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ALTERNATIVE METHODS FOR COAL RESOURCE CLASSIFICATION OF THE GEOLOGICALLY COMPLEX WITBANK COALFIELD

By

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Science in Engineering (Mining)

to the faculty of engineering and the built environment, University of the Witwatersrand, Johannesburg



Date of final submission **25 May 2017**

DECLARATION

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ABSTRACT

The Australasian code for Reporting of Exploration Results, Mineral Resources and Ore Reserves, of the Joint Ore Reserves Committee (JORC) sets out minimum standards, recommendations and guidelines for Public Reporting in Australasia. (JORC, (2012)). The Committee for Mineral Reserve International Reporting Standards (CRIRSCO) created a set of standard international definitions for reporting Mineral Resources and Mineral Reserves based on the evolving JORC code's definitions (CRIRSCO, (2013)).

CRIRSCO's members are National Reporting Organisations (NRO's) which are responsible for developing mineral reporting codes for Australia (JORC), Canada (CIM Standing Committee on Reserve Definitions), Chile (National Committee), Europe (PERC), Russia (NAEN), South Africa (SAMCODES) and USA (SME) (JORC, (2012)).

The NRO's for; South Africa (SAMREC), Australia (JORC) and Canada (CIM Standing Committee on Reserve Definitions) published supporting standards for Coal Resource and Reserve Classification and Reporting namely, South African National Standard: South African Guide to the Systematic Evaluation of Coal Resources and Coal Reserves (SANS10320:2004), the Australian Guidelines for the Estimation and Classification of Coal Resources (Australian Guidelines (2014)) and the GSC Paper 88-21: A Standardized Coal Resource/Reserve Reporting System for Canada (Hughes, et al., (1989)).

With the objective to identify the most appropriate Coal Resource Classification approach for the Witbank Coalfields in South Africa, Coal Resource Classification methods applied elsewhere in the world were investigated, these countries include Canada and Australia.

SANS10320:2004 relies on a minimum drillhole spacing dependant on two different coal seam deposit types, whereas the Australian Guideline for the Estimation and Classification of Coal Resources (2014) provide a guide as to which geological aspects need to be considered when classifying a coal deposit into the appropriate confidence category, and no fixed drillhole spacing is recommended. The Canadian Standardized Coal Resource/Reserve Reporting System (1989) differs from the afore mentioned standards in that it is a prescriptive method based on specific levels of geological complexity, governed by specific fixed parameters. None

of the other Coal Reporting codes/standards use a broad sweeping fixed drillhole spacing to classify Coal Resources as in South Africa.

It is noted from experience as well as by Coal Resource Classification methods used elsewhere in the world that the use of proposed fixed drillhole spacing, such as currently in use in SANS10320:2004, is an unsatisfactory method for assessing the uncertainty and variability associated with coal deposits. The Coal Resource Classification methodologies utilised on a local scale in South Africa, were investigated to establish how mining houses manage and assess the variability in their Coal Resources. Fourteen mines operating throughout the Witbank coalfield were compared, it was found that although the Coal Resource Classification of the governing code requires a 350m drillhole spacing for highest level of confidence, the mines drill to a much smaller grid for increased confidence. Despite this, the mines still report on the SANS10320:2004 minimum standard in the public domain. A map was created based on the average drillhole spacing drilled per mine. From this it was deduced that there are zones of higher coal seam variability which required a closer spaced drilling grid to derive sufficient geological confidence in the estimates. Based on these deductions four zones of comparable continuity/variability, were identified. The zones identified by means of geological investigation and those identified by differences in variability as perceived by the Competent Person (CP) correlate. The highest variability and smallest drillhole spacing is located toward the western portion of the coalfield whereas the lowest variability with the largest drillhole spacing is located toward the east.

The geologically complex Witbank coalfield was divided into four geo-zones/domains based on the depositional environment, basement rocks and post depositional influences. It is evident that a suitable Coal Resource Classification approach; which considers the characteristics of the geozones are followed. The question of which other classification methods are appropriate if not a predetermined drillhole spacing is addressed by this research.

Statistics on relevant variables can provide a measure of uncertainty and therefore reliability in the estimates, for this reason three methods of uncertainty and probability characterisation were investigated. Of the three, namely; Non-linear estimation approach, conditional simulation (CS) and global estimation variance (GEV), the latter was deemed the most appropriate. GEV forms the basis of Drillhole Spacing Analysis (DHSA) and was applied

to a mid-sized coal mine within the western portion of the Witbank coalfield. The analysis did not result in robust Coal Resource classification of estimates but rather provided more insight into the variability of the deposit. The results of DHSA are easily manipulated and are open for interpretation, it is therefore suggested as a valuable exercise/tool for understanding and assessing coal seam variability and to be used as a guide in Coal Resource classification.

Onsite practical geological information should not be underestimated and geostatistics should always confirm the geology. A purely mathematical approach to Coal Resource classification would be a gross oversight, a combination of geological factors in association with statistical inferences is suggested. A scorecard method with associated weights is proposed to improve the confidence in the Coal Resource classification.

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1. INTRODUCTION

1.1 Background

Within South Africa there are 19 known coalfields (Figure 1). Of these, three constitute 70% of the recoverable Reserves, namely: Highveld, Witbank and Waterberg coalfields, which fall into two deposit types as defined by the South African National Standards (SANS10320:2004). The Highveld and Witbank coalfields are grouped together as multiple seam deposit types since their coal measures are within the same formation, namely the Vryheid formation of the Karoo Supergroup. The Waterberg coalfield is defined as a thick interbedded seam deposit type and forms part of the fault-bounded Ellisras sub-basin of the Kalahari Basin (Hancox & Gotz, (2014)).

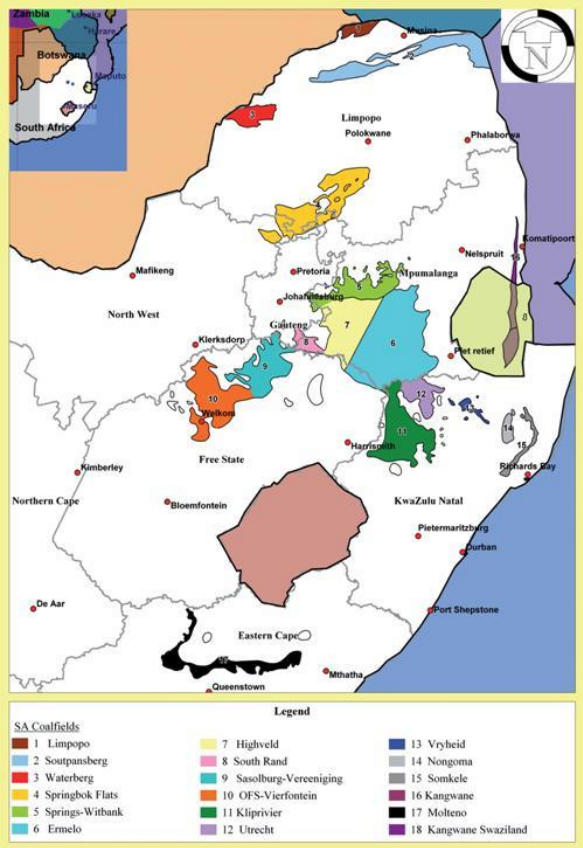

Figure 1: Coalfields of South Africa. (Sprintelligent, 2017)

The Waterberg coalfield and the Highveld/Witbank coalfields are classified into Coal Resource categories based on different drillhole spacing parameters. The South African code for the reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC (2016)), requires reports that deal with Mineral Resources to be classified into Measured, Indicated and Inferred Resources based on geoscientific knowledge and confidence. Mineral Resources

are converted to Mineral Reserves through the application of Modifying Factors to the Measured and Indicated Resources, into Proved and Probable Reserves. This relationship for Coal Resources and Coal Reserves specifically is shown in Figure 2.

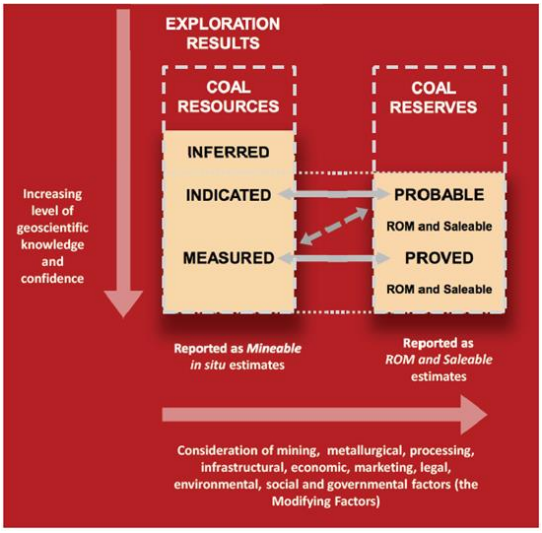

Figure 2: *Relationship between Coal Exploration Results, Coal Resources and Coal Reserves* (SAMREC, (2016)).

The premise therein is that geoscientific knowledge and confidence is increased by decreasing the spacing between drillholes which increase the geological knowledge of the deposit under investigation.

The focus of this study will be on the Witbank coalfield, the Waterberg coalfield will not be discussed further.

1.2 Problem statement

SANS10320 is a published supporting document to the SAMREC code. This Standard must be read in conjunction with the SAMREC code as it provides standards, definitions and common terminology for the estimation, evaluation and reporting of all Coal Exploration Results, Inventory Coal, Coal Resources and Coal Reserves (Mathuray, (2015)).

SANS10320:2004 defines the minimum drillhole spacing for each Coal Resource classification category, based, on a multiple seam deposit type, as follows:

- Reconnaissance; 2000m
- Inferred; 1000m
- Indicated; 500m
- Measured; 350m

Even though the SANS10320:2004 clearly dictates the minimum drillhole spacing for a Coal Resource to be classified into the different Resource categories within the relevant coalfield, it also states: "*Although the minimum drillhole density allows for a reasonable estimate of the coal deposit with a lower level of confidence in most situations, this does not necessarily hold true for sedimentologically and structurally complex areas. The Competent Person (CP) shall make the judgement as to whether the physical continuity can be assumed, and state the basis of the decision*."

The uncertainty within a coal deposit, not only depends on the spatial density and location of the drillholes, but also the inherent complexity of the deposit. Therefore, the problem statement can be divided into two important points of discussion;

1. Unsatisfactory aspects of distance methods for Coal Resource Classification.

   The most widely used method of classifying uncertainty in Coal Resource estimations is that of geological confidence categories, as previously discussed, which are based on circular areas of influence. The inherent pitfall of these methods is that coal was not deposited in circles, as is implicitly assumed when a circular range of influence is used. It further fails to recognise direction of highest continuity often present in deltaic/fluvial coal depositional environments. Distance methods do not consider spatial fluctuations resulting in a misrepresentation of reliability of estimates causing a false sense of security (Cornah, et al., (2013)).

   The numbers quoted in the Coal Resource classification categories do not actually provide measures of the reliability in the statistical sense of the word. Complexities cannot be quantified by simple rules, such as distance to closest drillhole, resulting in indirect measurements of uncertainty and are poor predictions of discrepancies to be

encountered. Geostatistics is the only tool that can give a quantitative measure of spatial uncertainty, for this reason geostatistical analyses should be carried out, prior to making statements regarding geological confidence. (Olea et al., (2011)).

2. Geological variability and complexity.

   Not all coal deposits within South Africa are comparable, therefore SANS10320:2004 differentiates between multi-seam deposit types (such as the coal measures within the Main Karoo Basin (MKB)) and thick interbedded seam deposit types (such as the coal measures within the Kalahari Basin) for Coal Resource classification purposes. The northern and southern portion of the MKB basin, separated by the Smithfield ridge, is divided into the Witbank coalfield and the Highveld coalfield respectively. Even though the coal measures of the Highveld and Witbank coalfields are found within the same formation, their characteristics and complexity are not comparable. Furthermore, within the Witbank coalfield there are regional differences in paleo-topography, depositional environment, seam sequence and quality characteristics, as well as structural events and magmatic activity.

   Therefore, the Coal Resource classification method used within the Witbank coalfield should vary from that used in the Highveld coalfield, in addition, the Classification within the Witbank coalfield should also vary within itself.

   In summary, it is unrealistic to assume that all coal deposits have similar variability or that every drillhole has a fixed radius of influence. This variability is mainly due to inconsistent depositional environments and post depositional influences, which cannot be quantified by means of standard distance methods.

This information leads one to question the blanket classification as set out by the SANS10320:2004 guideline. The Witbank coalfield has a complex depositional environment; therefore, this research aims to provide a more appropriate method than a fixed drillhole spacing, for Coal Resource classification. A score card approach is suggested to this end, such a score card will adhere to the core principles of the SAMREC code, which are transparency, materiality and competence.

2. LITERATURE REVIEW OF COAL RESOURCE CLASSIFICATION SYSTEMS USED INTERNATIONALLY AND LOCALLY

Mineral/Coal Resources are the key factor in assessing the economic value of mineral/coal companies, for this reason public reports are prepared for informing investors and their advisors of the Resources held by a specific mineral company. As these public reports, can be impervious and misleading, such as in the case of the Bre-X scandal, a challenge for regulators of mineral company security markets is to ensure appropriate levels of transparency and assurance over the Resources and Reserves reported to the market. Coal Resource estimates are not clear-cut calculations and is reliant on the interpretation of restricted information on the location, shape and continuity of the deposit as well as the available sampling results, which further complicates the reliable estimation of available Coal Resources. Reporting codes for all the world's main stock exchanges have been developed over the past three decades, with the aim to protect the investing public from using misleading information that could lead to fraudulent transactions (Dohm, (2015A)).

2.1. International Coal Resource Classification methods

The Committee for Mineral Reserve International Reporting Standards (CRIRSCO) has released an international reporting template for the public reporting of Exploration Results, Mineral Resources and Mineral Reserves (CRIRSCO, (2013)).

Most of the reporting codes have commodity specific sections of which the codes are either prescriptive (America or Canada) or descriptive (South Africa and Australia) (Hancox & Pinheiro, (2016)).

On a global scale the reporting of Coal Resources is governed by CRIRSCO. CRIRSCO is an alliance of National Reporting Organisations (NRO's), the member countries include; Canada, Europe, USA, Chili, Brazil, Russia, Kazakhstan, Mongolia, Australia and South Africa. As an indication of how other coal mining countries, governed by CRIRSCO, classify geologically complex areas the guidelines of three of these countries, namely Australia and Canada together with South Africa are considered below.

The Australian, South African and Canadian coal measures were deposited in the late carboniferous, therefore the coal measures of these countries resemble each other in composition and clastic facies (Hobday, 1987).

