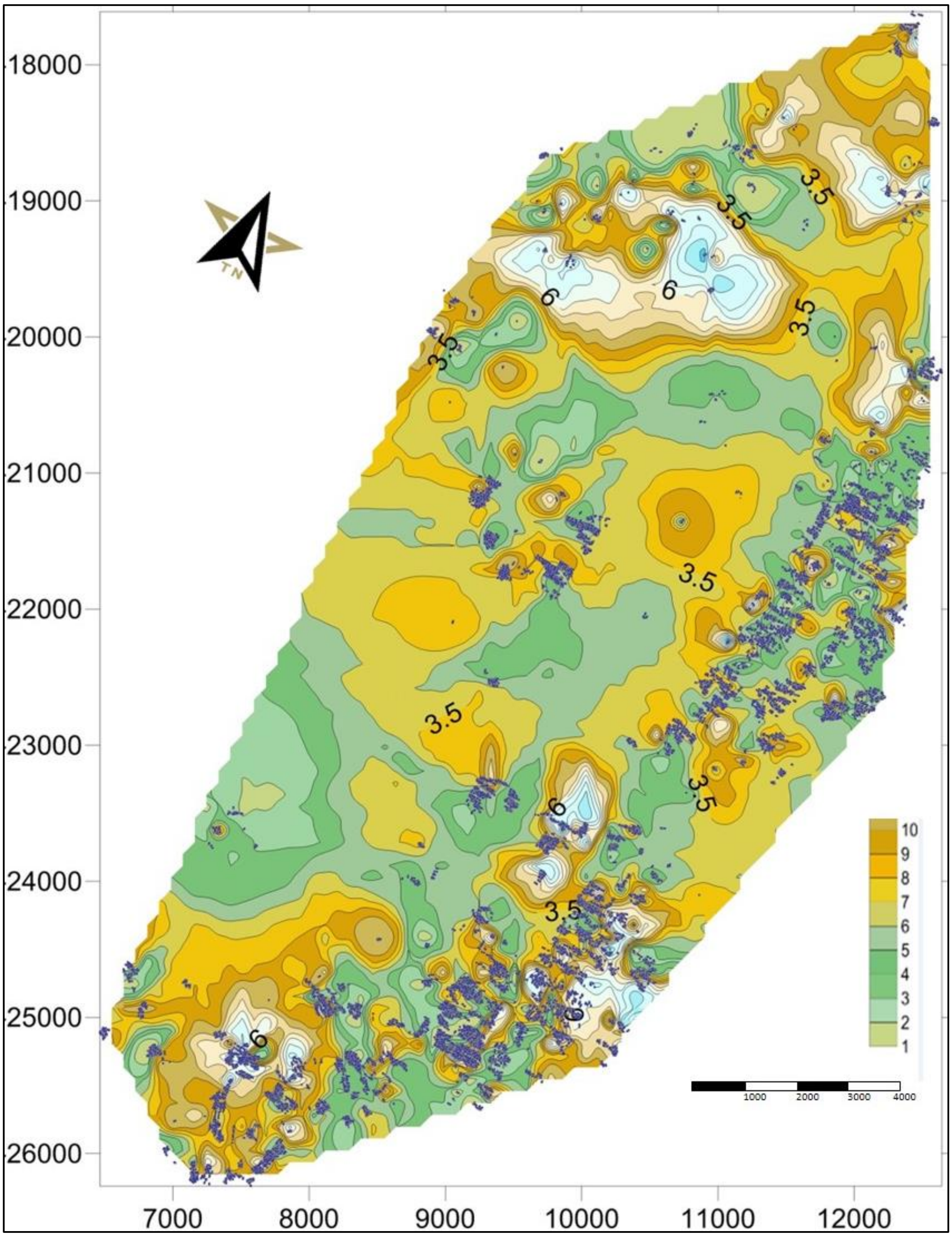

Figure 25: IDW of nine larger sedimentological domain.

A summary of the averages of the combined sedimentological domains and their combined facies can be observed below in Table 11.

Table 11: Domains with sub-domains – average values

Sedimentological domain	Sub domains	CW	cmg/t	% conglomerate	Pebble max (mm)
1	6	119	2 114	71	59
	7	105	2 847	67	58
	8	113	2 296	72	58
2	20	75	1 358	80	30
	21	65	973	92	29
	22	90	1 268	83	29
3	16	141	550	95	79
	17	121	460	88	68
	18	151	750	87	71
	19	138	780	79	65
4	15	148	1 850	65	65
5	11	130	2 743	95	57
	12	138	1 617	95	59
	13	118	1 990	89	52
6	10	90	3 114	85	51
7	9	133	1 996	93	26
8	4	98	2 570	93	63
	5	84	2 419	88	60
9	1	95	3 813	88	58
	2	104	3 133	89	51
	3	102	3 173	91	51

The nine final sedimentological domains across Kloof Gold Mine can be seen below in Figure 26.

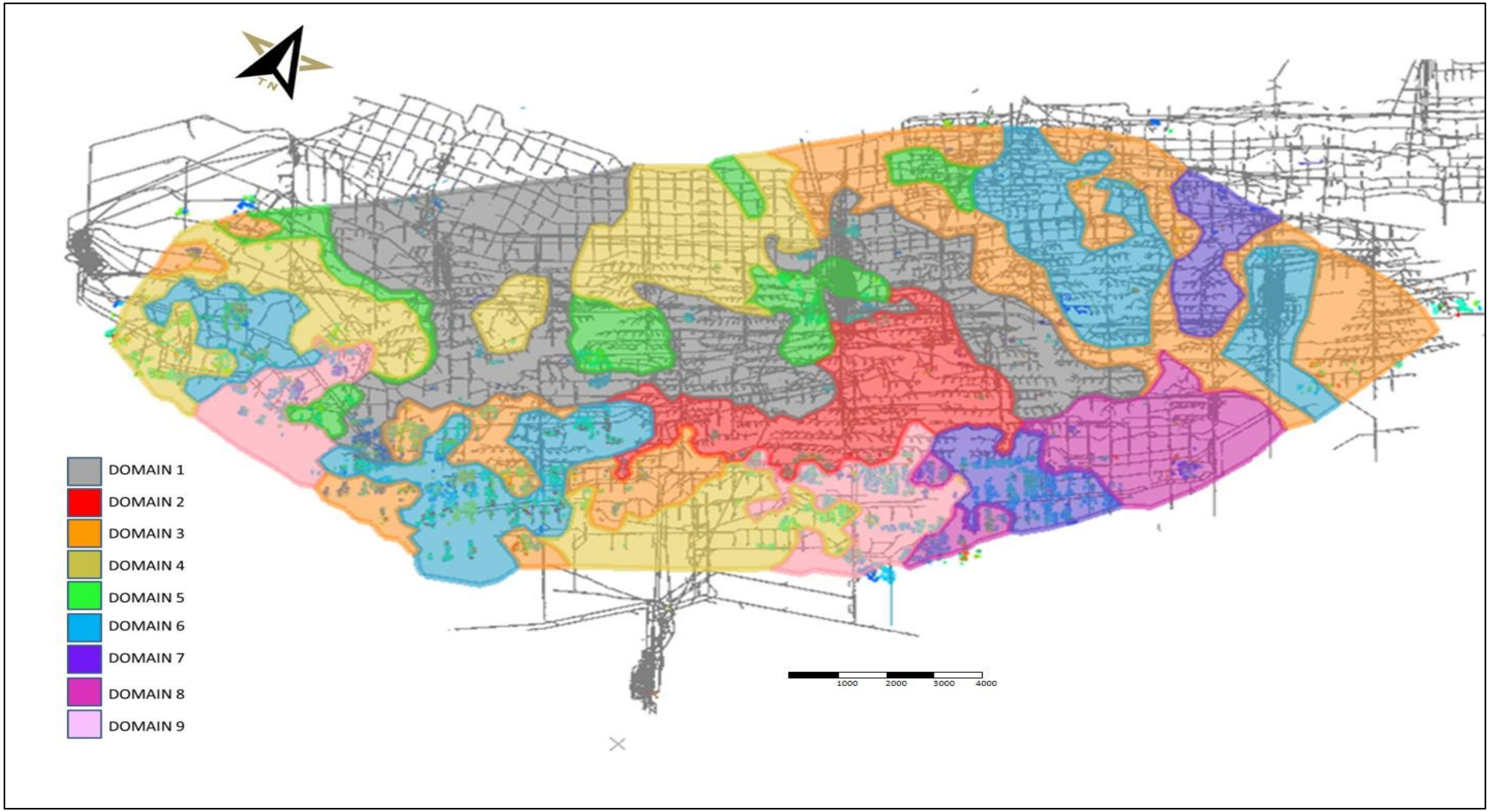

Figure 26: Nine sedimentological domains across Kloof Gold Mine.

Overlaying the sedimentological domain data points with the exaggerated CW, the geology is clearly defined across varying geological depositional environments, which can be used to delineate facies boundaries (Figure 27). Spatially the geology correlates well with the CW. The larger depositional features are well preserved and correlate well to changes in CW, where a good, positive relationship between deposition and geological attributes can be observed. CW can be considered as constraining criteria across lithological boundaries, but not within them, and should be used to delineate tentative boundaries.

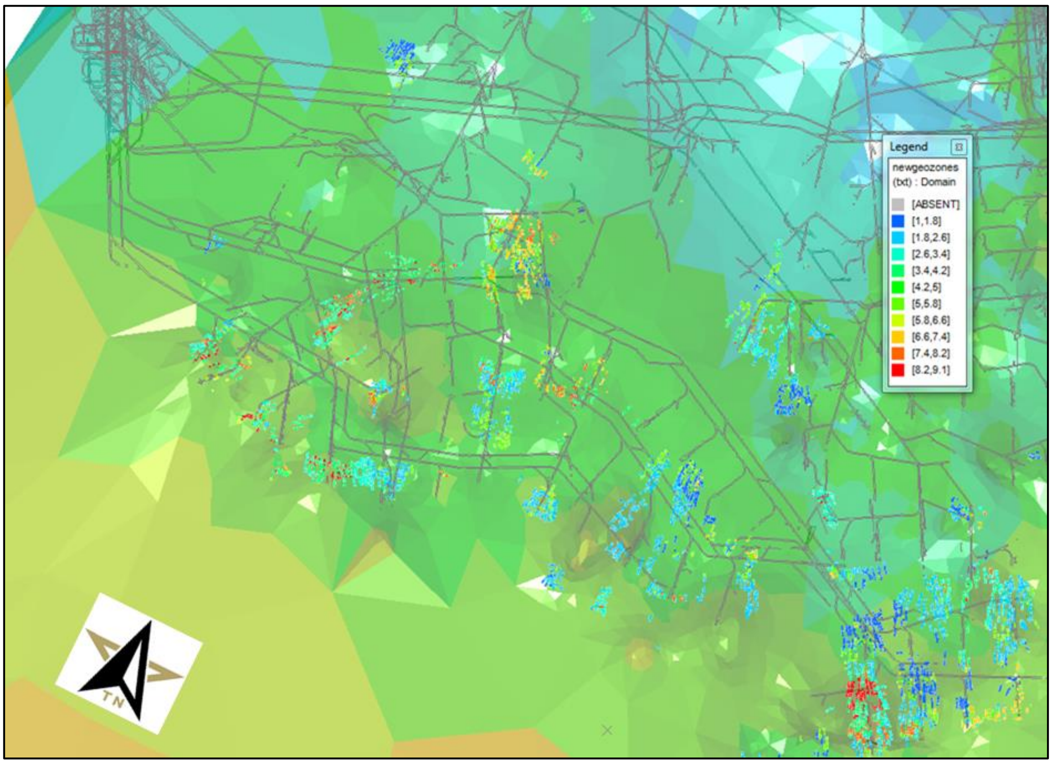

Figure 27: Exaggerated CW with delineated facies data points.