South Africa

The SAMREC code provides the framework and minimum standards, recommendations and guidelines for public reporting of Mineral/Coal Exploration Results, Mineral/Coal Resources and Mineral/Coal Reserves for the Johannesburg Securities Exchange (JSE), based in South Africa. The SAMREC 2016 code under Clause 48, defines a Coal Resource as "*a concentration or occurrence of material of economic interest in or on the earth's crust in such a form, quality or quantity that there are reasonable and realistic prospects of eventual economic extraction. The location, quantity, grade, continuity and other geological characteristics of a coal Resource are known, or estimated from specific geological evidence, sampling and knowledge interoperated from an appropriately constrained and portrayed geological model*." (SAMREC, (2016))

SANS10320 is a supporting document which outline the best practise for Coal Resource Classification as set out in the SAMREC code, therefore these documents need to be read in conjunction. The characterisation of coal in accordance with SANS10320:2004 into Measured, Indicated and Inferred Resource categories rely on the minimum cored drillholes with coal quality data per hectare, the quantity, distribution and quality of data available as well as the level of confidence attached to the data. This Standard note the average drillhole spacing required per Coal Resource classification category, as converted from drillholes required per hectare for ease of interpretation. It is recognised that not all coal deposits within South Africa are equal in terms of variability and therefore differentiates between multiple seam and thick interbedded seam deposit types (Figure 3 and Figure 4) respectively, for classification purposes.

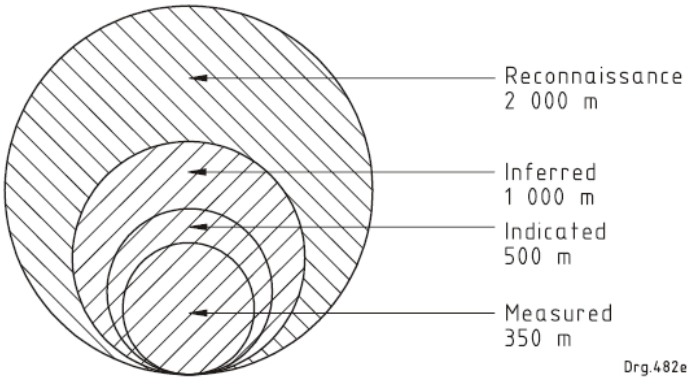

Figure 3: *Minimum drillhole spacing required by SANS10320:2004 for multiple seam deposit type.*

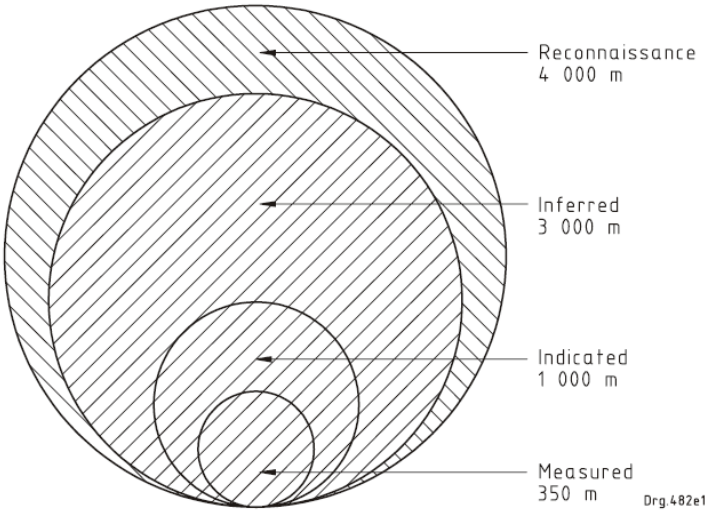

Figure 4: *Minimum drillhole spacing required by SANS10320:2004 for thick interbedded seam deposit type.*

The minimum drillhole spacing allows for a reasonable estimate but does not necessarily hold true for geologically complex areas, in which case the CP needs to determine which drillhole spacing is sufficient per Coal Resource category. In such geologically complex areas SANS10320:2004 provides a guide to which aspects need to be investigated prior to classification; density of points of observation, physical continuity of the coal seams, distribution and the reliability of the sampling data, quality continuity, reliability of the geological model and the evaluation method. Table 1 shows the criteria for classifying Coal Resources per the SANS10320:2004 standard.

Table 1: Criteria for classifying Coal Resources (Mathuray, (2015))

CLASSIFICATION CATEGORY	CONFI-DENCE	DATA INTEGRITY	CONTINUITY REQUIREMENTS			
			Physical		Coal Quality	
			Seam Geometry	Structure	Raw Coal Quality	Washed Coal Quality
Reconnaissance Inventory Coal	very low	uncertain or unreliable	assumed at low level of confidence	assumed at very low level of confidence	limited raw data	limited or no washability data
Inferred	low	uncertain or limited	assumed at low level of confidence	assumed at a low level of confidence	assumed at low level of confidence	assumed at low level of confidence
Indicated	moderate	reliable	confirmed	assumed at a moderate level of confidence	assumed at moderate level of confidence	assumed at moderate level of confidence
Measured	high	reliable	confirmed	confirmed	confirmed	confirmed

SANS10320:2004 has been updated as SANS10320:2016, although not yet published it has passed the committee draft stage. The 2016 re-write is scheduled to be released during the last quarter of 2016. There are a few changes to definitions and reporting of Coal Reserves and tonnages in public reports in the SANS10320 2016 re-write. But the essence of the new SANS10320 remains essentially the same for all practical purposes (Hancox & Pinheiro, (2016)).

Australia

The Joint Ore Reserves Committee (JORC) code and the SAMREC code are similar in their principles of governing the application of the codes. Both codes are based on the general relationship between exploration results, Mineral Resources and Ore Reserves with respect to geological confidence and prospects of economic extraction. The process and procedures outlined in the Australian standard for estimation and classification of coal are recommended by the JORC code. The guideline includes a variety of assessment tools that can be used for the estimation and Classification of Coal Resources, to replace the use of maximum distances between points of observation that were included for guidance in previous versions. The reviewed guidelines are broad in nature, to accommodate the variations in coal deposits found throughout Australia (Guidelines Review Committee, (2014)).

To classify a Coal Resource, an assessment of the confidence in the estimate should be undertaken and the criteria used, documented to support the classification given. The

confidence in estimates should include the quality and physical characteristics such as faulting, dip etc. Confidence in classification categories can be determined by means of statistical analysis, geostatistical analysis or critical assessment of relevant geological features to name a few. These Coal Resource estimates should be accompanied by an assessment of the most influential risks to the estimation, such as coal quality variability, computational uncertainty due to structure, geological modelling risk etc. The Australian Guidelines for the Estimation and Classification of Coal Resources states that it is necessary to analyse variability and confidence for individual seams in relation to critical parameters and assign confidence on a seam basis. The estimation process needs to consider quality parameters that are critical to the mineability and marketability of the products as this has a direct impact on the cut-off limits and reasonable prospects of eventual economic extraction (Guidelines, (2014)).

Understanding the geology of the deposit should be the key factor of Coal Resource classification and estimation. Coal deposits are heterogeneous and typically vary vertically and horizontally in complexity and quality therefore it is important to identify areas that show similarity. These areas are known as geological domains, which may require different data density to yield high geological confidence (Guidelines Review Committee, (2014)).

A 'one size fits all' approach has been deemed an inappropriate method of Coal Resource Classification. Fixed drill-hole spacing for Coal Resource classification is therefore not good practise and for this reason the use of geostatistical methodology whereby the classification is driven by variability is recommended (Bertoli, et al., (2013)).

The Australian guidelines does not prescribe a specific approach to arrive at the key assumptions or the level of confidence required, it simply provides prompts to the factors that need to be considered. It is up to the CP to determine and justify the confidence categories.

Canada

The Canadian standardised coal reporting system was compiled in 1989 and has not been updated since. The geological complexity of Canadian coal deposits has necessitated the use of several definitions and methods for quantity estimation and the ability to differentiate based on geological complexity is critical (Hughes, et al., (1989)).

After the geology/deposit type has been established the Coal Resource and Reserve criteria can be applied to classify the coal quantities. The Canadian code is, as with the Australian and South African codes are governed by the classification of coal based on geological confidence in its estimates.

The Canadian code use four categories of geology types, based on differences in the complexity of the seam geometry. These categories include; Low, Moderate, Complex and Severe. The first category: Low is classified as generally unaffected by tectonic deformation and seams are flat to gently dipping ($0\text{-}5^0$). This category is further separated into type A through to C, to account for differences in overall seam geometries. Coal deposits that fall within the Moderate category have been affected to some extent by tectonic deformation. Folds are open and have wavelengths of greater than 1.5m whereas faults are uncommon and if present, have displacements of less than 10m. The Coal Resources classified within the Complex category have been subjected to relatively high levels of tectonic deformation. Folds are tight and overturned and faults are common. The Severe category consists of coal deposits that has been subjected to extreme levels of tectonic deformation. The main difference between the Complex and Severe categories is that coal deposits where, the stratigraphic succession between the faults are difficult to correlate, and seams that are structurally thickened or thinned falls within the Severe category (Hughes, et al., (1989)).

The Canadian guideline does not use the term geological confidence to distinguish between Coal Resource categories but rather “assurance of existence”, in addition the term “inventory” is replaced by “speculative”. Coal Resources are further divided into coal of immediate interest and future interest, as these deposits have not been subjected to mining feasibility studies and therefore not classified as Reserves. Classification of Coal Resources into immediate and future interest categories are predominantly based on seam thickness, depth from surface and location. Geological experience within Canada suggest minimum drillhole spacing as set out in Table 2, depending on the deposit type (Hughes, et al., (1989)).

***Table 2**:* Criteria used to define assurance of existence for deposits within Canada of various geology types replicated from (Hughes, et al., (1989))

Geology Type	Criteria	Assurance of Existence Category		
		Measured	Indicated	Inferred
Low - Type A	Distance from nearest data point (m)	0 - 800	800 - 1600	1600 - 4800
Low - Type B	Distance from nearest data point (m)	0 - 600	600 - 1200	1200 - 3600
Low - Type C	Distance from nearest data point (m)	0 - 450	450 - 900	900 - 2400
Moderate	Distance from nearest data point (m)	0 - 450	450 - 900	900 - 2400
Complex	Cross section spacing (m)	150	3000	600
	Minimum number of data points per section	3	3	3
	Mean data point spacing along section (m)	100	200	400
	Maximum data spacing along section (m)	200	400	800
Severe	Cross section spacing (m)	75	150	300
	Minimum number of data points per section	5	5	5
	Mean data point spacing along section (m)	50	100	200
	Maximum data spacing along section (m)	100	200	400

In summary, the main differences between the reporting codes for the countries investigated, are as follows;

- Although the SAMREC code does not state a spacing it advises the CP to investigate all relevant information per SANS10320:2004, this standard relies on a minimum drillhole spacing dependant on two different coal seam deposit types.
- The Australian standard gives a guide as to which geological aspects need to be considered when classifying a coal deposit into the appropriate confidence category. The set drillhole spacing approach was deemed insufficient and therefore completely removed from the code update in 2014.
- The Canadian standard is prescriptive as to the minimum drillhole spacing related to specific levels of geological complexity, of which the geological complexity is governed by set parameters on drilling grids.

Although the deposits in all three countries were deposited within the same era, the Coal Resource classification methodologies are markedly different. There is no one definitive

method for Coal Resource classification, the aim is simply to find the most appropriate method of classification for the coal seams and depositional environment involved. What can be deduced is that, unlike South Africa, both the Australian and Canadian standards deem a fixed drillhole spacing for Coal Resource classification inappropriate, for the classification of complex coal geological settings.

2.2. Coal Resource classification of mines operating within the Witbank coalfield

Several mines throughout the Witbank coalfield, were selected based on representative coverage of the coalfield and availability of data. Based on this criterion fourteen mines from two main companies operating within the coalfield, namely Exxaro Resources and Anglo American Coal were chosen. The drillhole spacing of these mines were obtained from Resource and Reserve statements in the public domain or from personal communication with the CP. The average drillhole spacing was then captured and plans created.

The No.2 Seam will be considered in discussions and comparisons. In alignment with SANS10320:2004 a Coal Resource, within the multiple seam deposit type, is classified as a Measured Resource if the minimum drillhole spacing is equal to or less than 350m. Upon investigation, it was found that even though this is a minimum guideline, all the mines investigated used this 350m classification for Coal Resource reporting purposes even though the geologist drills to a much smaller spacing for increased confidence for operational purposes.

The general investing public may not fully appreciate why the mines drill on a smaller grid while SANS10320:2004 specifies a 350m grid is sufficient for the highest level of confidence. Consequently, to avoid confusion, some published reports adhere to SANS10320:2004 as a minimum requirement even though a closer drill spacing has been used. Whilst this practice may seem acceptable it can be misleading and a transgression of the materiality principle of the SAMREC code. As a 350m radius for the Measured Resource category implies depositional and geological continuity that may not necessarily be true in all cases. The CP is aware of areas where the geology is more erratic and therefore require a denser drilling grid to be classified as a Measured Resource. To adhere to the transparency and materiality principles the CP should report the confidence at the drilling grid considered and comment on the reason for

that specific grid to avoid perceived geological confidence (hence decrease financial risk) of the deposit.

The purpose of the SAMREC code and the SANS10320 standard is to protect the investing public against misleading Resource and reserve statements. Blindly applying the SANS10320 minimum drillhole spacing to coal deposits can lead to misrepresentation of the confidence in available Coal Resources.

The average drillhole spacing deemed sufficient for the highest level of confidence is somewhat arbitrary, and difficult to establish for any specific mine or Coal Resource area. As there are no set statistical parameters to gauge a coal deposits uniformity it is very much left up to the CP's opinion and experience. Variogram modelling is often used as an indication of continuity and therefore confidence limits for Coal Resource estimation, although this method is not ideal for bulk commodities, such as coal, with wide drillhole spacing making short range spatial continuity difficult to establish.

Upon communication with CP's from the mines investigated, it was found that due to financial reasons (optimising NPV) the areas of higher qualities as well as those that yield more favourable mining circumstances are mined early during the mine's life, for which a 350m drillhole spacing was sufficient to classify coal into a high geological confidence category. But as more geologically complex areas are being exploited, a 350m spacing may no longer be adequate or appropriate.

The risk appetite of the CP and the company also influences the perceived required drillhole spacing to classify a Coal Resource into a Measured category. Geologists from the mines investigated had the following to say when asked about their Coal Resource drilling strategies and level of confidence:

"Even if the budget allowed, it is not possible to eliminate all possible variability, we will handle it as it comes" and "I would love to drill on a smaller grid but our budget does not allow for it". These statements are quite different and emphasise the variability of relying on the CP's opinion regarding the confidence required for reliable Coal Resource classification.