Comparing the same for the sedimentological domains with the mapped underground facies plan, it can be observed that the facies correlates well with the sedimentological domains with a good correlation observed between underground mapping and the delineated sedimentological domains (Figure 28).

Overall, a good correlation between geological attributes and facies can be observed, informing the conclusion that geological attributes of deposition can be used to clearly delineate homogenous domains.

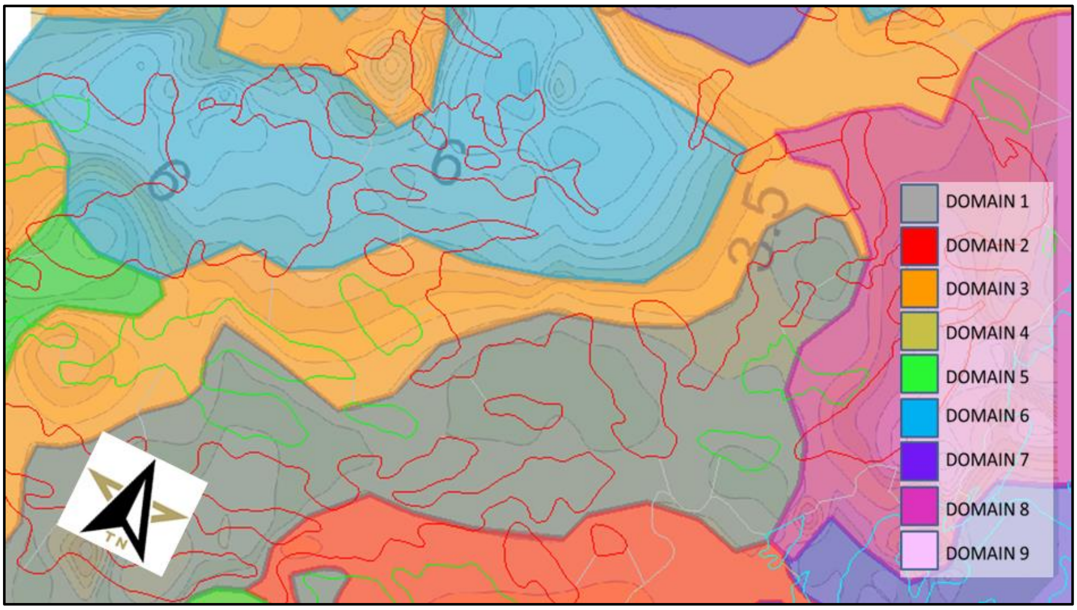

Figure 28: Sedimentological domains correlate well with facies.

An F-test was performed on each of the nine domains to check for homogeneity using a 100 m x 100 m search radius (Figure 29 and Table 12).

The ANOVA illustrated that seven of the nine differentiated domains were homogenous and could be considered to display homogeneity (Table 12), based solely on geological attributes. The remaining two domains were subjectively deemed as homogenous due to their similar processes of deposition. Further complicating the homogeneity of the domains is the inclusion of slope reef. Slope reef has not been excluded from the dataset and has been included into the domains due to its erratic and therefore hard to predict nature. Slope reef can potentially have a major impact across lithological boundaries between sedimentological domains, and boundaries should be treated as "soft" (Kasmaee, et al., 2019). Slope reef may also have an impact on the homogeneity of the domains due to differing local sedimentological attributes.

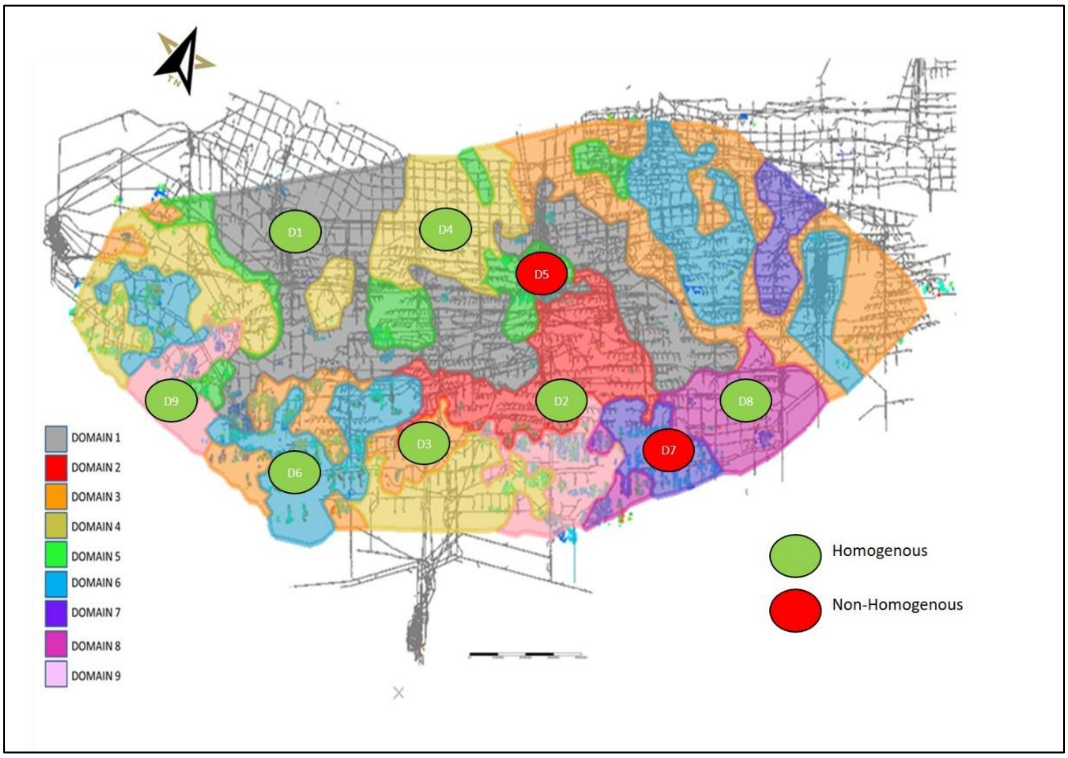

Figure 29: Spatial distribution of Sedimentological Domains.

Table 12: ANOVA results of sedimentological domains based on cmg/t.

Domain	Fcrit	F observed	Variance	Mean	Homogenous
1	3.6	3.5	261 552 566	2 700	Yes
2	7.7	3.3	39 106 310	980	Yes
3	6.6	5.7	7 316 651	1 220	Yes
4	6.0	6.0	11 526 392	1 850	Yes
5	2.2	2.5	16 004 359	2 043	No
6	3.8	3.1	55 167 695	3 115	Yes
7	6.6	7.1	312 225 485	2 000	No
8	3.5	3.5	14 731 701	2 520	Yes
9	3.4	2.9	2 427 609	3 170	Yes

In this chapter, and specifically from Table 12, it was observed that by examining only similar geological processes (each with unique geological characteristics) and sedimentological attributes, in conjunction with the exaggerated CW plot and the mapped palaeomorphology plan, provided an excellent platform to define homogenous domains. However, due to the inclusion of slope reef and using a simple IDW to delineate the boundaries, further refinement of the process using spatial plots could be considered. The degree of homogeneity was acceptable and was used as the final geological model.

4.3 Geozone Definitions

From the nine sedimentological domains, pebble size, buckshot pyrite, mineralisation extent, basal contact and presence/absence of flyspeck carbon were observed as the constraining characteristics within the major sedimentological domains and which were used in the qualitative assessment of the VCR's economic potential. The simplified VCR domains are summarised below in Table 13.

Table 13: Summary of geological attributes per domain.

Facies	Average CW (cm)	% Conglomerate	Average max. pebble size (cm)	Average grade (cmg/t)	Basal Contact (S=Sharp, G=Gradational, B=Both)	Flyspeck Carbon (A=Absent, P= Present)	Mineralisation (Well = W, Absent =A)	Buckshot Pyrite (A=Absent, P= Present)	Pebble Size (Small, Medium, Large)
1	108	70	59	2 700	G	A	W	A	MPC
2	82	85	29	980	B	A	W	A	SPC
3	110	91	62	1 220	B	P	W	P	LPC
4	148	65	65	1 850	B	A	W	P	LPC
5	126	93	57	2 043	S	A	W	A	MPC
6	98	77	51	3 115	B	A	W	A	MPC
7	133	92	26	2 000	B	A	A	A	SPC
8	96	90	61	2 520	B	A	A	A	LPC
9	108	91	53	3 170	B	P	W	A	MPC

A supplementary qualitative assessment of the VCR's economic potential was constructed in accordance with the nine sedimentological domains, to allow for the possible delineation of cmg/t value and facies ahead of the face with future exploration where information is scarce (Figure 30). This decision tree could also be used by the mine geologists, to allow for quick, on site domain delineation based solely on geological attributes.