Bearing this in mind, and to standardise Coal Resource classification over the entire mining group, some mining companies have established internal criteria of when what drillhole spacing is adequate. Aspects which are investigated include any geological features that may influence the continuity of the seams' geometry or quality characteristics. These aspects include, but are not limited to; seam thickness variations, dip and depth below surface, dykes, sills, paleo highs, sub-outcrops and the 100-year flood line area, water bodies and wetlands. Based on these aspects the appropriate drilling grid is chosen although the minimum 350m spacing is still used for public reporting purposes.

2.3. Drill spacing analysis of mines operating within the Witbank coalfield.

The average drillhole spacing of the fourteen mines investigated is used as an indication of the spacing required to provide sufficient geological confidence for Coal Resource and Reserve calculations. It is noted that more complex areas require closer spaced drilling, influencing this mode of classification. In this study, these minor deviations were taken into consideration and deemed insignificant.

Exxaro Resources use a circular drillhole spacing grid, as suggested by SANS10320:2004, whereas Anglo Coal use an elongated drillhole spacing grid, at two of the mines investigated as part of this study, with the long axis in the direction of highest continuity. The drillhole spacing tabulated represent the current average drillhole spacing per mine (Table 3). Upon further investigation, it was found that the current drillhole spacing utilised was chosen mainly due to budget constraints and not only sufficient geological information. All mines listed below are in production phase except Zibulo from Anglo American which is still in project phase.

Table 3: *Anglo Coal and Exxaro owned coal mines operating within the Witbank coalfield.*

Company	Mine	Actual drillhole spacing (m) used for the highest level of geological confidence
Exxaro Resources	Matla	250
	Arnot	200
	NBC	350
	Mafube	250
	Inyanda	200
	Belfast	300
	Dorsfontein	250
	Tumelo	250
	Leeuwpan	150
Anglo Coal	Landau	100 x 50
	Greenside	200 x 100
	Bank	200
	Goedehoop	200
	Zibulo	350

From the data listed in Table 3 a map was produced (Figure 5) to establish the geographic relationship between the mines that require smaller drilling grids for the highest level of geological confidence. Distinct clusters of similar drillhole spacing are observed.

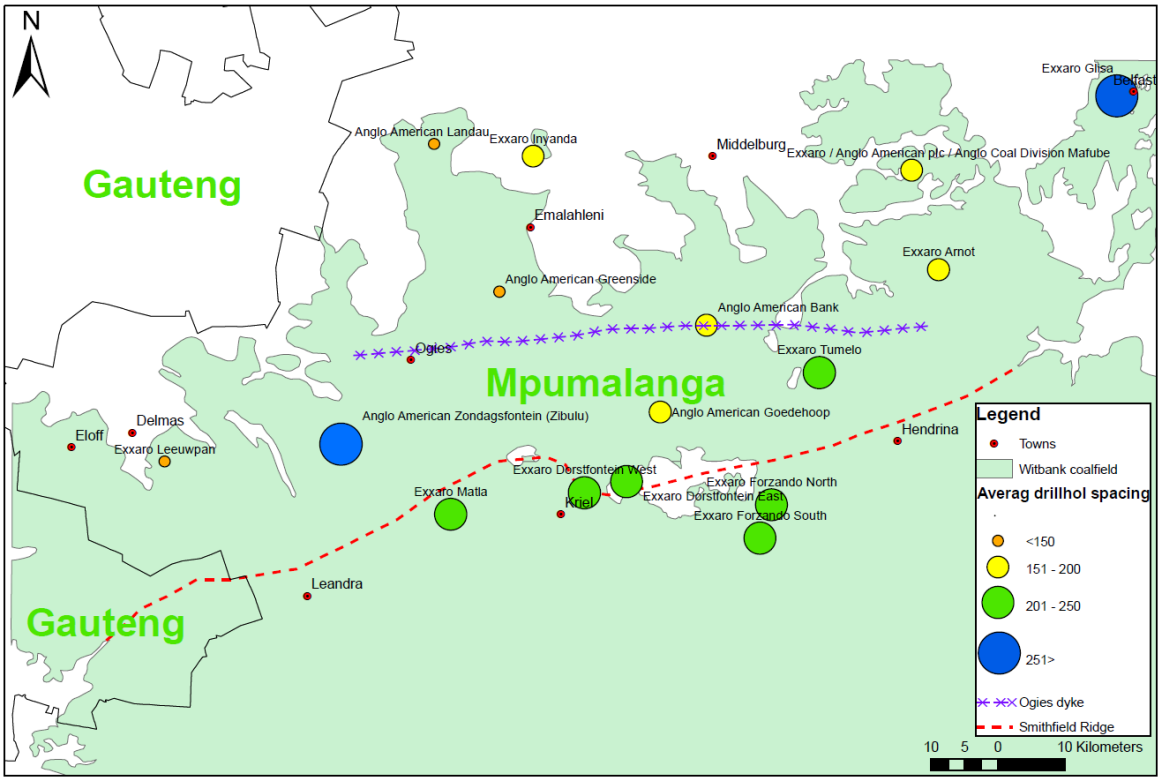

***Figure 5**: Geographic relationship between the mines and their required drillhole spacing for highest level of confidence by the CP.*

Based on the drillhole spacing it is suggested that the entire coalfield be separated into different zones dependant on areas of highest continuity. There is a grouping of mines toward the north east of the study area that requires a smaller than 150m drilling grid (shown by orange circles) to obtain high geological confidence. Anglo's Zibulo mine seems to be an outlier, but as it is the only mine that is still in project phase, it will probably require a smaller drilling grid prior to Reserves being declared and mining commences.

The grouping of decreased drillhole spacing gives a good indication of the increased variability in this region of the coalfield. The variability is due to the underlying dolomites which led to variable fill because of variable accommodation space. In addition, this portion of the coalfield was dominated by deltaic systems adding to the variability of the deposited coal seams.

The mines operating in the southern portion close to the Smithfield ridge and therefore close to the southern boundary of the coalfield, together with the mines located in the most northern portion of the Highveld coalfield has an average drillhole spacing of 201m to 250m

(shown in green circles). The variability is less in this region of the coalfield as the floor consists of the Ecca group of the Karoo Supergroup which yielded a more stable depositional environment.

The drillhole spacing regarded as sufficient in the north-western portion of the coalfield is larger than the drillhole spacing deemed sufficient in the north-eastern portion but smaller than that of the southern portion. The average spacing in this area is 151m to 200m (shown in yellow circles). The basement in this area of the coalfield is Rooiberg felsites, Bushveld Complex (BC) gabbronorites and late stage granites resulting in a less variable depositional environment. The depositional environment is dominated by stable peat swamps resulting in less variable deposits. The main factors increasing the variability in this region of the coalfield are post-depositional events. The increased weathering which weathered away most of the upper coal seams inevitably affected both the seam thickness and seam qualities. Founded on these observations, four zones were identified (Figure 6).

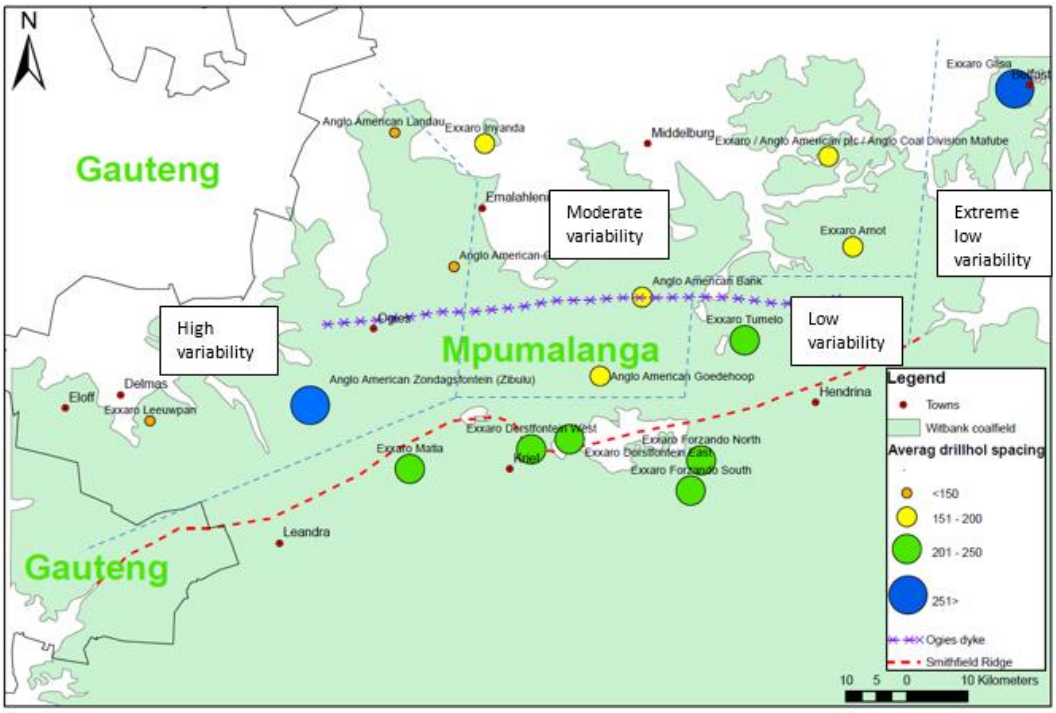

Figure 6: *Four zones based on decreased drillhole spacing, used as indication of variability was identified and indicated by blue lines.*

The zones identified are open to interpretation. For more reliable estimates, information from more mines operating within the Witbank coalfield is needed.

3. LITERATURE REVIEW OF THE GEOLOGY OF THE WITBANK COALFIELD

The most significant risk in the evaluation of coal mining projects is the uncertainty surrounding the estimation of tonnage and quality data. These characteristics are difficult to estimate due to their spatial variability as a result of the complex depositional environment and post depositional geological influences. Consequently, the lack of ability to accurately estimate the tonnage and quality characteristics influence the related investment risks (Pardo-Iguzquiza, et al., (2013)).

Based on the geological complexities, muddling reliable Coal Resource Classification, geo-zoning is suggested to aid the design of a fit for purpose Coal Resource Classification approach aimed at decreasing variability and hence investment risk. Geo-zones are chosen based on the mode of deposition (including the nature of the hinterland and basement) and post depositional large scale structural influences. Understanding the geology and the depositional environment of the coalfield is crucially important to creating practical geo-zones, leading to reliable Classification of Coal Resources. For this reason, a short summary of the coal geology will be discussed including the mineralogical, structural, igneous constraints investigated and proposed geo-zones highlighted. The proposed geo-zones for each constraint will be identified, and combined to yield the most appropriate geo-zones for highest continuity, bearing in mind the practicality of the chosen zones chosen.

The focus of this research is the No.2 Seam within the Witbank coalfield therefore the investigation will be limited accordingly, except where the upper coal seams are considered of importance.

To assist in establishing such geo-zones, a database was created within ArcGIS containing the areal extent of the Witbank coalfield as well as province and major towns for geographic reference. ArcGIS is a geographic information system often used within the mining industry to create maps, compiling geographic data and analysing mapped information. A shape file of the Smithfield ridge, was digitised to delineate the southern boundary of the Witbank coalfield as well as the dominant geological structure, namely the Ogies dyke. Finally, all proposed geo-zones identified are presented on a map for representation and ease of interpretation.

3.1. Tectonic setting

All the coalfields within South Africa are found in the stratigraphic succession of the MKB including the Witbank coalfield. The South African coalfields have been the topic of academic research from the 1980's even though the Witbank coalfield has been exploited from as early as the 1880's. There is abundant academic literature available on the geology of the MKB in the public domain.

The MKB is thought to be an asymmetrical depository with a stable cratonic platform in the northwest and a foredeep with the Cape fold belt toward the south. As a result of the asymmetry of the Karoo foreland basin the strata thin and pinch out toward the north. The differences in stratigraphy between the northern and southern portions of the MKB are related to the modes of deposition, where the northern portion represent a shallow water fluvial delta depositional environment and the southern portion that of marine turbiditites and sub-marine fan deposits (Catuneau, et al., (2005)).

The oldest group within the MKB, the Dwyka Group, represents glacial deposits which retreated north causing the formation of several north-south trending glacial paleo-valleys (Figure 7) along the northern margin of the MKB (du Plesis, (2008)).

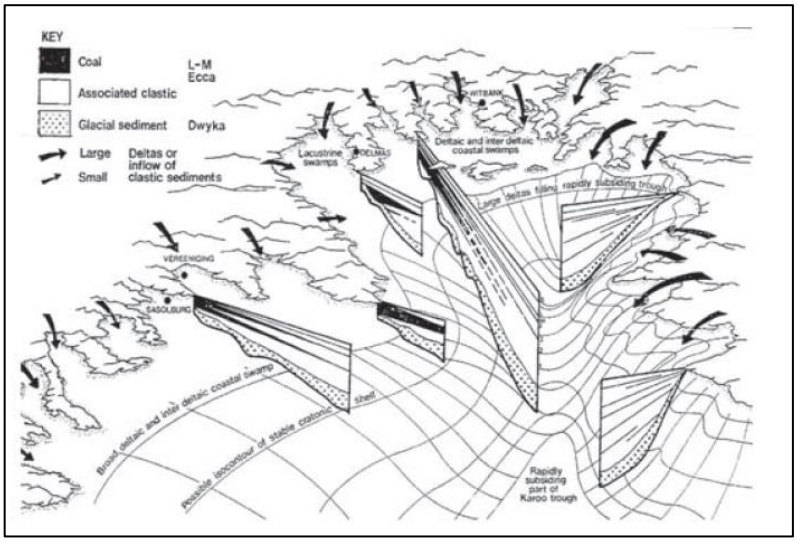

Figure 7: *Deposition environment of the Witbank coalfield on the northern edge of the Karoo Basin, as modified from Claasen, (2013).*

The Ecca group, which overlies the Dwyka group hosts the Vryheid formation. The general consensus is that the Vryheid formation was deposited by means of a fluvial deltaic

depositional system, where the coal is found in interconnected troughs, ravines and sinkholes (Claasen, (2013)).

Valleys and sinkholes result in the fill having irregular thicknesses and complex facies relationships, resulting in the sedimentary rocks of the Witbank Coalfield not conforming to a “layer-cake geometry” (Grodner & Cairncross, (2003)).

The swamps of the MKB formed under cold temperate conditions associated with the disappearing of the foregoing ice age. Coals associated with the Gondwana province have been found to be characteristically rich in minerals, difficult to beneficiate and highly variable in rank and organic matter composition. The reason being that majority of the coal consist of vegetation that was washed into open waters by seasonal floods, accompanied by mineral matter from the mountainous areas in the hinterland (Falcon & Ham, (1988)).