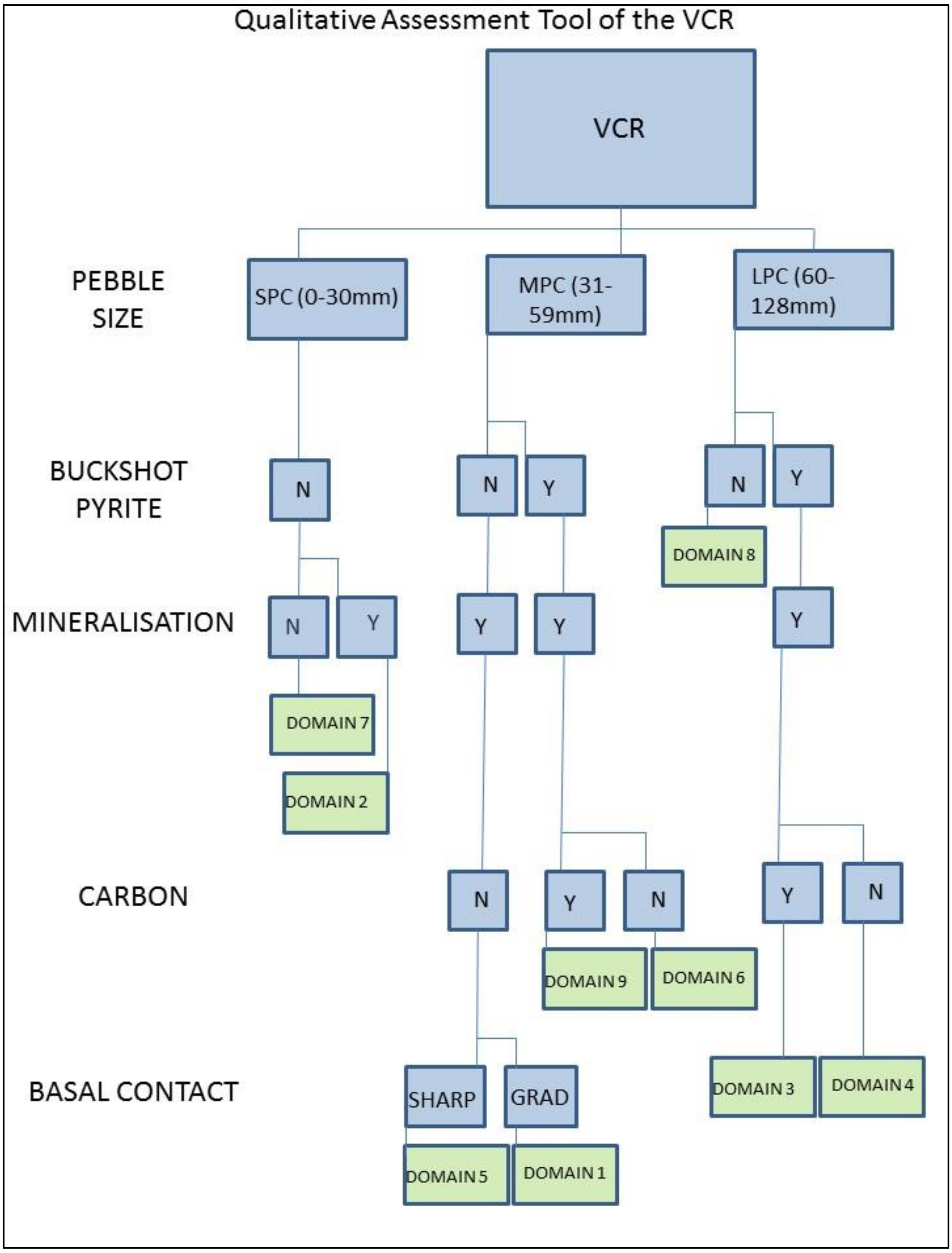

Figure 30: Qualitative assessment of the VCR.

From the defined sedimentological domains, an expected value for each domain (mean cmg/t value of domain samples), is presented in Table 14, and which could be used to assess the potential value (cmg/t) ahead of the face with exploration boreholes once a sedimentological domain had been assigned to an exploration sample.

Table 14: Average (expected) grade per sedimentological domain.

GEOZONE	Mean cmg/t
DOMAIN 1	2 700 cmg/t
DOMAIN2	980 cmg/t
DOMAIN3	1 220 cmg/t
DOMAIN4	1 850 cmg/t
DOMAIN5	2 043 cmg/t
DOMAIN6	3 115 cmg/t
DOMAIN7	2 000 cmg/t
DOMAIN 8	2 520 cmg/t
DOMAIN 9	3 170 cmg/t

4.4 Estimation Reef Potential Utilising a VCR Scoring System

An alternative methodology for estimating reef potential based on the reef architecture can be seen in Table 15. It is non-linear and gives the highest score (6) to the most favourable value of the reef characteristic and the lowest score (2) is assigned to the least favourable value and the acceptable value gets a score of 4. This scoring system could be applied and adapted further by mine geologists during future VCR drilling programmes ahead of the face to ascertain the potential of the block and utilises a combination of the most prominent geological characteristics to ascertain the potential of gold through borehole intersections, based primarily on the sedimentological characteristics of deposition. This method can also be used by the mine geologist underground to ascertain the viability of the exposed reef in the face in conjunction with the qualitative assessment tool in Figure 30.

Table 15: Scoring system utilising VCR sedimentological attributes.

Reef characteristics		Score
% Conglomerate	<50%	2
	50-70%	4
	70-100%	6
Buckshot pyrite	Absent	2
	Visible	6
Carbon presence	Absent	2
	Visible	6
Pebble size	SPC-MPC	2
	MPC-LPC	4
	LPC-COBBLE	6
Mineralisation presence	Low	2
	Medium	4
	High	6
Packing	Clast	6
	Matrix	2
Basal contact	Faulted	2
	Gradational	4
	Sharp	6
Rounding	Angular	2
	Rounded	6
Assemblage	Polymictic	2
	Oligomictic	4
Conglomerate development	Internal quartzite	4
	Sandy	2
	Conglomerate	6
High potential : >55 Medium potential: 35-55 Low potential < 35		

Using a combination of the two qualitative tools, a sound estimate of the value (cmg/t) ahead of the face can be achieved, based solely on geological characteristics. If used in conjunction with kriging, a powerful tool is available that can lead to improved confidence and reduced errors in estimations ahead of the face.

5. Definition and Validation of the Refined Sedimentological Geozones

5.1 Geozone Identifications using Macroscopic Definitions

To test the robustness of the model, through the combination of the qualitative assessment tools and mapped facies, each domain (unique fingerprints) was assigned an idealised set of identification values of the most prominent geological characteristics, through an analysis of the calculated weightings. These were used in visually identifying the facies in question. A distinct spatial correlation between the domains can be observed. The more distal the domain, the less preserved the terrace and pronounced the geological features observed (Figure 31), where each defined geozones characteristics can be said to be a unique geological fingerprint of the spatial deposition.

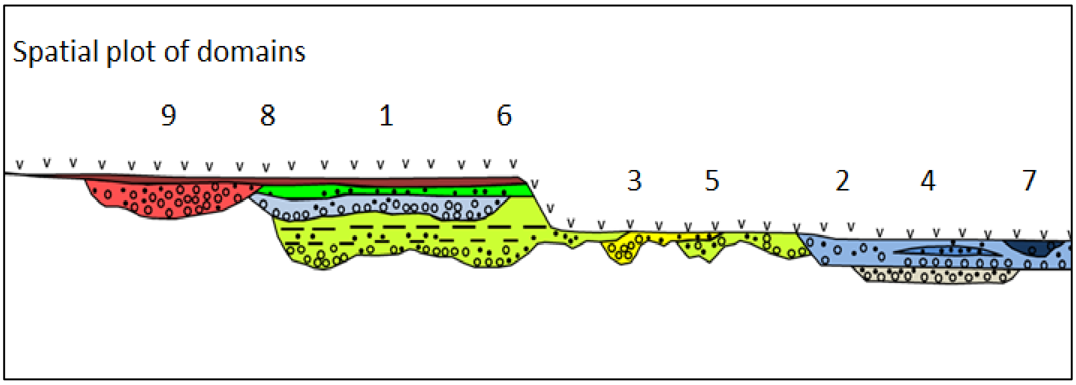

Figure 31: Idealised stratigraphy thought Kloof Gold Mine with spatial schematic plot of the 9 sedimentological domains identified.

5.1.1 Macroscopic Definition Domain 1

Domain 1 is a well-developed, well mineralized, moderately packed, medium pebble conglomerate (MPC 31-60 mm) unit (Figure 32). Often two conglomerate bands separated by a thick, internal quartzite. The internal quartzite is gritty, coarse grained, light- dark grey and up to 100 cm thick.

The internal quartzite is often poorly mineralised. The basal contact is gradational. There is no flyspeck carbon or buckshot pyrite present.

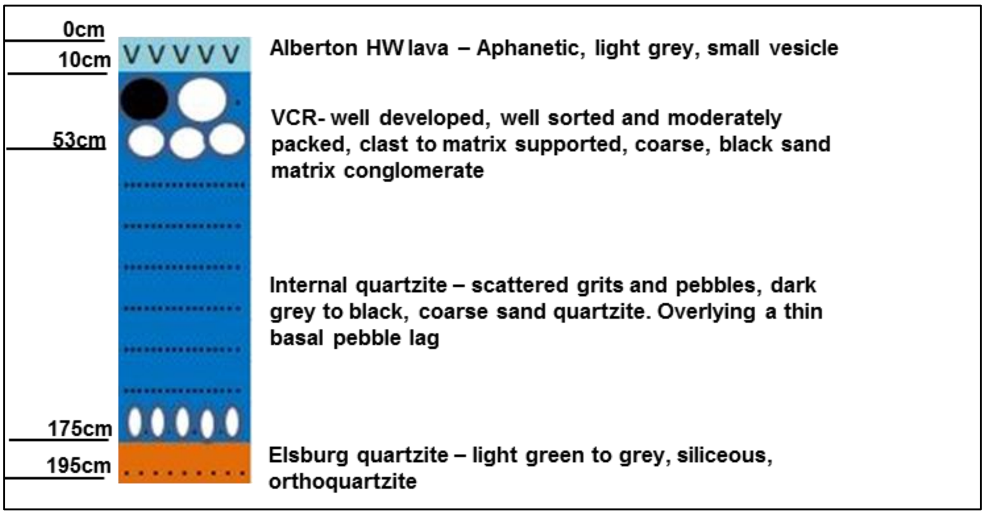

Figure 32: Macroscopic characteristics of Domain 1.

5.1.2 Macroscopic Definition Domain 2

Domain 2 is characterised by a medium- low channel width (Average 80 cm). There are commonly small to medium, angular pebbles (0 - 30 mm). Domain 2 is generally observed as a transition between two larger, well defined domains, and is normally at the base of a palaeohighs. The matrix is well mineralised with pyrite and chalcopyrite. However, buckshot pyrite and flyspeck carbon are absent. CW's are expected to be up to 100 cm at the most (Figure 33).

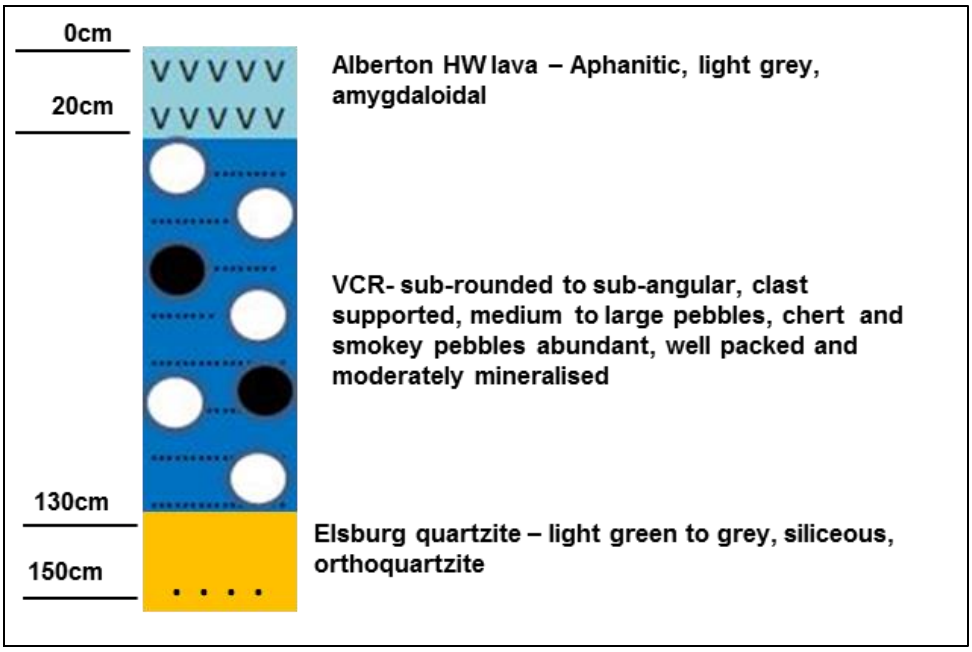

Figure 33: Macroscopic characteristics of Domain 2.

5.1.3 Macroscopic Definition Domain 3

Domain 3 is a distinct unit characterised by the presence of flyspeck carbon, buckshot pyrite and an abundance of secondary mineralisation (Figure 34). Domain 3 has large (61 - 128 mm), sub-rounded pebbles.

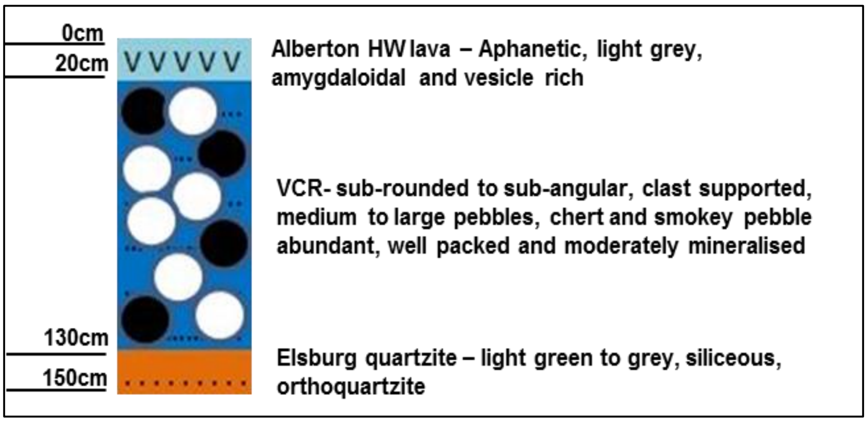

Figure 34: Macroscopic characteristics of Domain 3.

5.1.4 Macroscopic Definition Domain 4

Domain 4 is represented by a thick, gritty, internal quartzite and usually two conglomerate bands (Figure 35). The upper conglomerate band is poorly developed and often expressed as a pebble lag. The higher the % conglomerate, the better the expected grade with large (61 - 128 mm), sub-angular pebbles. Similar to Domain 3, there is the presence of flyspeck carbon and buckshot pyrite.

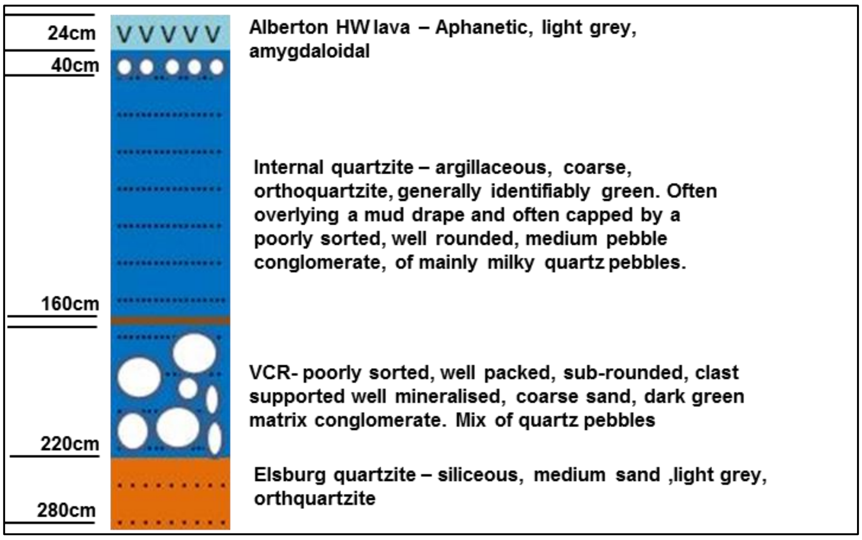

Figure 35: Macroscopic characteristics of Domain 4.

5.1.5 Macroscopic Definition Domain 5

Domain 5 has medium (31 - 60 mm), well rounded pebbles with a sharp basal contact (Figure 36). There is generally a well-developed, well mineralised conglomerate with the absence of flyspeck carbon and buckshot pyrite. The CW varies between 1.0 - 1.3 m thick.

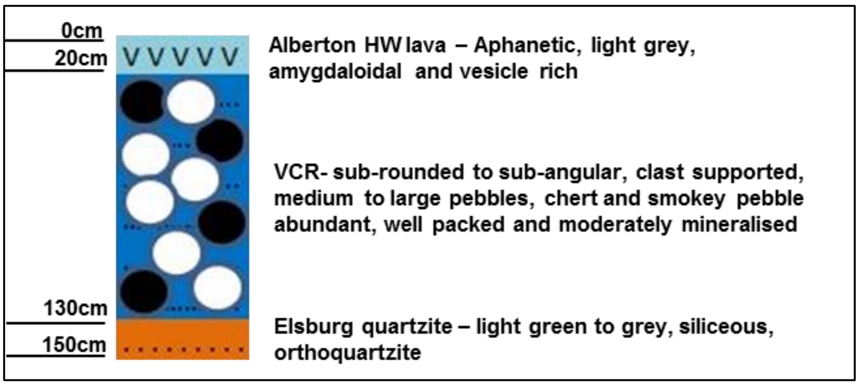

Figure 36: Macroscopic characteristics of Domain 5.

5.1.6 Macroscopic Definition Domain 6

Domain 6 is often characterised by two conglomerate bands separated by an internal quartzite (Figure 37). There is an abundance of buckshot pyrite throughout the matrix. Flyspeck carbon is absent, and the conglomerate has medium (31 - 60 mm), rounded pebbles. The matrix is well mineralised, and the conglomerate is overlying a sharp basal contact. The upper conglomerate unit is often better developed than the basal unit and has smoky and white quartz pebbles in a clast supported matrix.

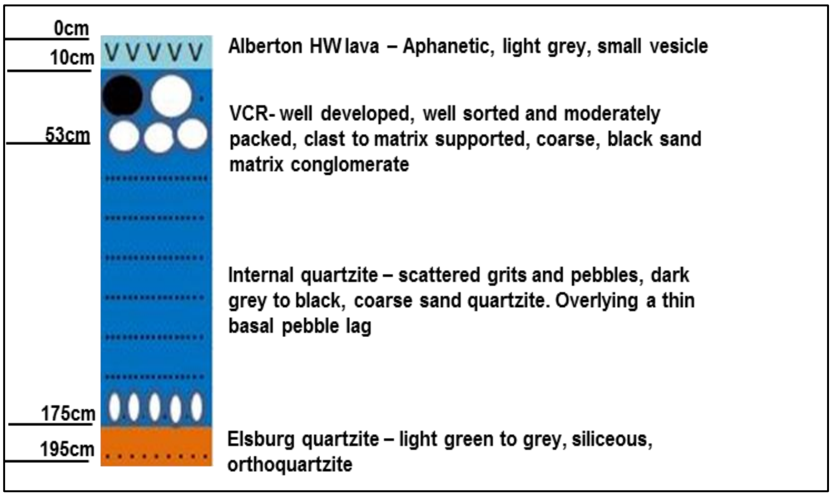

Figure 37: Macroscopic characteristics of Domain 6.

5.1.7 Macroscopic Definition Domain 7

Domain 7 represents a poorly developed conglomerate unit (Figure 38). The conglomerate is poorly packed with small (less than 30 mm), angular pebbles. There is a thick, gritty matrix with no visible mineralization. There is no flyspeck carbon or buckshot pyrite.

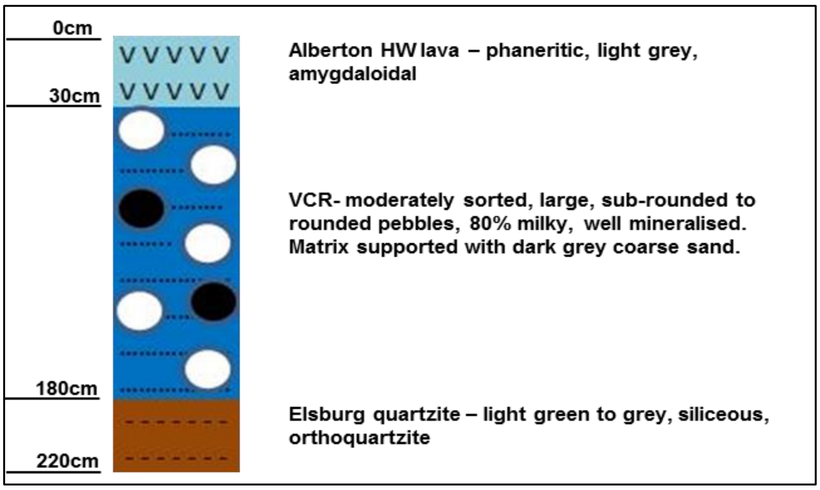

Figure 38: Macroscopic characteristics of Domain 7.