The Vryheid formation is described as an upward coarsening sequence which display continuity across the MKB. The coal seams are associated with the coarser-grained facies at the top of each sequence, where the variations in petrography, grade and rank of the coal can be attributed to changing climatic, sedimentary and tectonic settings with time (Hancox & Gotz, (2014)).

The northern boundary of the Witbank coalfield is formed by pre-Karoo basement rocks, and the southern boundary by a basement paleo-high named the Smithfield ridge (Figure 8). The pre-Karoo basement rocks are a combination of metasedimentary, metavolcanic and dolomitic rocks of the Transvaal Supergroup, Waterberg Group, felsites and granites of the Bushveld Igneous Complex (Hancox & Gotz, (2014)).

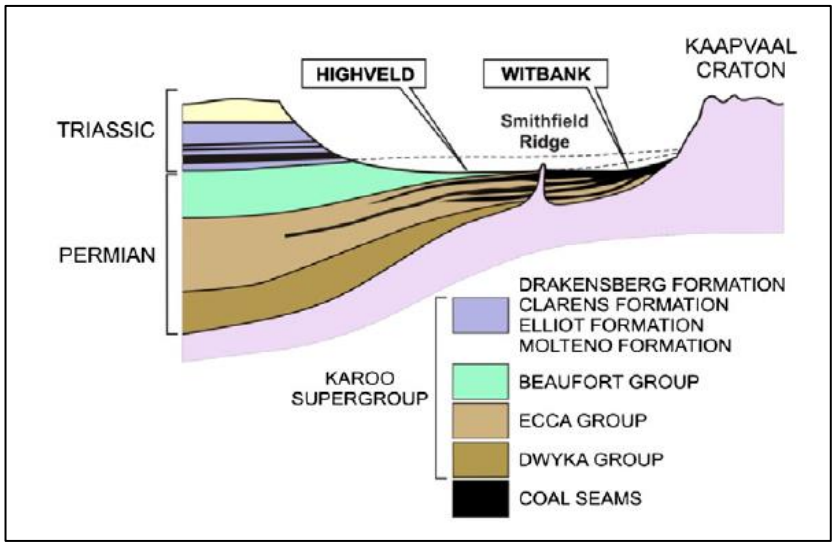

Figure 8: *North-south section of the Witbank and Highveld coalfields, separated by the Smithfield ridge as modified from Hancox & Gotz, (2014).*

3.2. Basement paleo-topography

Glacial scouring and the induced basement paleo-topography is the greatest factors impacting the distribution of the coal seams in the Witbank coalfield. Five regional paleo-valleys have been identified within the coalfield (Figure 9). These valleys created variable accommodation space which was filled by the sediments of the Vryheid formation. The valleys merge toward the south where their impact becomes less (Hancox & Gotz, (2014)).

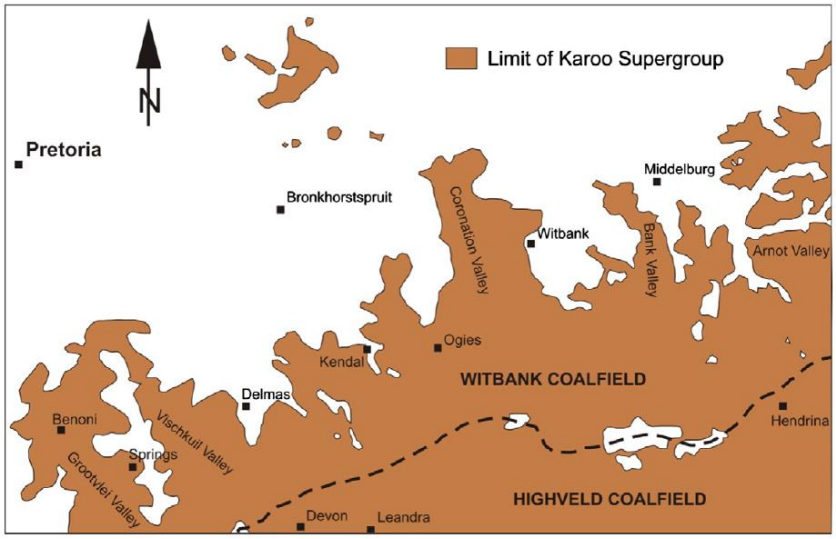

Figure 9*: Limit of the Karoo Supergroup also showing the location of the Smithfield Ridge and five paleovallleys as modified from Hancox & Gotz, (2014).*

The distribution and characteristics of the lower coal seams (No.2 Seam) was controlled by glacial valleys and topographic highs, whereas the upper seams were controlled by the basin-ward migration of fluvic-deltaic propagation (Smith, (1986)).

Irregular compaction of the sediment deposits further complicated the varying seam thickness of the lower seams.

The continuity within valleys are greater than across, hence Coal Resource Classification along the main axis of the five paleo valleys, namely Grootvlei, Vischkuil, Coronation, Bank and Arnot, will yield less variability and therefore more reliable Coal Resource estimates. Figure 10 shows the five, dominant paleo-valleys within the coalfield and the ellipses indicate the direction of highest continuity. The direction of highest continuity varies across the coalfield, from NW-SE in the west to NNW-SSE in the central and E-W in the east. Even though smaller scale deviations from these generalized trend directions is to be expected, it gives an indication of the overall direction of continuity. Where the valleys merge and their influence become less, directional continuity cannot as easily be established.

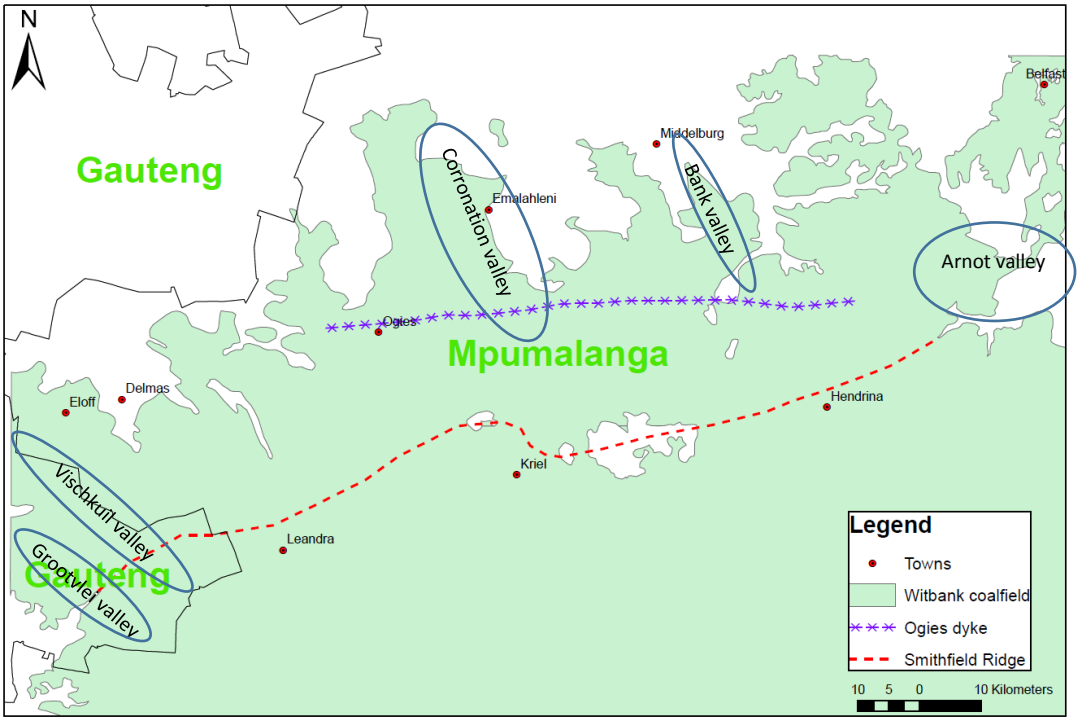

Figure 10: *The Witbank coalfield and five paleo-valleys as modified from Hancox and Gotz (2014). The ellipses indicate the direction of highest continuity as well as a rough indication of the relationship between the long and short axis associated with each valley.*

3.3. Depositional environment

The generally accepted depositional model associated with the Witbank coalfield ranges from glaciofluvial through to deltaic. Within the glaciofluvial/delta environments there are different types of deposits (Figure 11). The deposits vary depending on the position relative to the feeder channel, consequently no one environment is regarded as characteristic of a delta. Deltas can be subdivided into three main depositional environments, namely; delta plain (fluvial processes dominate), delta front (fluvial and basinal processes are prominent) and the prodelta (basinal processes dominate) (Virtual soil science learning resources, n.d.).

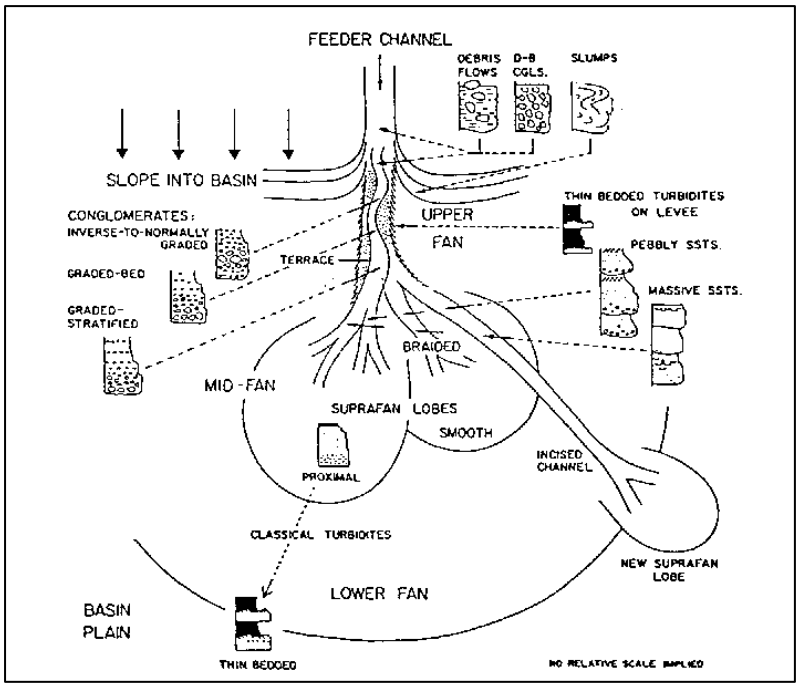

Figure 11: *Depositional environment of deltaic deposits as modified from* (VICAIRE, (2009))

The nature of the depositional environment can be used to give an indication of the expected variability of the coal seam. Areas of higher variability, associated with deltaic deposits and those of less variability associated with fluvial deposits can be utilised in identifying reliable geo-zones.

A 3D model was used to identify the depositional axis of the fluvial, deltaic and beach deposits controlling the deposition of the main economic seam (No.2 Seam) within the coalfield (Figure 12). This 3D model was based on drillhole information from mines operating within the Witbank coalfield. It is recognised that such a model is susceptible to inaccuracies stemming from differences in nomenclature between the mines, survey deviations between drillholes

etc. To build a regional scale 3D model of the Witbank coalfield for academic research purposes (not for mining or production) this information is more than sufficient.

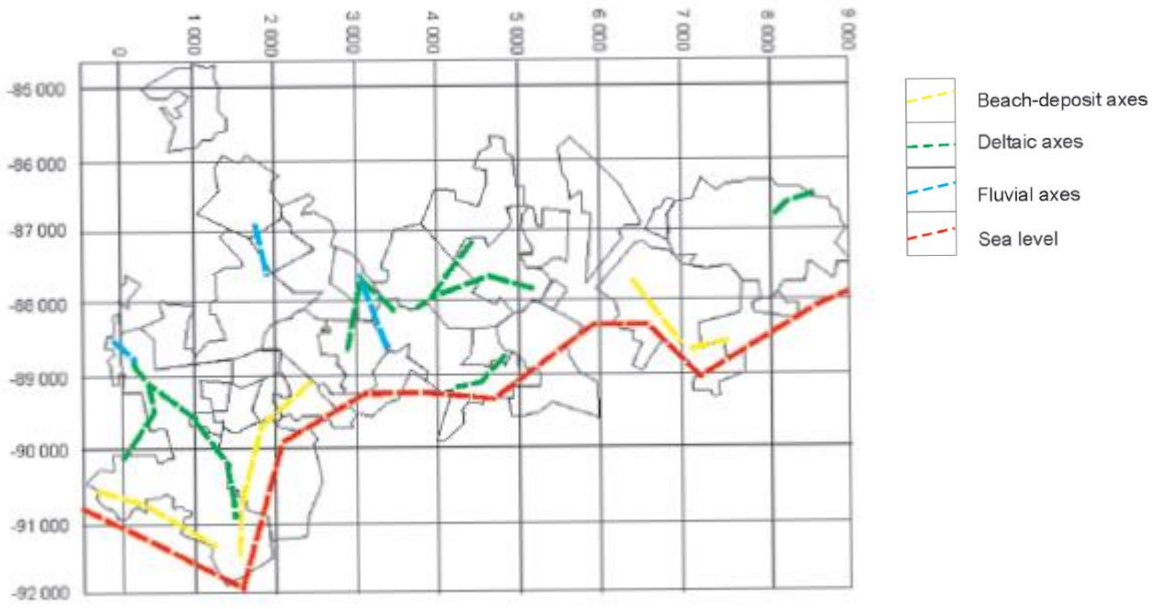

Figure 12: *Depositional environment axis that ruled during the deposition of the No.2 Seam modified from Grodner & Cairncross, (2003).*

The depositional axis of the fluvial, deltaic and beach deposits which controlled the deposition of the No.2 Seam give an indication of zones of less variability as well as direction of continuity. Although this model does not have a high resolution it provides a broader view of the depositional environment of the seams deposited within the Vryheid formation (Grodner and Cairncross (2003)).

Areas of higher variability, associated with deltaic depositional environments are highlighted in green, areas of less variability associated with fluvial depositional system is highlighted in blue and areas of least perceived variability, beach deposits, highlighted in yellow (Figure 12).

The variability associated with the depositional environment is localised, whereas the scale of this research is on a larger scale, therefore no additional subdivisions of geo-zones will be added due to structural influences. The dominant axis of the depositional environments however need to be considered on a mine by mine scale during exploration campaigns and Coal Resource Classification.

3.4. Seam sequence and coal quality

There is significant variation in the petrography, grade and rank of coals within the Vryheid formation. These variations result due to changes in climate, tectonic and sedimentary settings during deposition, as previously discussed.

The Witbank coalfield is generally accepted to have 5 (sometimes 6) coal seams separated by sandstone and siltstone partings (Figure 13). In places the No.2 Seam is split into No.2 Seam lower and No.2 Seam upper by intra seam partings, an additional in seam parting is sometimes present, further dividing the No.2 Seam upper into a No.2 Seam A. The No.2 Seam displays 7 zones of differing quality characteristics, although the seam is generally of high quality the top zone is of inferior quality and therefore historically not mined (Hancox & Gotz, (2014)).

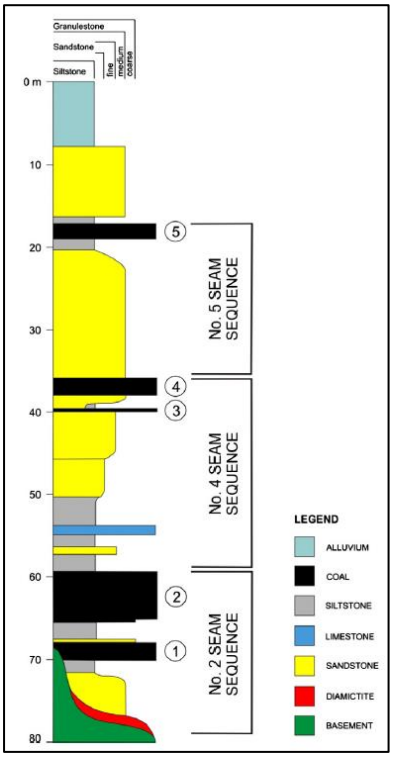

Figure 13: *Generalised stratigraphy of the Vryheid formation of the Witbank coalfield* (Hancox & Gotz, (2014))**.**

Each of the seven zones had been influenced by different depositional factors resulting in the zones to vary horizontally in a unique manner. This further complicates the geological modelling of the seam qualities making accurate Coal Resource estimation difficult. The variability of the pre-Karoo basement rocks plays a significant role in the quality characteristics of the coal seams. Hence the basement rocks were also digitised and added

to the ArcGIS database and plot (Figure 14). Due to the changing basement rocks the type of vegetation, amount and type of non-organic sediments that was transported by the deltaic deposition system differs.

The change in basement rocks and vegetation allows for another tool to aid in creating reliable geo-zones. The coal seams deposited in zones of similar basement and hinterland material should be more similar than areas that were deposited within areas of differing basement lithology. Figure 14 highlight five areas that are more similar based on this assumption. Again, the line separating the zones are somewhat arbitrary and is open for discussion, but, for this research study, is sufficient.

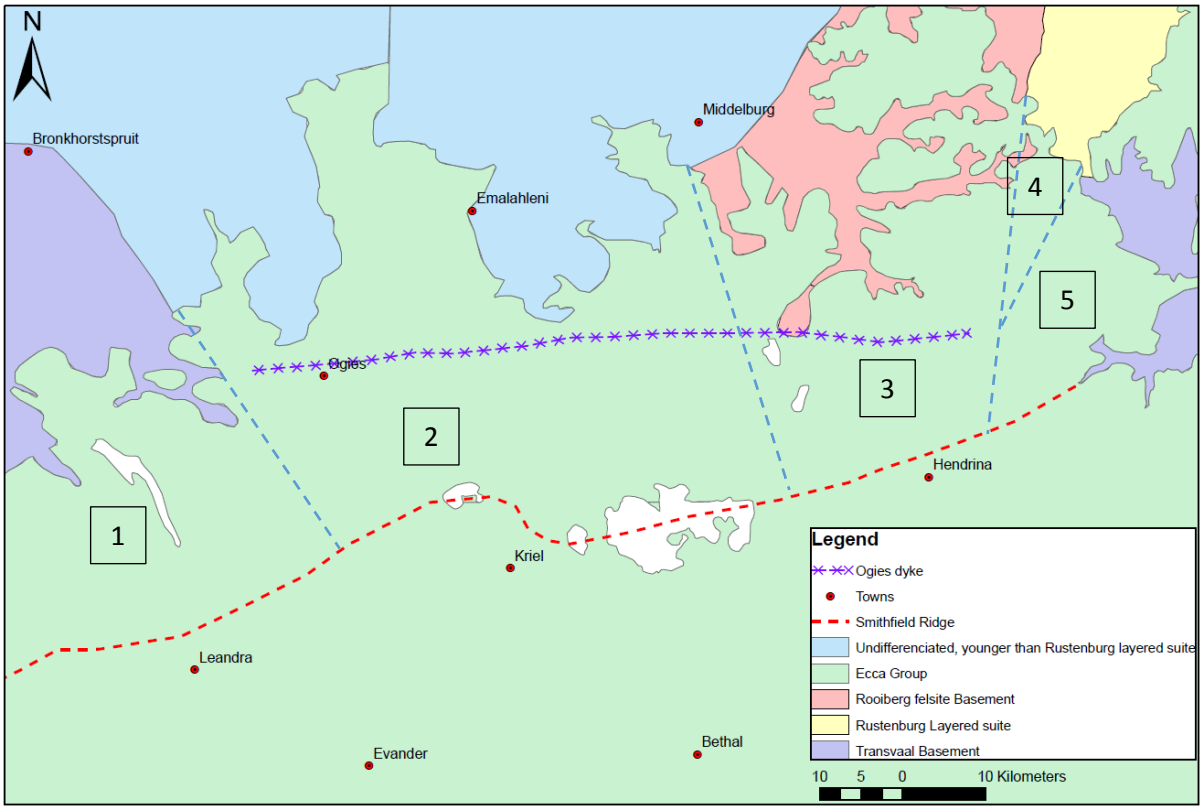

Figure 14: *Changing pre-Karoo basement rocks of the Witbank coalfield as modified from (du Plesis, (2008)). Five geo-zones identified based on basement rocks separated by blue lines.*

3.5. Structural and magmatic activity within the Witbank coalfield

The Witbank coalfield has not been subjected to any large scale structural events. The strata are often faulted in areas where there is dolerite activity but displacement is rarely more than a few meters. Compaction joints on the pre-Karoo valley flanks are common and small scale graben type faulting has been reported in association with the Ogies dyke. The pre-Karoo topography is non-compactable and is reflected through the entire sequence, due to differential compaction the material overlying valley flanks would have slid and fractured related to the gradient of the basement topography (du Plesis, (2008)).

As the fractures related to the basement topography is localised and the scale of this research on a larger scale no additional subdivisions of geo-zones will be added due to structural influences.

Dolerite intrusions add to the complexity of the Witbank coalfield (Claasen, (2013)).

The coal deposited in the Gondwana provinces have remained at shallow depths, but have been subjected to frequent igneous intrusions. These dolerite intrusions have significant effects on the coal quality and mineability related to the varying size and type of the intrusions. Dolerite intrusions can have two very opposite effects on coal, namely;

- Highly uneven increase in the maturity (rank) of the coal within localized areas, increasing the coal quality in a narrow area surrounding the intrusion.
- Burning the coal, increasing the ash content and decreasing the volatile matter resulting in increased weathering due to augmented water movement.

These influences have noteworthy localised effects on both the Coal Resources and Reserves. If coal is upgraded it presents a yield and therefore financial benefit, conversely if the coal is burnt and weathered it will have an undesirable mining and financial impact. The generally accepted distance of metamorphism is 0.6 to 2 times the thickness of the intrusive.

The uneven increase in rank makes modelling the Coal Resource more complex. The metamorphic effect of the Karoo-aged intrusions is associated with narrow contact aureoles and increase in rank of the coal in vicinity of the intrusions are negligible. Despite this the negative impact of the intrusions with regarding mining, safety and reported Reserves cannot

be overlooked. The amount of uneffaced coal that needs to be sterilized for practical and safe benching configurations surrounding prominent intrusions have a large influence on the declared mineable Reserves. In addition, blasting of these dykes/sills are costlier than blasting coal increasing the operating costs. For small scale miners, these costs can have a significant influence on their profitability (Snyman & Barclay, (1989)).

The current Coal Resource classification methods are exclusively dependent on drillhole information. However, dolerite intrusions are not easily identifyable from drilling methods alone (Mahanyele (2010)).

There is a high probability that an exploration program on a 350m grid (Measured Resource category) would not intesect prominent dykes resulting in erreneous deductions regarding continuity. These erreneous deductions can have an influence on the reliability of the Coal Resource model and consequintly have on the economic viability of exploitation. It is important to understand the location, trends and infuence of the most dominant intrusions within the coalfield to be able to accurately asses the risk.

The Karoo Igneous Province (KIP) is described as a thick succession of lava flows and extensive arrays of dyke and sill complexes that are similar in composition. The KIP is one of the largest flood basalt systems in the world consequently dolerites outcrop over two thirds of South Africa, these intrusions influence the coal bearing Vryheid formation, leaving it structurally and metamorphically disturbed (du Plesis, (2008)).

The most prominent dyke is the Ogies dyke (Figure 15) which strikes east over 180km and has a maximum thickness of 14m, this major dyke pre-dates it's associated smaller dykes. Devolatisation and deformation caused by the intrusion influences the coal up to 20m around it. It has been suggested that the overriding controlling factor of the stratigraphic position of the main sill in the Vryheid formation is basin tectonics (Hancox & Gotz, (2014)).

The dykes, north of the Ogies dyke strike predominantly NS and EW whereas dykes south of the Ogies dyke strike EW while there is a complex network of randomly orientated smaller intrusions present in the south-eastern portion of the coalfield. These orientations are governed by pre-Karoo fabric and weakness planes. Although these are the dominant strike directions there are a variety of subordinate dykes with various strike directions on both sides

of the Ogies dyke. The more randomly orientated dykes near the Ogies dyke are as a result of cooling and pressure release joints related to this dominant structure as well as localised zones of weakness (du Plesis, (2008)).

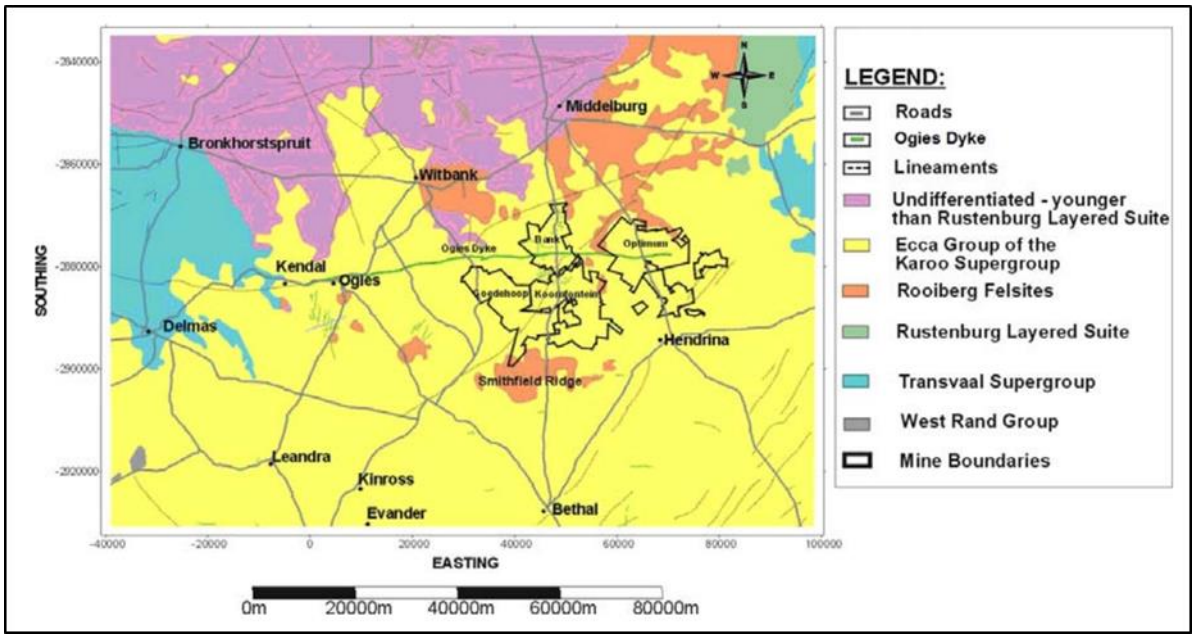

Figure 15: *The Ogies dyke is the most prominent dyke within the Witbank coalfield, denoted in green as modified from Henckel (2001).*

The main sill in the Witbank coalfield is around 20m thick undulates and bifurcates regularly to form off shoots or stringers. The thermal effect of the sill affects the coal seam qualities significantly, especially in the No.2 Seam. There is a subordinate sill above the main sill of around 9m thickness. The sill transgresses a wide area through the entire coal sequence. The contact between the sill and the country rock is generally sharp and displace the coal rather than replacing it (du Plesis, (2008)).

As with the structures identified, the magmatic intrusions are related to the fractures and basement topography. These features are localised, therefore the scale of this research does not allow for additional subdivisions of geo-zones to be added as a result of magmatic activity.

4. PROPOSED GEOZONES

The above discussed aspects were considered and combined to develop geo-zones that are suitable for the scale of investigation. Geo-zones have been identified based on areas of similar continuity, as deduced from the geology of the Witbank coalfield. The previously proposed zones for each aspect investigated was combined and plotted on the same plan (Figure 16).