5.1.8 Macroscopic Definition Domain 8

Domain 8 is a massive conglomerate unit that is well mineralised with the absence of buckshot pyrite and flyspeck carbon (Figure 39). Pebbles are large (61 - 128 mm) and are rounded to sub-rounded. The unit is clast supported and exceptionally well packed with a mix between smoky and white quartz pebbles.

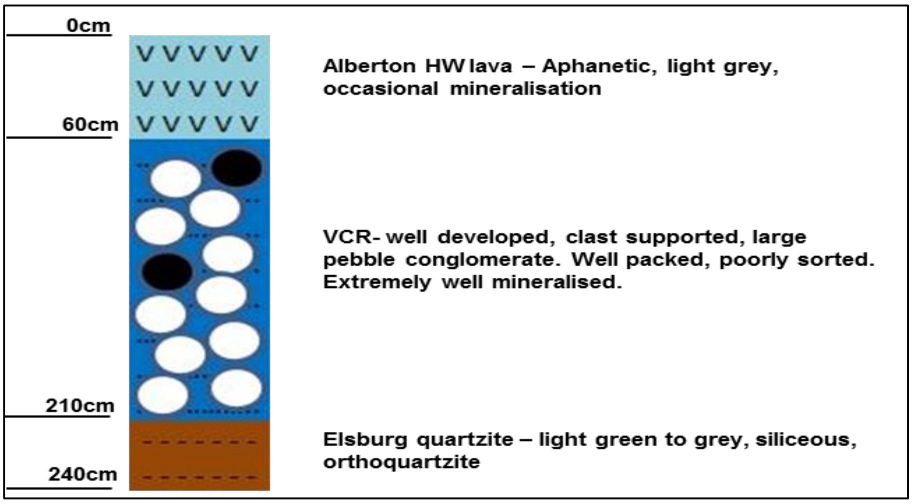

Figure 39: Macroscopic characteristics of Domain 8.

5.1.9 Macroscopic Definition Domain 9

Domain 9 is characterised as a massive, well developed conglomerate with medium (31 - 60 mm) well rounded milky pebbles (Figure 40). Carbon, buckshot pyrite and secondary mineralisation are all present.

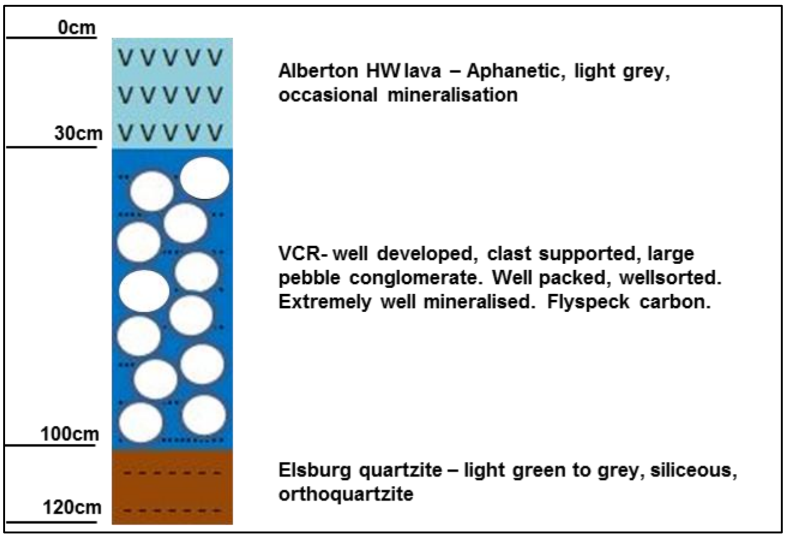

Figure 40: Macroscopic characteristics of Domain 9.

In this section, an observable set of geological characteristics was assigned to each sedimentological domain. These characteristics are part of the unique geological fingerprint for each geozone and when used in conjunction with the qualitative assessment tools led to a comprehensive identification of the orebody at a specific point. This identification further led to a better understanding of the proximal and distal relationship due to the preservation of the observable reef characteristics.

5.2 Model Validation within known facies areas

To establish the effectiveness of the qualitative assessment tools and the associated geological attributes, underground mappings and a borehole drilling programme were carried out into an area of known facies and grade. The observable definitions of the domains (geozones) were used to test the robustness of the model(Figure 41) through the implementation of an underground mapping programme. The underground mapping was performed by the researcher over the course of this research project. The sedimentological domain model was compared against actual underground intersections (control points) mapped on Manyano (K7) and Ikamva (K4) shafts, highlighted in Figure 41. The results of the underground investigations are summarised in Table 16.

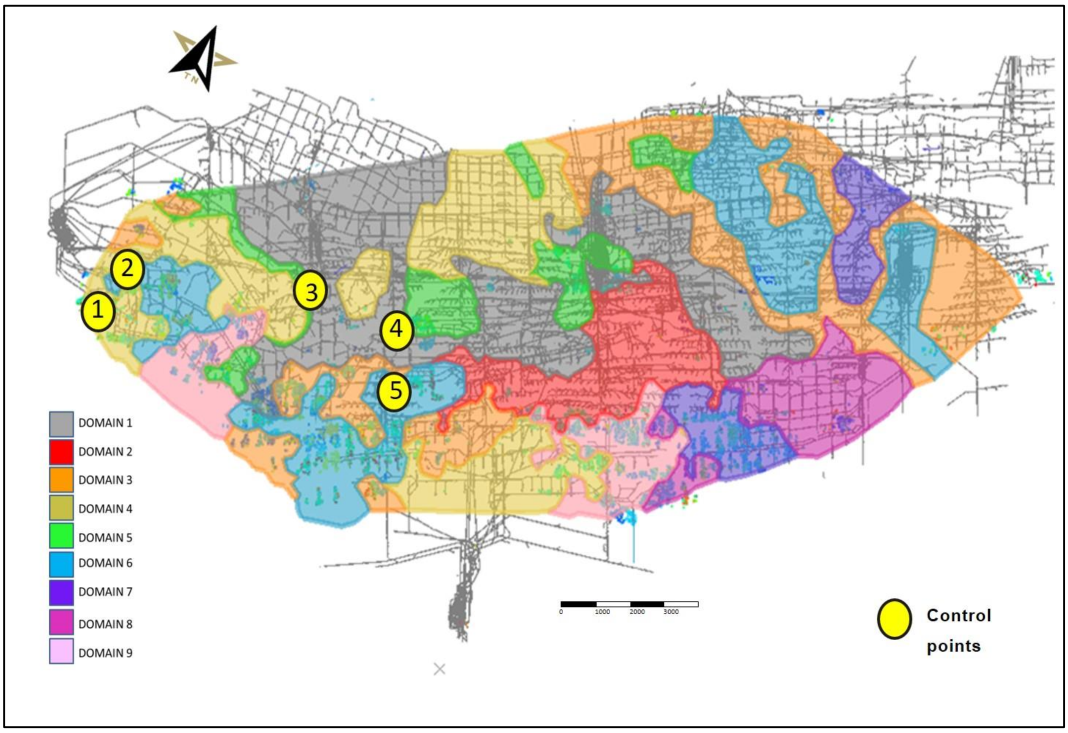

Figure 41: Control point positions for refined domain model validation.

Table 16: Summary of underground investigations.

Control Point	Expected Domain	Actual Domain	Model Result
1 VC40-89	Domain 4	Slope	FAIL
2 VC37-85	Domain 6	Domain 6	PASS
3 VC31-74	Domain 5	Domain 5	PASS
4 VC35-69	Domain 5	Domain 1	FAIL
5 VC40-73A	Domain 1	Domain 1	PASS

VC40-89:

VC40-89 was expected to be mining in Domain 4. However, the face had intersected slope reef and the entire panel was mined as waste on contact (WOC). No result could be achieved as slope reef has been included into all the domains (Figure 42).

Slope reef can be observed as a thin, poorly preserved veneer of reef between the hangingwall and footwall lithologies, as observed by the clinometer in the picture.

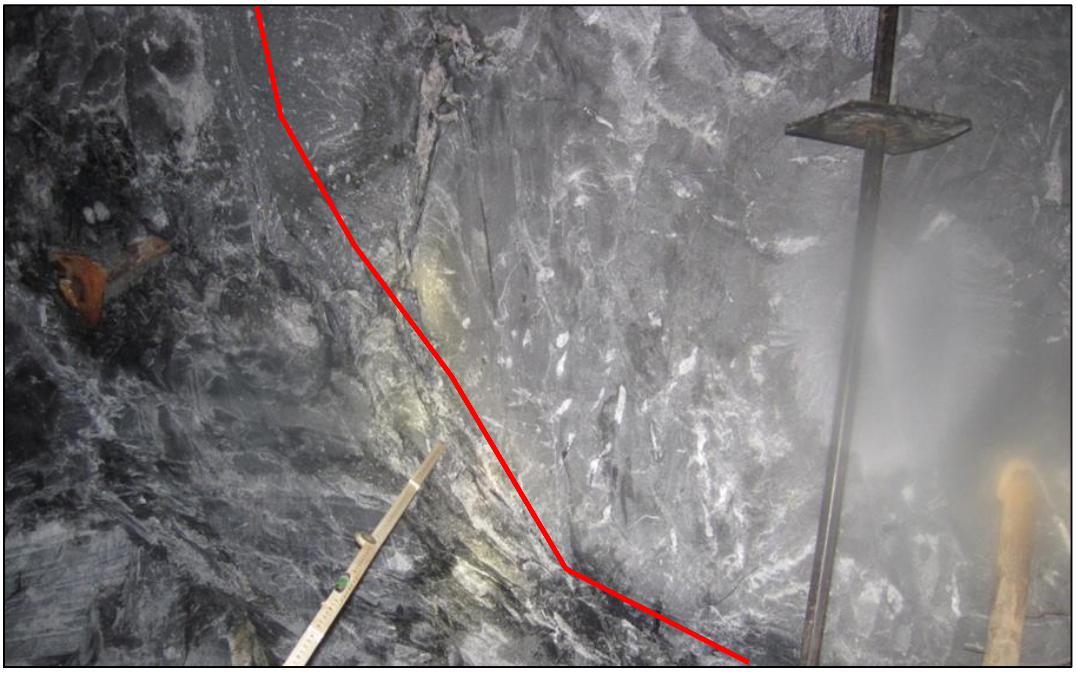

Figure 42: VC40-89 underground stope geological observations.