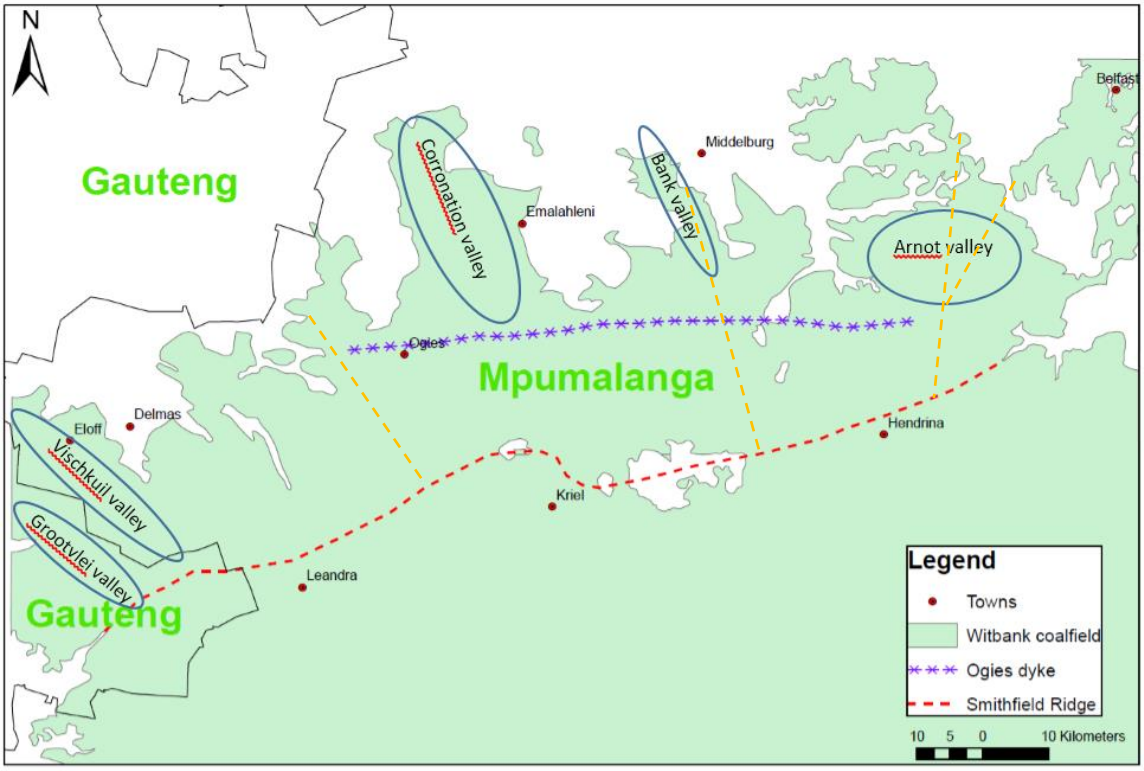

Figure 16: *Identified geozones with similar seam continuity.*

The areas of higher continuity as deduced from the geology of the Witbank coalfield is combined to give an indication of proposed geo-zones. The direction of continuity of the valleys are indicated by blue ellipses and the orange dashed lines indicate areas of similar hinterlands therefore similar quality characteristics.

Based on the combination of zones, four geo-zones are proposed which reflect homogeneity within them (Figure 17). The four geo-zones suggested are similar in basement topography, depositional environment, seam sequence and quality as well as direction of highest continuity. The proposed score card approach to follow in section 6 of this research report takes these zones into consideration for Coal Resource Classification purposes.

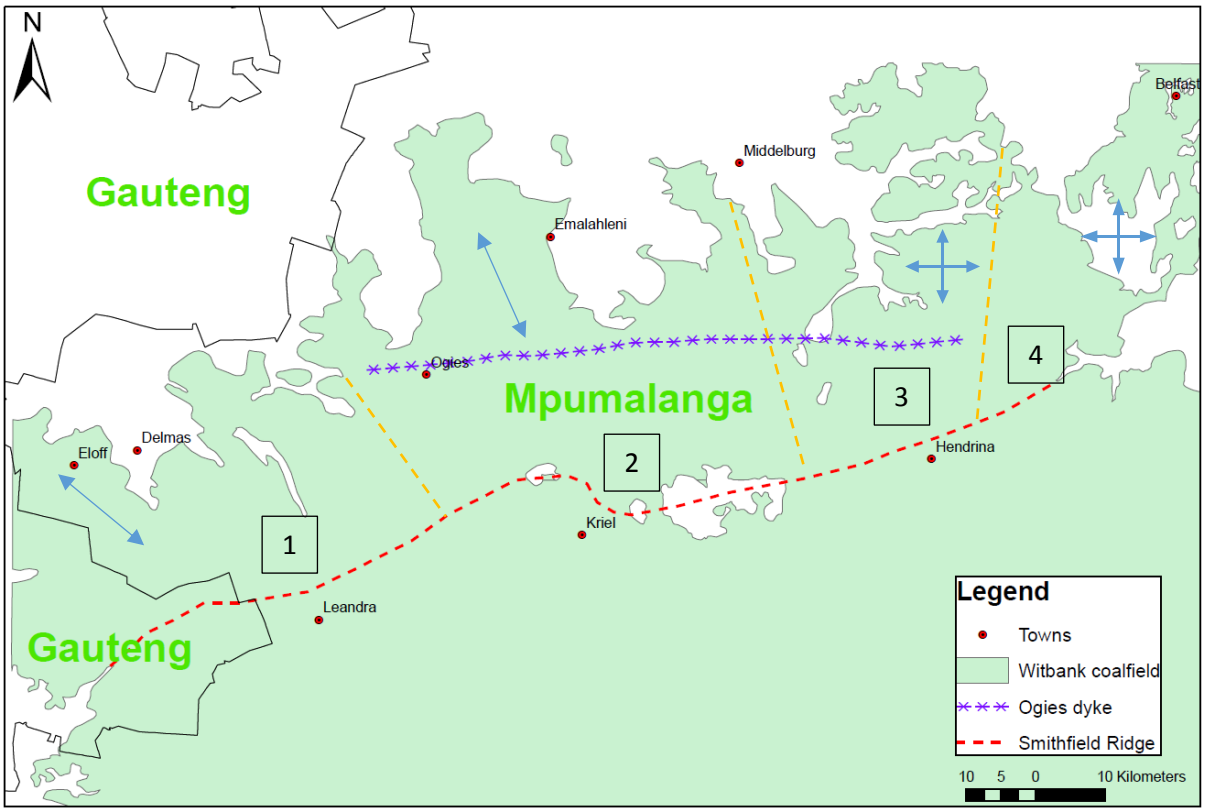

Figure 17: Proposed final geozones reflecting broad scale homogeneity and directions of continuity.

Orange dashed lines indicate proposed geo-zones, based on available information. Blue arrows indicate direction of highest continuity. The characteristics of the four zones discussed below are generalisations and may vary on a smaller scale from mine to mine.

Zone 1: Two prominent valleys, namely Grootvlei and Vischkuil is present in this zone hence the zone is anisotropic resulting in directional continuity. The direction of highest continuity is NW-SE, for this reason elliptic area of influence may be more relevant. The depositional environment of the No.2 Seam varies from fluvial in the north, deltaic in the central portion to beach deposits in the south in addition to this the irregular nature of the dolomite floor further increase the variability. This geo-zone requires a small, directional drillhole spacing to obtain a high level of confidence. The quality data within this zone is unique compared to the other zones.

Zone 2: This zone is less variable than zone 1. There is one prominent valley, namely the Coronation valley resulting in the direction of highest continuity to be NW-SE. As with zone 1 an elliptical area of influence may be more relevant due to the anisotropic nature of the

depositional environment. The depositional environment ranges from fluvial to deltaic resulting in moderate to high variability. The stable basement topography lends itself to decrease the variability within this zone when compared to zone 1.

Zone 3 and 4: There is no obvious preferred direction of continuity within these zones therefore circular areas of influence per drillhole is sufficient. The largest post depositional influence encountered in these zones is the effect of weathering which weathered away the upper coal seams. The limit of weathering may have influenced the No.2 Seam in isolated instances. The only difference between these zones is the basement and hinterland composition influencing the quality and washability of the seam. These two zones are the least variable of the four zones identified.

The unique classification strategies for these zones, as set out in the proposed score card to be discussed in coming sections, will aid in a more reliable estimate. Such an estimate adheres to the principles of the SANS10320 standard and protect investors from making erroneous deductions regarding the continuity/riskiness of the investment.

5. STATISTICS AND GEOSTATISTICS IN THE COAL ENVIRONMENT

This section does not aim to investigate the most appropriate modelling techniques or functions. The aim is to identify methodologies to establish a more reliable statistical perspective on minimum drillhole spacing required for geological confidence in the Witbank coalfield.

Geological phenomena are tremendously complex in their interrelationships and geographic extent or exact description of a system is neither practical nor possible consequently the results are necessarily uncertain. This uncertainty is not an intrinsic property of the system but rather of incomplete knowledge by the observer (Olea, (2009)).

Can the age-old question related to how much drilling is sufficient to be confident in the estimation be clarified by means of geostatistical methods? The most difficult question to answer is: "when the drillhole is spacing 'just right'?" Too little drilling results in decreased confidence in the estimate whereas too much drilling wastes valuable time and money.

With the aim to move away from "guestimate" Coal Resource estimation techniques based on the CP's experience, a short summary of statistics and geostatistics used throughout the coal industry needs to be considered. The base of geostatistical estimation is centred on the following; shape of the statistical distributions, stationarity and spatial correlation or variability which are quantified by means of variography. These elements influence the reliability of the classification of both volume and quality estimation, and will therefore be investigated to reach an understanding of their influence and use in the identification of appropriate Coal Resource Classification techniques in the Witbank coalfield. Basic knowledge of statistics is assumed therefore only its use/importance in coal will be discussed.

5.1 Statistics

In statistics, a population is the collection of all possible outcomes comprising the complete system of interest. An important aspect of statistics is organising several measurements in the same way to understand and interpret the data, to meet the required objective of the study. It is concerned with location, spread and shape of the statistical distribution of the data

As part of geological modelling Exploratory Data Analysis (EDA) is the first step in understanding the data. The following discussion focusses on the four most common parameters considered in an EDA process.

5.1.1. Location of a statistical distribution

The location of a distribution is expressed by means of the mean, median and mode. These parameters give an indication of the central tendency of the data. In the coal environment, the central tendency gives a good indication of most occurring values of the seam thickness and the quality data being investigated.

5.1.2. Spread of a statistical distribution

Measures of spread include the variance and standard deviation amongst others. These parameters give a good indication of the dispersion of the data. Due to its uniformity when compared to other economic deposits, coal data often has a narrow spread.

Coal Resources that have been exposed to tectonic activities resulting in faulted, folded or magma intruded coal seams, will display a larger spread in thickness and coal qualities than their undisturbed counterparts. The larger the spread, the higher the variability expected within the coal Resource.

5.1.3. Shape of a statistical distribution

Skewness and kurtosis are measures of the shape of the distribution used to respectively measure the asymmetry and peakedness of the data distribution. Coal seam thickness usually represents a symmetrical distribution if undisturbed, whereas the sulphur data usually represents a strongly skewed distribution due to its depositional characteristics. Other variables such as ash, volatile matter and calorific value can either be skew or symmetric depending on post depositional influences.

5.1.4. Graphical presentation of Sample information visualisation

Sample information visualisation is used to represent the data in such a way that it is easy to understand and interoperate. Examples include box plots, frequency tables, cumulative frequency plots and histograms. Of these the histogram is the most often used, it displays

the proportion or number of data values in each class, showing the centre, spread and shape of a distribution of the data being investigated. If the histogram displays a symmetrical bell curve it can be modelled by a normal distribution (Figure 18). Geostatistical methods are optimal when data are normally distributed.

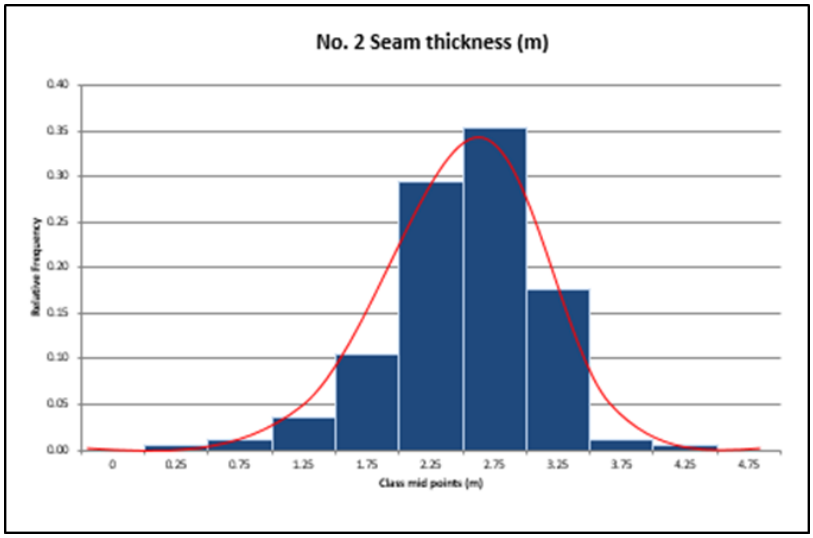

Figure 18: *Typical normal distribution, known as a bell curve.*

5.2 Geostatistics

The following section is a summary of the geostatistical work of Dohm, Srivastava, Morgan and Olea. The summary has been adapted to the current research.

Geostatistics was specifically developed for mining applications in the early 1960's. It is a branch of statistics that focusses on spatial datasets, if the data show no spatial correlation, the application of geostatistics is pointless. This spatial variation is the foundation of geostatistical evaluation of Mineral Resources, separating it from pure statistics. In Coal Resource evaluation, the purpose of geostatistics is to enhance the understanding of the spatial patterns of coal quality and seam thickness, the models created are then used in the estimation of the variables.

Linear geostatistical methods such as inverse distance (IWD) and growth algorithm modelling are often used due to the difficulty in quantifying the spatial variability related to non-linear methods. Linear and non-linear methods are both considered with the aim to establish a mathematical approach to Coal Resource Classification.

Linear methods are widely used within the coal environment due to the relative simplicity (when compared to vein deposits) and stratified nature. The drawback of these methods of estimation is that they do not provide a measure of variability or confidence in the estimate. More complex methods such as kriging, gives various measures of variability ranging from estimation variance, standard error and coefficient of variation to block variance if utilised for block estimations. These measures of spatial variability give an indication of the continuity of the seams which in turn gives an indication of the reliability of the estimate. If the variability is high, a decreased drillhole spacing may be used. If the drillhole spacing is too large it could mask underlying variability, consequently the drilling grid on which the variogram was calculated has a large influence on the resulting model.

Geostatistical methods are optimal when the data is normally distributed and stationary. These properties as well as variability is discussed below together with their application in the coal environment.

5.2.1. Spatial Variability

Spatial continuity involves the idea that small values of the variable under study are in geographic proximity to each other, similarly high values are in geographic proximity to each other and transitions in value are gradual. Spatial covariance and variance (co-variogram and variogram) are classical tools to measure the spatial correlations of the variables under study. These geostatistical methods are necessary in the application of most estimation methods, Ordinary Kriging (OK) being the most common. Covariance and correlation are measures of the similarity between two variables, and are used to display the spatial similarity of a single variable at specific distances apart. The variogram is the inverse of the covariance plot. As the interest is in the dissimilarity between the data points of the same variable at a specified distance apart the variogram is an important function in coal geostatistics.

In Coal Resource estimation, the two key elements that need to be considered, are the confidence in the geology, as previously discussed, and the confidence in the mathematical estimation technique. The confidence in the estimation technique is related to the variability and therefore the variogram of the variable being investigated. The variogram cannot be

used to establish the degree of geological confidence related to the variability in isolation. A good spatial correlation does not necessarily translate into high geological confidence.

A variogram is a graphical representation used to understand spatial variation (Figure 19), and displays variation (square difference between points of data) as a function of distance. The pairs of data points are grouped into distance classes (lags). In practise a representative variogram requires at least several dozen data points, when paired together result in hundred pairs of data points with different spacing or lags apart. With fewer data points the number of pairs in each lag becomes so small that the variogram has a nonsensical structure. The spatial patterns seen in geology are much more complex than a variogram can capture. Even though the variogram cannot capture the complex inter relationships of geological variability, it is the best numerical method available. It is important to not blindly accept the models or predictions and to bear in mind their short commings. (Srivastava, (2013)).

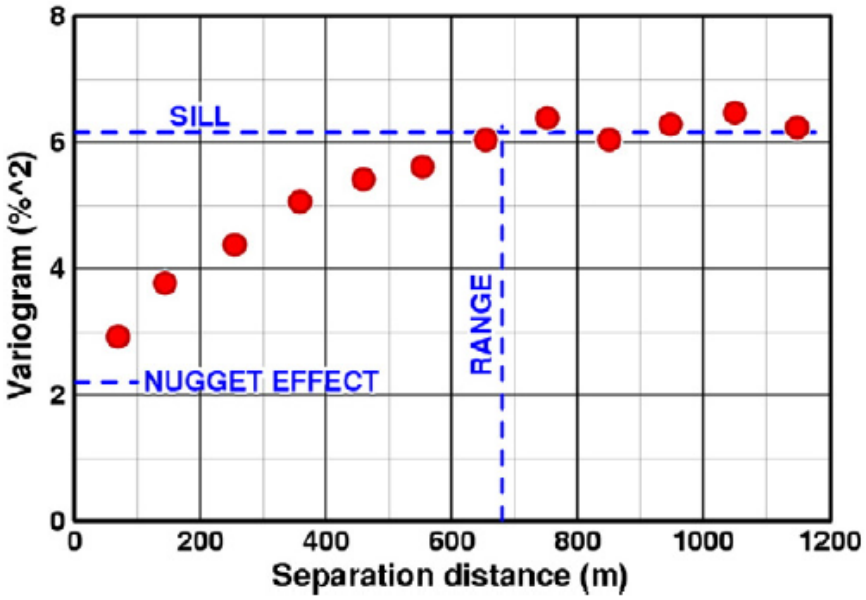

***Figure 19**: A variogram is a graphical representation used to understand spatial variation.*

A variogram displays variation (square difference between points of data) as a function of distance. The pairs of data points are grouped into distance classes (lags) (Srivastava, (2013)).

Olea (2011) recommends that there be at least 30 samples in any direction. As coal is a bulk commodity and small exploration drilling grids are not the norm, nonsensical variogram

structures are often the largest pitfall. Variogram structures consist of a nugget, sill and range (Figure 19).

The nugget effect:

The variogram value at zero distance between observations, should in theory be zero, the nugget effect is the variability between data points that are right next to each other, i.e. at a very small distance apart, if this variability is different from zero it is referred to as the nugget effect. The nugget is expressed as a discontinuity of the semi-variogram at the origin (Morgan, (2012)).

The nugget is described as high variability over short distances. This can be because of sparse data, noise in the data or genuine variability. Geometric variables like seam thickness rarely vary over short distances whereas quality variables can vary considerably, mainly due to physical and chemical processes that created the deposit or post depositional influences. (Srivastava, (2013)).

If a variogram shows pure nugget effect, the spatial correlation is estimated as zero. The variogram displays this behaviour in the coal environment for one of two reasons;

- The data is not spatially correlated, irrespective of drillhole spacing, stemming from low spatial variability.
- Insufficient data, i.e. drillholes too far apart. Coal seam quality variograms often displays a pure nugget effect showing no spatial correlation between points of observation. The reason for this is commonly scarcity of data, in which case smaller drilling grid needs to be drilled.

If the data shows pure nugget effect the average is a good estimator. However, it needs to be considered that as coal is a bulk commodity and it is unlikely to have closely spaced samples for the reliable estimation of the nugget there is no real measure of the spatial correlation at distances shorter than that of the drill spacing.

The sill:

The sill represents the overall variance of the data and is represented by the plateau/sill the variogram reaches.

Anisotropy

Anisotropy in variogram modelling indicates that the continuity of the variable has different variogram structures in different directions. There are two types of anisotropy (Bohling, (2005)):

- Geometric anisotropy: the semivariogram reaches the same sill in all directions, but over different ranges in the directions considered.
- Zonal anisotropy is where the total variance, i.e. the sill, has different values in different directions.

The range:

The range is the distance at which the variogram reaches its sill (highest variance), it is considered to reflect the range of influence of the mineralisation (Bohling, (2005)).

The distance over which there is correlation for coal quality deposited in deltaic environments will typically be shorter with more directional anisotropy than coal seams deposited in n lacustrine depositional environment. The range of correlation typically depends on direction, especially in deltaic type deposits with a definite grain (Srivastava, (2013)).

Variogram models are estimated using visual fitting by the CPs, taking their knowledge of the deposit into account to interpret the semi-variogram as reliably as possible.

5.2.2. Stationarity

A stationary random function is homogeneous and self-repeating in space. Many depositional mechanisms, such as the depositional environment of the Witbank coalfield, causes directional thickening or thinning, which is termed a trend or a drift. The lack of stationarity is easily identified in the semi-variogram, as the experimental variogram trending above the total variance of the data. (Dohm, (2015B)).

If a trend is present care needs to be taken when utilising Ordinary Kriging (OK) as an estimation tool, as OK assumes stationarity. In such a case the data should not be modelled beyond the trend. There are techniques to deal with data that has a prominent trend which is outside of the scope of this research paper.

5.2.3. Sources of estimation errors

Connectivity:

Understanding connectivity is important in that sparser data may create an erroneous impression of higher connectivity, but as geological knowledge and drilling information increase the connectivity may be much less. The example presented in Figure 20, highlights the pitfalls of perceived connectivity when modelling. The danger in this is that although the ore body may have significant tonnages of sufficient grade, this may be dispersed making it difficult to find, model and exploit economically. Data density and configuration of the drilling grids has a bearing on the interpretation of connectivity and Classification of Coal Resources. The effect of connectivity cannot be eliminated as it is a function of the deposit and depositional environment, but can be minimised by sufficiently small drilling grids and drilling patterns.

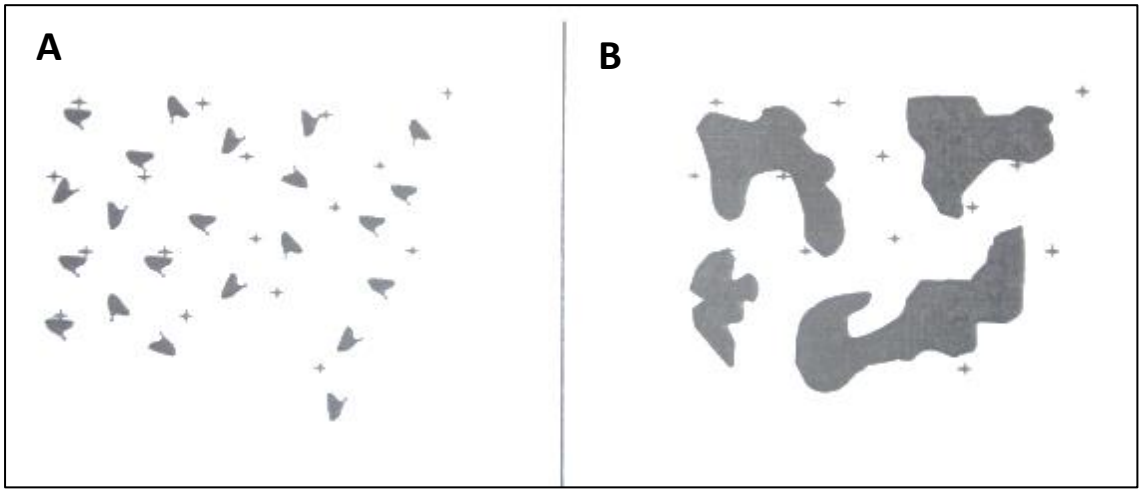

Figure 20: *Figures A and B represent the same drilling data, but with different characteristics in continuity of mineralisation. A is patchy and B more continuous (Dohm, (2015B)).*

Information effect (IE)

At the exploration or estimation stages one do not have full information of the deposit being investigated, hence one makes decisions regarding waste/ore based on partial information. The effect of the level of information available at the time of estimation is generally poorly understood and often ignored. The result is a reduction in selectivity in the mining process and accounts for the observed selectivity often being lower than estimated (Dohm, (2015B)).

The IE can be calculated from the block variance and kriging variance. The tonnage and grade estimates can be estimated in relation to the calculated IE, whereby an indication of the impact of the IE can be established. By additional pre-mining sampling the IE can be minimised but this too, is reliant on budget constraints. If the calculated impact of the IE is significant it would be more than sufficient justification for increase drilling/sampling campaigns.

Support effect

The support effect is related to the variability in grades related to the size and shape of block being investigated (Figure 21). There are two types of variance under discussion when considering the support effect, namely; variance between blocks and the variance inside the blocks for a specific block size. As the block increases in size the variance between the blocks decrease whereas the variance inside the block increase, conversely as the block decreases in size the variance between the blocks increase and the variance inside the block decrease. For this reason, the way in which data is combined in the neighbourhood of a block estimate is critically important (Dohm, (2015B)).

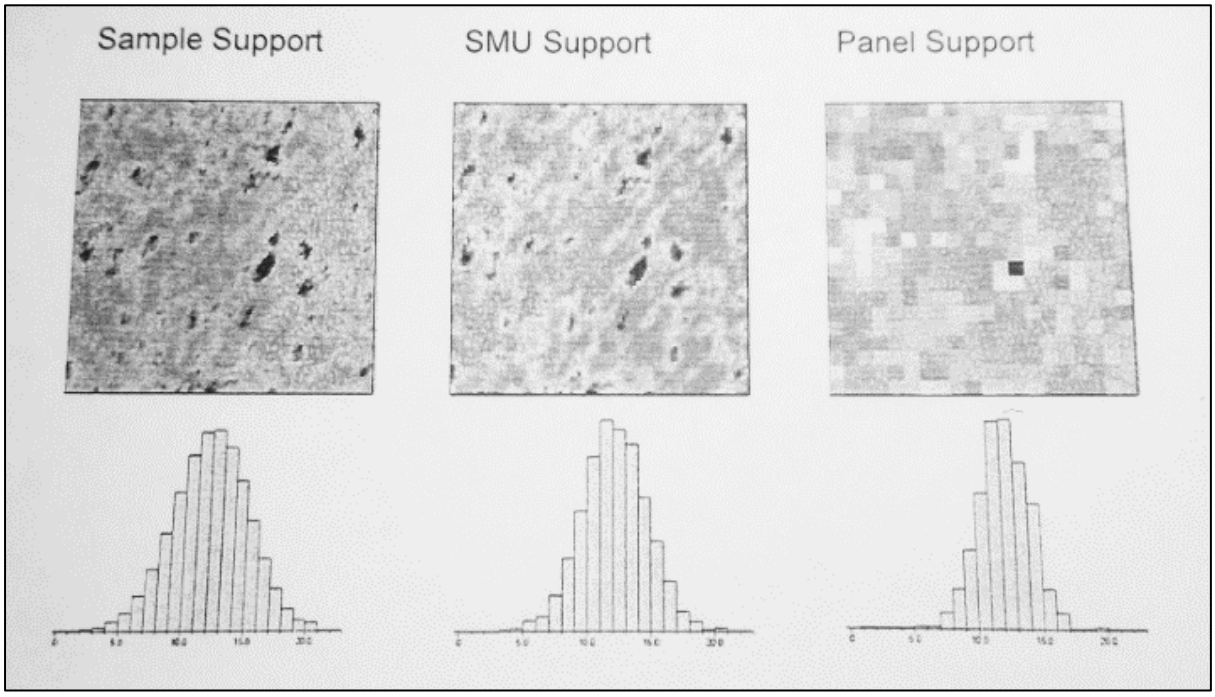

Figure 21*: The variance decreases with increasing support (Dohm, (2015B))*.

Regression effect or Conditional Bias

The support effect and the IE gives rise to the regression effect which relates to the underestimation of low grades and the over estimation of high grades of blocks of volume V. If for a Block Volume V, the actual block values Z_V (Y-axis) are plotted against the estimated block values Z^*_V (X-axis) as in Figure 22, the data points do not plot along a line with a gradient of 1 i.e. $Z_V \neq Z^*_V$.

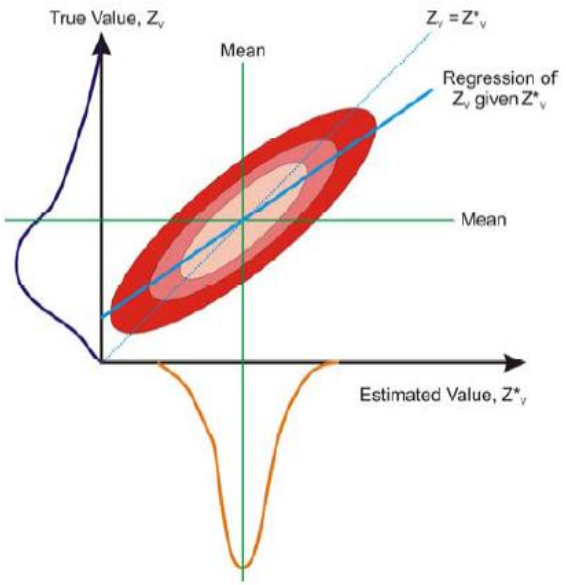

***Figure 22**: Actual Block Values Z_V versus Estimated Block Values Z^*_V, for block volume V (Deutsch, (2007)).*

If the actual block values and estimated block values were the same, i.e. the perfect or conditionally unbiased estimator, the slope of the plot values would be 1, and there would be no cloud around the 45° line. Instead for OK a cloud as in Figure 22 is typically observed with a slope less than 1. The deviation from a gradient of 1 is known as the regression effect.

The regression of the true values given the estimates is an indication of conditional bias. The slope of the regression of Z_V given Z_V*is an approximation for the conditional expectation. (Deutsch (2007))

The slope of regression gives an indication of degree of over and under estimation of the blocks evaluated (Clark, (2015)).

A line is fitted through the points of data to give an indication of the actual slope of the data, the slope of regression is then given by:

$$Slope\ of\ regression\ = \frac{(between\ block\ variance - kriging\ variance + LaGrange\ multiplier)}{(between\ block\ variance - kriging\ variance + 2\ x\ LaGrange\ multiplier)}$$

A small LaGrange multiplier is indicative of a case where there is good coverage and limited clustering. However, if the LaGrange multiplier is large, it dominates the equation and the slope of regression tends to a half.