VC37-85:

VC37-85 was expected to be mining in Domain 6. There were two conglomerate bands observed separated by a thick, gritty quartzite. An abundance of buckshot pyrite within the conglomerates and the internal quartzite was present. There was no flyspeck carbon and the pebbles averaged 55 mm. Using the qualitative assessment tool, VC37-85 was classified as Domain 6 (Figure 43) as per the geological model.

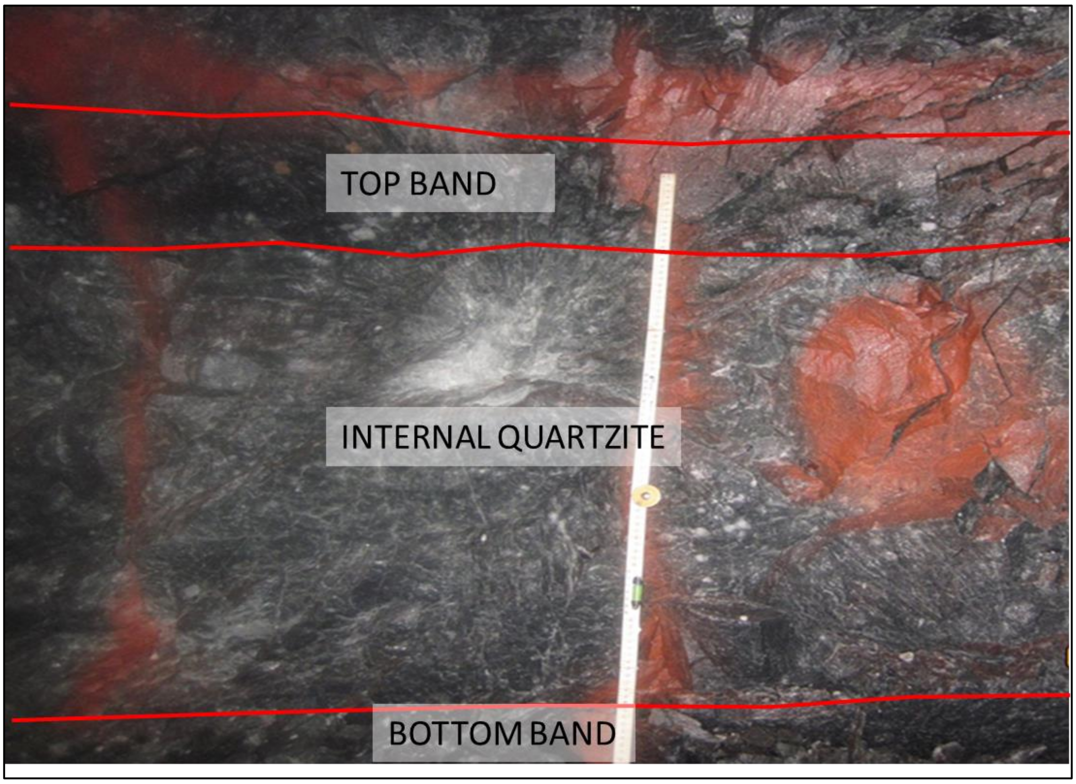

Figure 43: VC37-85 underground stope geological observations.

VC31-74:

VC31-74 was expected to be mining in Domain5, characterised by a single conglomerate band with well rounded (31-60 mm) pebbles. The face was mined at a grade of 2081cmg/t where Domain 5 has an average, expected value of 2043 cmg/t. Upon investigation, there was a well-developed, well mineralised conglomerate with well-rounded pebbles (up to 60 mm) and a CW of 1.1 m with a sharp basal contact (Figure 44). Using the qualitative assessment tool, VC31-74 was classified as Domain 5 as per the geological model.

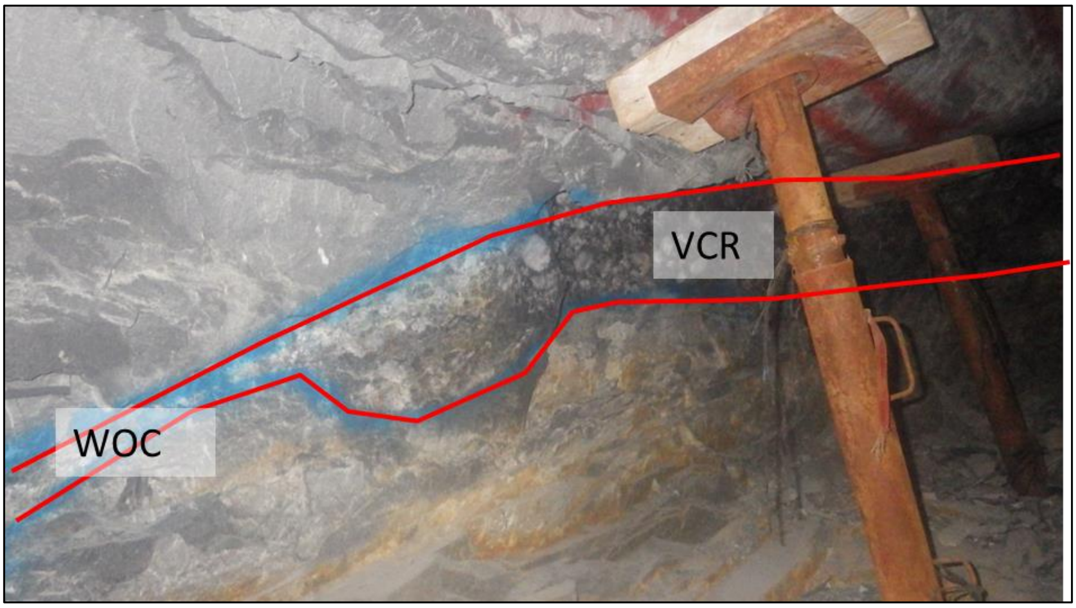

Figure 44: VC31-74 underground stope geological observations.

VC35-69:

VC35-69 was expected to be mining in Domain 4 which has the presence of flyspeck carbon, buckshot pyrite and is exceptionally well mineralised with secondary mineralisation. The pebbles in Domain 3 should be in excess of 60 mm. The underground investigation showed a large pebble conglomerate with an absence of buckshot pyrite and flyspeck carbon. Using the qualitative assessments, the panel was classified as Domain 5 which was not representative of the geological model (Figure 45).

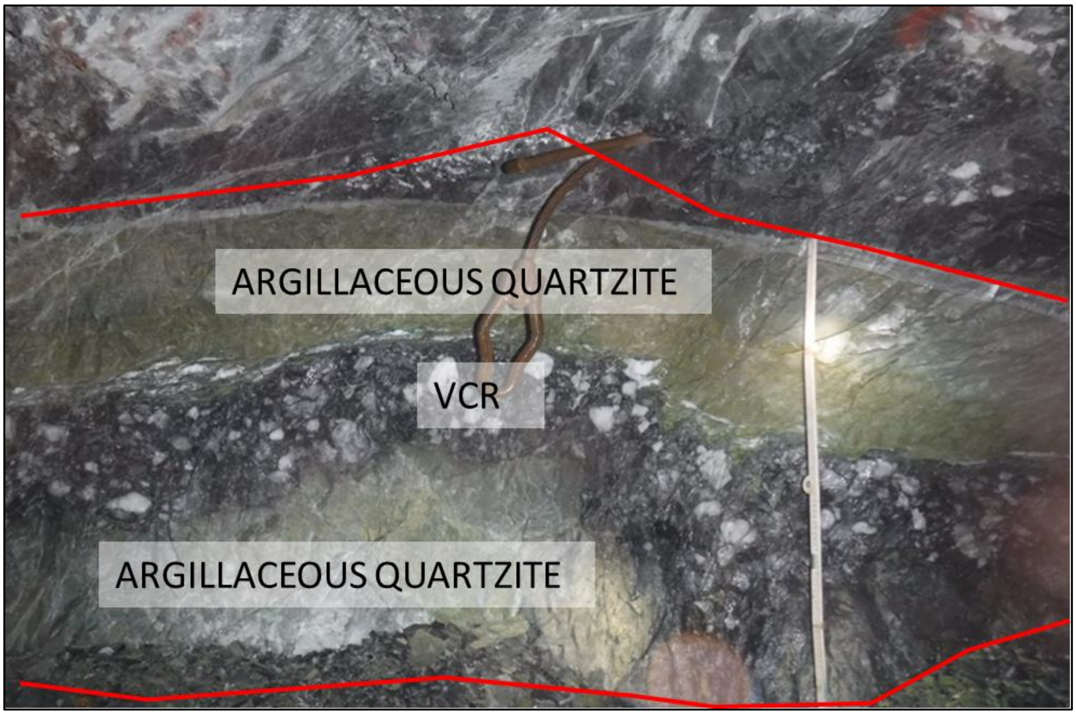

Figure 45: VC35-69 underground stope geological observations.

VC40-73A:

VC40-73A was expected to be mining in Domain 1, which is represented by a medium pebble conglomerate with occasional large to very large clasts. There is often a massive conglomerate band, with a coarse, gritty matrix. CW's are in excess of 100 cm, with the absence of flyspeck carbon and buckshot pyrite. Underground investigations showed a massive conglomerate unit (1.5 m) with medium to large, sub rounded pebbles in a gritty matrix with no flyspeck carbon or buckshot pyrite present. VC40-73A was classified as Domain 1 which agreed with the geological model (Figure 46).

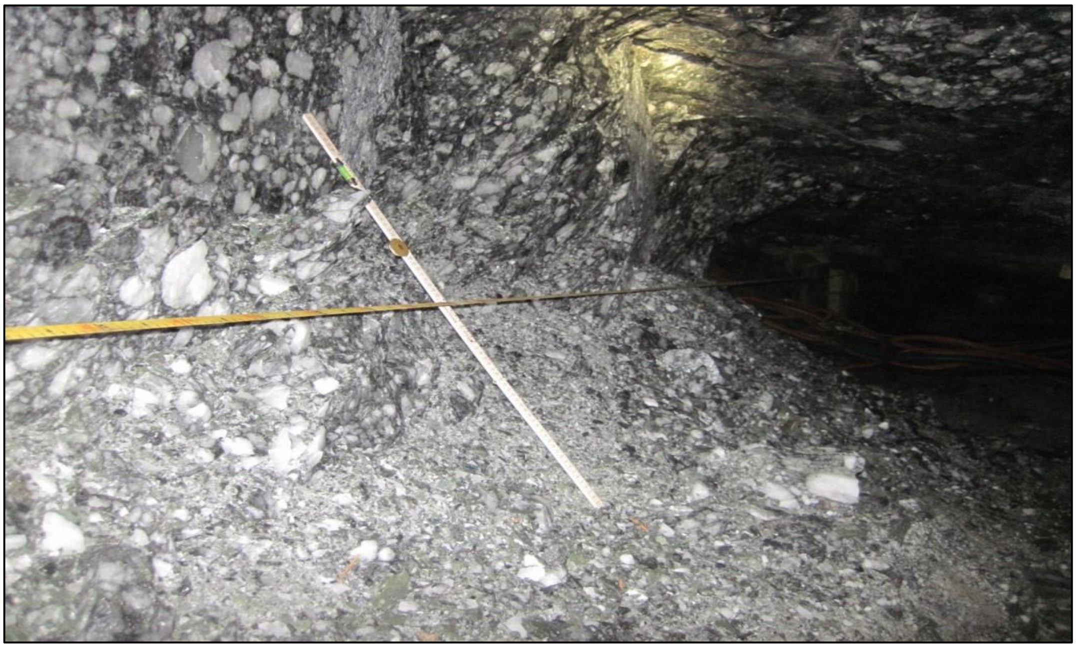

Figure 46: VC40-73A underground stope geological observations.

In summary it was observed that of the five underground control points, three intersected the expected lithology with an overall 60% success rate. From these underground observations, it was concluded that the refined macroscopic domain model, although successful was not particularly reliable across or near domain boundaries. This could be a function of the boundary delineation using IDW or the inclusion of slope reef into the domains which separates major lithological boundaries which is a function of deposition. This may have also been a function of the search radius, which could be optimised to include more localised geological characteristics. The model, although successful, still requires further optimisation and refining with regards to domain boundaries but is promising in the fact that macroscopic domains and associated grade "ahead of the face" could be partially predicted.

5.3 Refined Domain Model (Macroscopic Definition) Validation through Borehole Intersections – known domains

To further test the refined domain model and the delineation of the macroscopic attributes, a drilling programme was established by the author. Three boreholes were drilled from Manyano (7#) and Ikamva (4#) shaft and once logged by the author, were input into the qualitative assessment tools (

Figure **47**) for analysis.

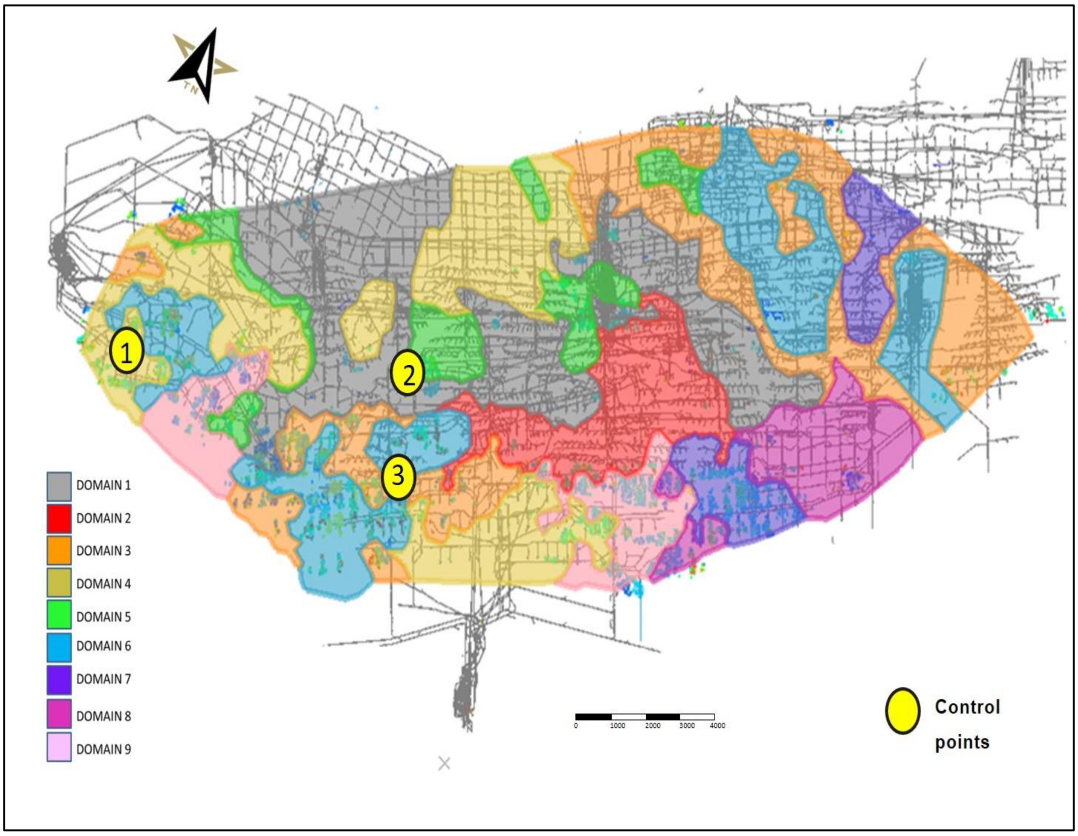

Figure 47: Borehole control points used to test the model validity.

The results based on the physical drilling evidence provided in Figures 48 to 50 are individually discussed and summarised in Table 17.

VC40-89: Borehole K7E3388

At VC40-89 Domain 4 was expected – In the borehole there was flyspeck carbon, buckshot pyrite, and a thick, gritty internal quartzite separating two conglomerate bands (Figure 48). The conglomerate units had large, sub-angular to sub-rounded pebbles, all of which were qualifying criteria for Domain 4. Using the qualitative assessment tools, the borehole was classified as Domain 4 as per the geological model.

Figure 48: Borehole K7E3388 intersected Domain 4 as per the model.

VC35-69: Borehole K7E3929

At VC35-69 Domain 5 was expected – The borehole intersection however went through a fault plane, and the reef was mostly eliminated (Figure 49). Using the remnants of the reef, large, angular pebbles were observed with a poor packing and poor development. Using the available information, the borehole was classified as Domain 7, which did not agree with the geological model.

Figure 49: Borehole K7E3929 intersected Domain 7 against model expected Domain 5.

VC40-73: Borehole K7E3443

At VC40-73 Domain 6 is expected- this was confirmed with borehole K7E3443, which intersected two conglomerate bands separated by an internal quartzite and an abundance of buckshot pyrite within the gritty quartzite (Figure 50). There was a sharp basal contact and an exceptionally well mineralised matrix. Using the qualitative assessment tools, the borehole was classified as Domain 6 which agreed with the geological model.

Figure 50: Borehole K7E3443 intersected domain 6 as per the model.

Table 17: Summary of exploration drilling.

Location/ Control Point	Expected Facies	Mapped Facies	Model Result
1 VC40-89	Domain 4	Domain 4	PASS
2 VC35-69	Domain 5	Domain 2	Faulted out – FAIL
3 VC40-73	Domain 6	Domain 2	PASS

Overall, from sections 5.2 and 5.3, it can be concluded that five out of eight control points (63%), were classified correctly according to the sedimentological domain model using the qualitative assessment tools (Figure 51).

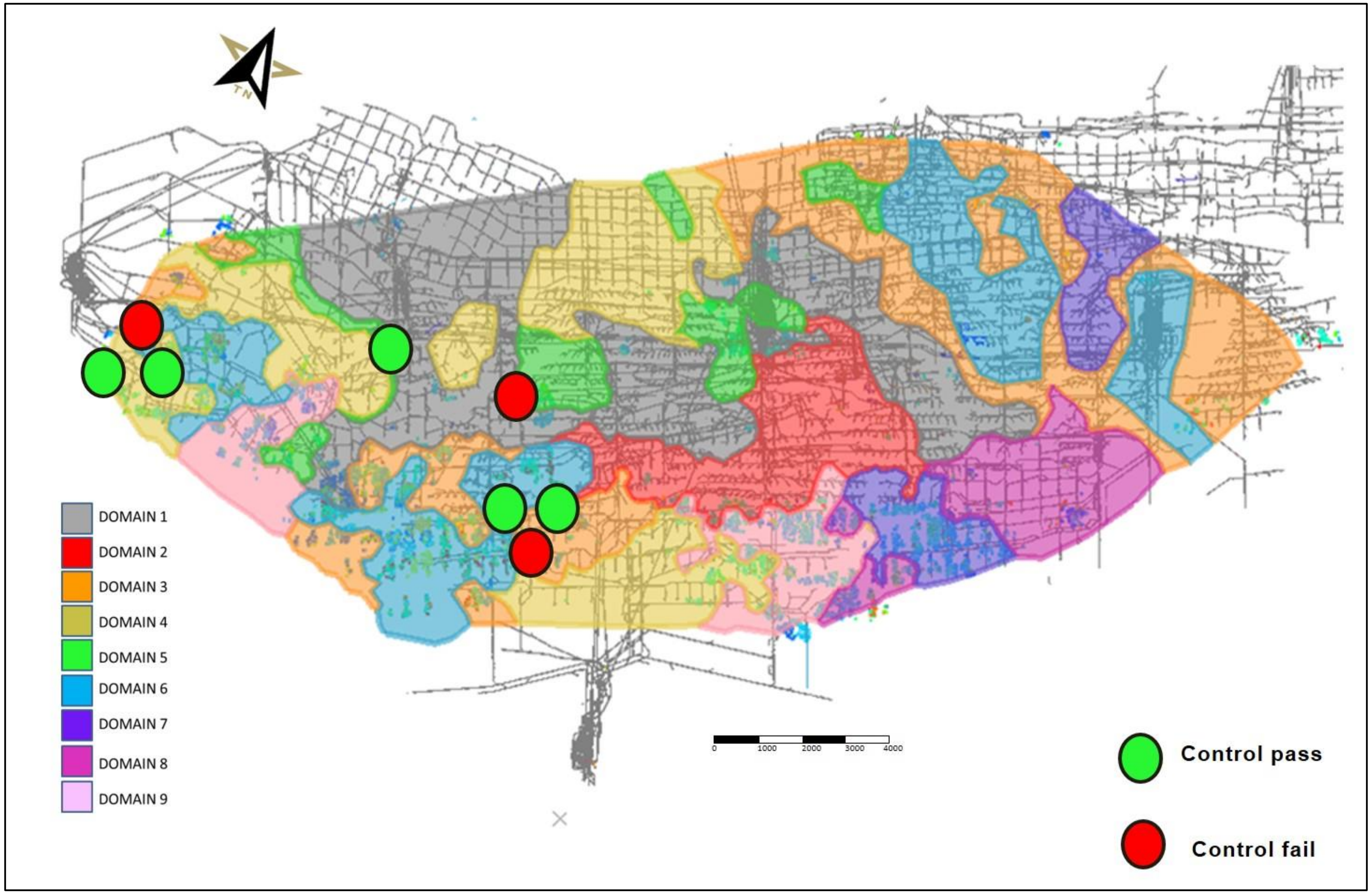

Figure 51: Overall model validity.

It was observed that uncertainty across geological boundaries was persistent as well as that larger zones being geologically similar to each other. This is likely a function of the search radius and the model assuming global attributes which would ignore any local variations in geology.

Assigning an observable (macroscopic) description to each geozone was successful and provided a good representation of the unique geological fingerprint according to deposition. The domains were observed to be homogenous and could further be used to estimate the grade within a specific sedimentological zone.

Using both underground observations and borehole intersections, it was observed that the macroscopic model is reasonably robust and works well in most geological settings, but caution must be applied where rapid, local variations of deposition or geological disturbance can be expected.

5.4 Refined Model Validation - Into the Unknown

As part of the validation process, a borehole was drilled into a VCR pillar on Kloof Manyano Shaft (K7) which was identified to be of an unknown facies type. The pillar was part of the mining cycle and was planned for extraction. The selected pillar was classified by the author into two resource categories, Measured and Indicated, based on kriging into 20 m x 20 m blocks (Figure 52).

The pillar was previously estimated by the author as a preliminary project to this report, and the kriging process was followed in line with the Sibanye Gold standard estimation process. Approximately 69% of the pillar was classified as Measured (red blocks), with the remaining 31% was classified as Indicated (blue blocks). The pillar had an estimated mean of 1 878cmg/t, (Table 18) and the global statistics with a 90% confidence suggested a gold value between 1 892 cmg/t and 1 970 cmg/t with an expected CW between 68.01 cm and 69.70 cm. Also 174 kg of gold could be expected from 1 236 tonnes of ore at 100% extraction based on the kriged estimate.

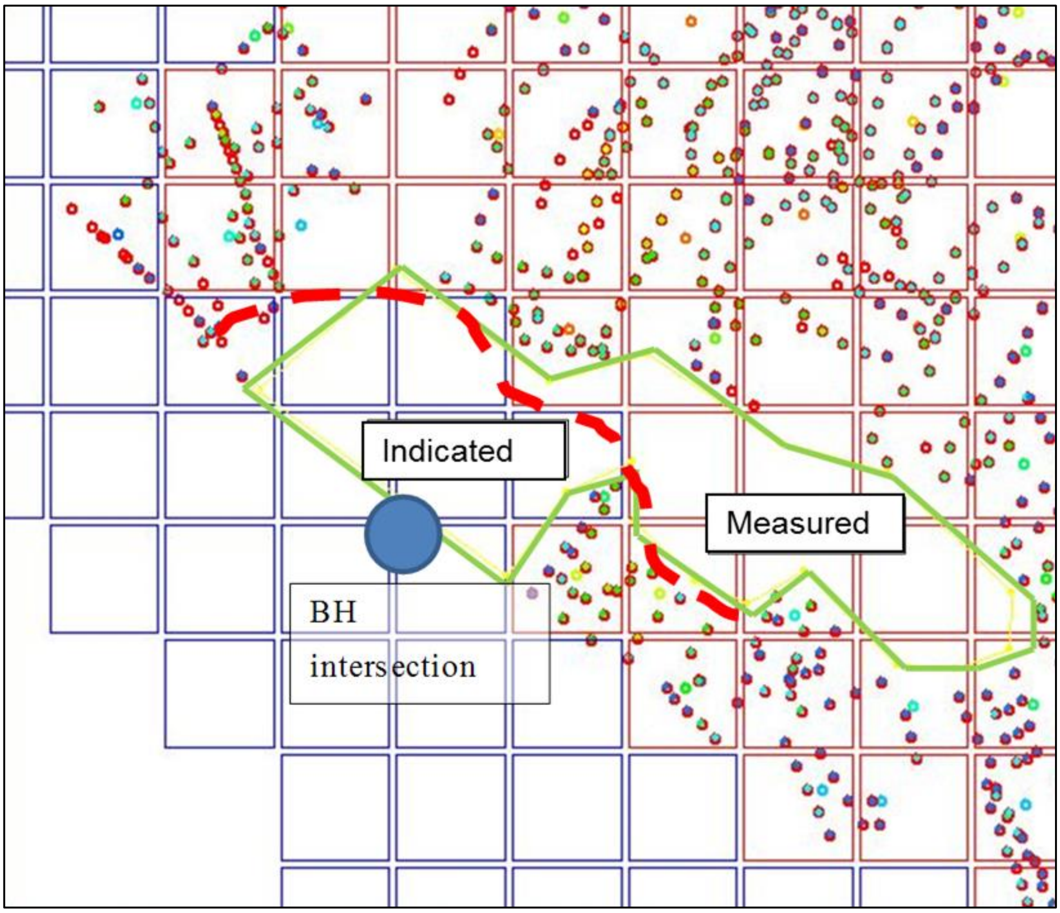

Figure 52: Measured & Indicated Resource (20 m x 20 m grid).

Table 18: Mineral Resource classification.

Resource Category	Area m^2	Estimated Gold Accumulation cmg/t	Estimated CW cm
Measured	2 723 (69 %)	1 982	69.5
Indicated	1 224 (31 %)	1 647	64.8
Total	3 947 (100 %)	1 878	68.1

The borehole for the model validation process was planned, logged and managed by the author. The BH drilled into the VCR pillar was K7E4152 (Figure 53). The BH was drilled at +45° and intersected the VCR pillar at 73.5 m and was logged as part of the drilling programme.

Figure 53: Borehole K7P4152.

The VCR was comprised of a medium to large pebble (MPC), clast supported conglomerate. The pebbles were sub-rounded to slightly angular with a well mineralized (pyrite and chalcopyrite) gritty, dark grey matrix. There was no buckshot pyrite or flyspeck carbon present. The reef intersection had a sharp, basal contact and an assay value of 648 cmg/t with a true channel width of 89 cm.

Using the qualitative assessments tool, the borehole was assigned to Domain 5, where an average value of 2 043 cmg/t can be expected.

Classification using the "scoring system" the BH was considered to have a high gold potential with a score of 48 based on the inherent sedimentological characteristics. Domain 5 suggests a CW of between 80 and 120 cm with a mean of 94 cm. The kriged grid estimate had a CW value of 69.5 cm while the actual average mined CW was 89 cm.

Extracted Measured grade of pillar:

The pillar was mined with a 100% extraction at an average value of 1 994 cmg/t over 3 947 m^2 and an average CW of 85 cm. The pillar produced 213.3 kg of gold.

In comparison, the kriging without the refined domain definition underestimated the pillar by 39 kg with an estimate of 174 kg (82% of the actual gold produced). Conversely, using the qualitative assessment, Geozone 5 suggests an average grade of 2 043cmg/t, with an estimate of 218.5 kg (102.3% of the actual gold produced). Using only the value of the borehole intersection at 648 cmg/t, the pillar was estimated at 69.3 kg or 32% of the actual gold produced.

This illustrated a poor correlation between borehole intersection values and the in situ gold due to the nugget effect, core loss and the fines being washed out with drilling fluids. Due to the poor correlation between borehole values and the realised value, there is a massive potential to underestimate blocks ahead of the face based solely on grade information obtained from boreholes (Table 19), leaving one to assume uneconomic grades, and a possible loss of value realisation.

Table 19: Shaft Pillar Actual vs. Kriging vs. Qualitative Assessment.

	Actual	**Kriging**	**Refined Geozone**	**Borehole intersection**
kg	213.3	174	218.5	69.3
CW	85	69.5	94	89

In summary, a final validation of the geozone model was performed by drilling a borehole into an unmined area, of an unknown geozone. The drilling results were analysed using the developed qualitative assessment tools and compared to the borehole reef intersection. The results were tabulated, and an expected content of the block was calculated based on the identified geozone. This estimate was compared to the kriged estimate, borehole value estimate and final mined content, which proved the pillar to be economic for extraction.

In conclusion, section 5 addressed the definition and validation of the refined sedimentological model developed, by assigning macroscopic, geological definitions to each sedimentological domain which were validated through an underground mapping and exploration drilling programme.

6. Conclusion

A distinct correlation between geological attributes of deposition and value distribution have been established to exist, which were used to define homogenous geozones based solely on geological attributes.

Through an exaggerated channel width plot with a superimposed kriged grid, and a terraflow drainage simulation, correlations between value and deposition could be observed, confirming that the deposition of the reef has control over the spatial grade distribution.

From an analysis of the sedimentological data, nine larger sedimentological domains were identified, with seven being homogenous and two heterogeneous. Each of the sedimentological domains is characterised by a set of relevant depositional attributes and associated weightings which were used to assign a macroscopic definition to each geozone, leading to a refined domain model.

The refined sedimentological domain model was tested against underground control points, and five out of the eight (63%) control points agreed with the geological model, which enabled the construction of a reliable, reef assessment tool based on the macroscopic attributes of the reef. This reef assessment tool was further supplemented by a reef scoring system, which enabled geologists to make quick, informed, economic decisions underground while mapping the face.

As final model validation, a borehole was drilled into a pillar of an unknown facies. The borehole intersected the VCR which evaluated the pillar at 69.3 kg against a kriged plan estimate of 174 kg of gold. Using the qualitative assessment tools, the pillar was identified as Domain 5, with an average value of 2 043 cmg/t. Evaluating the pillar using the average value from Domain 5, 218.5 kg's of gold were indicated. The pillar was extracted with 100% extraction rate and yielded 213.3 kg of gold, 97.7% of the sedimentological domain estimate, 309% of the BH value estimate and 123% of the kriged grid estimate.

In conclusion, the four research objectives were met: A detailed understanding of the role of geology with regards to deposition of the reef was achieved. Through this understanding, confirmation of the control of reef deposition on the gold mineralisation was observed, which consequently allowed for an improved estimate with a reduced error being achieved. Thus, by implementing the refined model, facies and grade ahead of the face, in areas where geological information is scarce could be predicted, leading to improved economic decisions.

The qualitative delineation of the orebody is a powerful tool and enables geological controls to be included into the estimation of the orebody, potentially reducing errors associated with the estimation. The qualitative delineations are still extremely subjective and a standard definition of sedimentological attributes must be applied across the mine to reduce the subjectivity of the data used.

Future research studies around this topic could be the incorporation of footwall controls into the sedimentological domain model as well as further work into the transitional boundaries between domains, as identified by Kasmaee, et al. (2019), as the slope reef within boundaries has proven to be erratic with mixed data being observed plotting across boundaries.

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