If the regression between the actual and estimated grades are close to one, it is indicative of a good correlation and thus limited over smoothing therefore also realistic estimations of the tonnage relationship above cut-off (Snowden, (2015)).

The estimates can, in theory, be adjusted for the regression effect by (Clark, (2015)):

Intercept (of regression line with the X-axis) + slope x kriged estimate

Although it has been found that this method of correction does not yield satisfactory results. The reduced major axis (RMA) method has been found to correct the estimate more satisfactorily where the slope is given by:

$$\text{Slope of regression} = \frac{\text{Standard deviation of actual value}}{\text{Standard deviation of estimate}}$$

These methods of correcting the regression effect is only useable if the actual values are known. If the actual values are not known the following equation can be used to calculate the slope:

$$\text{Slope of regression} = \frac{BV - KV + \lambda}{BV - KV + 2\lambda}$$

Where BV is the dispersion variance of block values and KV is the kriging variance obtained during the estimation of the blocks. This equation therefore gives a theoretical indication of the deviation from the actual values and therefore the reliability of the estimate. (Clark, (2015))

These corrections for the regression effect depend heavily on the sample values being normally distributed as variance and covariance has little meaning when applied to skewed data sets. Therefore, exploratory data analysis prior to geostatistical analysis is of utmost

importance. It is also noted that correcting for the regression effect does not improve confidence in individually estimated block values as a block will always be uncertain until it is mined (Clark, (2015)).

5.3 Characterisation of uncertainty and probability

Coal Resource estimates are intrinsically uncertain because of its relative lack of data compared to volumes being investigated, due to this fact, characterisation of uncertainty is enormously important. Coal Resource Classification schemes used globally rely, at least partially, on expert assessment of uncertainty (Cornah, et al., (2013)).

Coal Resource estimation implies a difference from the true grade, it is impossible to calculate this error exactly therefore confidence limits are often utilised to give a percentile of confidence in the estimate.

Sources of spatial variability can be divided into three components, namely; regional structured, systematic (trend) and a random component. The regional structured component represents the large-scale tendencies in the spatial distributions of the variable being investigated. The systematic component/trend reflects high and low grade changes on a smaller scale than that represented by the regional component. The random component represents the irregular fluctuations around a fixed surface. These components are not due to any error but rather a function of the seam being investigated and scale of investigation (Dohm, (2015B)).

The scale at which the data is investigated is of utmost importance. This will have an influence on the drillhole spacing deemed adequate for the highest confidence levels as per SANS10320:2004. If the drillholes are drilled closer, the random component will cause an increase in the apparent variability in the data, in the same way if the drillholes are drilled further apart the apparent regional component of variability will be affected. This further complicates the average drillhole spacing deemed sufficient for Coal Resource classification purposes.

To classify the Coal Resource and determine the best drillhole spacing for classification purposes an investigation, not only into its variability (variography) but also into the

uncertainty needs to be conducted. There are a few ways in which to classify uncertainty. The geostatistical approaches utilised within the industry include, but are not limited to; non-linear geostatistical approach, Conditional Simulations (CS) and Global Estimation Variance (GEV) (Cornah, et al., (2013)).

Linear methods, CS and GEV methods were investigated with the aim to give direction as to what technique is most user friendly and reliable. One of the cornerstones of Coal Resource classification techniques is the ability of the average man, referring to investors, to understand the principles on which the classifications are based.

Therefore, it has been the objective of this study to steer away from overly mathematical complex Coal Resource classification methodologies. Three methodologies have been investigated with this objective in mind and are discussed below.

5.3.1 Non-linear estimation approach

This approach is based on the Discrete Gaussian Model (DGM) frame work. Kriging as an interpolation method, provides the estimated point or block value as well as an indication of the local precision of that estimate via the Kriging variance. The disadvantage is that the Kriging variance only accounts for the spatial variability through the variogram and the geometry of the sample data assuming the local error distribution is symmetric (Gaussian distribution). In the case of skewed distributions and the proportional effect, the local error distribution will most likely also be skewed, therefore its variance will be related to the mean through the proportional effect. The local distribution of uncertainty therefore cannot be fully specified by the Kriged estimate and Kriging standard deviation. For this reason, confidence intervals derived will be suspect (Cornah, et al., (2013)).

If a variable conforms to a multi-Gaussian distribution the estimation error is fully specified by the mean and the variance of Simple Kriging (SK). A disadvantage is that few datasets in their original units adhere to multi-Gaussian properties. Therefore, the data need to be transformed into Gaussian values (normal score transformations).

The more complicated the method the larger the room is for error. Whilst this approach of data transformation, variogram modelling of the transformed data and then the kriging

thereof before back transformation to the original data, was considered, but ruled out as mathematically complex and had therefore not been further explored in this research.

5.3.2 Conditional Simulation (CS)

Kriging is a well-known grade interpolation technique, its application is however problematic with widely spaced drillholes being the norm in the coal environment and the smoothing effect that results in the regression effect, as previously discussed. CS has been proposed for overcoming the problems associated with Kriging. (Cornah, et al., (2013)).

CS is a statistical algorithm which produce detailed models and reproduce the statistics inferred from the available data. The most prominent advantage of this method is that it generates equi-probable statistical models from the same input data (de Souza & Costa, 2013).

In simple terms, CS is based on the generation of possible realisations compatible with the available data. The possible variations increase proportional to the decrease in available data or increasing geological complexity, thus increasing variability. The multiple realisations generated provide a probability distribution for the variable for each cell in the block model, which could be representative of the Selective Mining Unit (SMU) or drilling grid. As statistics rely on probability distributions for the assessment of uncertainty this method provides a more acceptable indication of variability and hence reliability than set drillhole spacing distances for Coal Resource Classification purposes (Olea, et al., (2011)).

A benefit of this approach is that the realisations collectively constitutes a versatile model of uncertainty which can be investigated at a variety of scales, from yearly down to weekly. One of the disadvantages is that this method is labour intensive, as the number of realisations generated to yield functional results typically range from 10 to 20. The more simulations are completed the higher the resolution of the distribution will be therefore the more simulations, the better.

CS calibrates every assessment of uncertainty per the complexity in the deposit. None of these complexities can be quantified by simple rules, such as distance to the closest drillhole, that results in indirect measures of uncertainty (Olea, et al., (2011))

There are some equally valid approaches to CS, of which the two predominantly used is the Turning Bands Method (TBM) and the Sequential Gaussian Simulation (SGS) method. Both have been found to yield similar outputs (Catuneau, et al., (2005)).

Simulation methods provide probability plots for each block estimated giving a good indication of the variability in the estimate associated with each block. The size of the confidence limits assigned to the estimate of each block gives an indication of its variability. In the case of large confidence limits and thus high variability a closer spaced drilling grid would be justifiable despite budget constraints.

There are a few specialised software packages that are designed for this type of simulation and adds greatly to the CP's understanding and knowledge of the deposit. However, this beckons the question, when are confidence limits sufficiently narrow for a deposit to be classified into the highest level of confidence? This decision should be left up to the CP which, as previously discussed, is reliant on the CP's appetite for risk and budget constraints. This methodology has also been considered as being too mathematically complex and time consuming and has not been applied further in this research.

5.3.3 Global Estimation Variance (GEV)/ Drillhole Spacing Analysis (DHSA)

Variability is used to describe the spatial distribution of the data set being investigated. At this point it is important to note the difference between variance and estimation variance. Variance is the average squared difference of a variable from its mean, and it informally measures how a set of numbers differs from their mean. Similarly, the estimation variance expresses the variance between the estimates and actuals.

The Global Estimation Variance (GEV) is the average estimation variance per block, assuming all blocks are roughly squares and that each block consists of one sample position. The GEV is a geostatistical approach which can be utilised to calculate the theoretical optimum drillhole spacing for a deposit with a predetermined confidence interval and specific volume. This process is sometimes termed Drillholes Spacing Analysis (DHSA). It can be used to recommend "a distance of continuity" between points of observation, which, in turn can be used in Coal Resource Classification. The method is simple to implement if the software package produces the estimation variance for each block in the modelled.

The estimation variance is an important function in the process of DHSA, as it represents the variance of the error of estimation. The first step in DHSA is to determine the estimation variance which in terms of the variogram is given by:

$$\sigma_E^2 \text{ (v,V)} = 2\,\bar{\gamma}\text{(v,V)} - \bar{\gamma}\text{ (v,v)} - \bar{\gamma}\text{ (V,V)}$$

Where v represents the sample volume and V represents the block volume being estimated and $\bar{\gamma}$ is the average variogram of the deposit being investigated. The estimation variance is therefore twice the average spatial variability between samples used to estimate the block and the block itself minus the average spatial relationship between all the samples used to estimate the block minus the average spatial variability of the block volume. It has been found that the estimation variance decreases linearly as the size of the block increases up to a certain point from where the estimation variance decreases at a lower rate. The rate at which the estimation variance increases with increasing block size is determined by calculating the estimation variance for several test block sizes.

Calculating the GEV is the next step in DHSA, calculating the estimation variance associated with the Coal Resource for a specific area of interest, this area typically reflects a period related to a mining cycle, i.e. the area that would be mined within one year. The GEV is the approximation of the estimation variance over the area of interest, given by:

$$\sigma_{EST}^2 = \frac{1}{N}\,\sigma_E^2$$

Where N is the number of blocks at the specified block size being investigated. This equation assumes all blocks are roughly squares. The final step in DHSA is converting the GEV into a standard deviation, by taking the square root and then calculating the relative error. DHSA is generally used to calculate percentage errors for large study areas, if the study area is too small the N value in the equation for GEV is small. making the approximation less effective. In larger study areas, the results obtained is similar to those obtained by CS. (Williams, et al., (2015)).

DHSA can be used to determine confidence limits for Coal Resource Classification purposes. The GEV can be converted to relative errors expressed as a percentage of the mean value.

Relative percentage errors can then be plot against the test block sizes and the percentage at which the 10% to 50% relative percentage error thresholds are reached can be used as classification distances (Williams, et al., (2015)).

The application or DHSA on exploration sites are more complicated and the CP needs to be more conservative in the estimates, purely due to the distance between drillholes.

5.4 Application of uncertainty and probability theory

As previously discussed, DHSA seems to be the least complex of the three methods investigated to establish uncertainty and probability.

A case study on the seam thickness of a mid-sized coal mine located in the western portion of the Witbank coalfield will be discussed. The deposit displays a typical Witbank coalfield type succession with No.4 Seam upper, No.4 Seam lower and No.2 Seam.

As with the rest of the research paper only the No.2 Seam will be investigated. The data set used constitutes 441 diamond drillholes on an average 150m drilling grid, drilled and logged over a period of 20 years. For simplicity and illustrative purposes only the seam thickness will be investigated.

The first step is EDA, where the histogram plays an important role in beginning to understand the data (Table 4).

Table 4: *Statistical summary of relevant EDA.*

No. S2 seam thickness (m)		Comments
N	441	
Minimum	0.15	
Maximum	4.84	
Central Value		
Mean	1.26	The 95% confidence limits for the average seam thickness are; LL: 1.21 m and UL: 1.31 m
Median	1.15	
Mode	1.25	
Spread		
Range	4.69	
Variance	0.29 m^2	
Standard deviation	0.54	
1st Quartile	0.97	
3rd Quartile	1.39	
Inter quartile range	0.42	
Shape		
Kurtosis	15.26	
Skewness	2.73	Positively skew

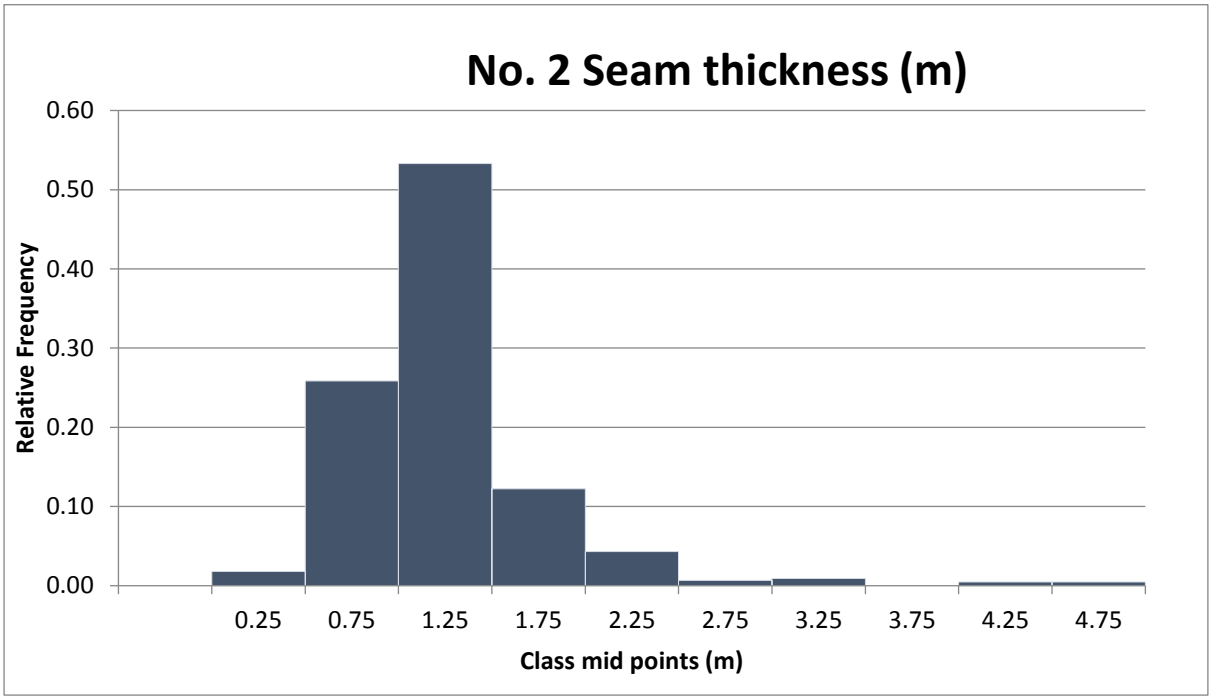

Figure 23*: Relative frequency histogram of the No.2 Seam thickness.*

From the histogram (Figure 23) there is a small tail, upon investigation the high values only constitute four samples and is therefore negligible. The estimated mean for the No.2 Seam thickness is 1.26 m with narrow 95 % confidence interval width of 0.10m or 10cm from Table 4.

Utilising a cumulative frequency plot to establish natural inflection points, the data was divided into five classes (Figure 24). This step is an important part of EDA, as it identifies where the data separates into different classes based on the depositional environment and characteristics of the data. If random points of separation were chosen, the character of the data might have been lost and an erroneous conclusion could have been made.

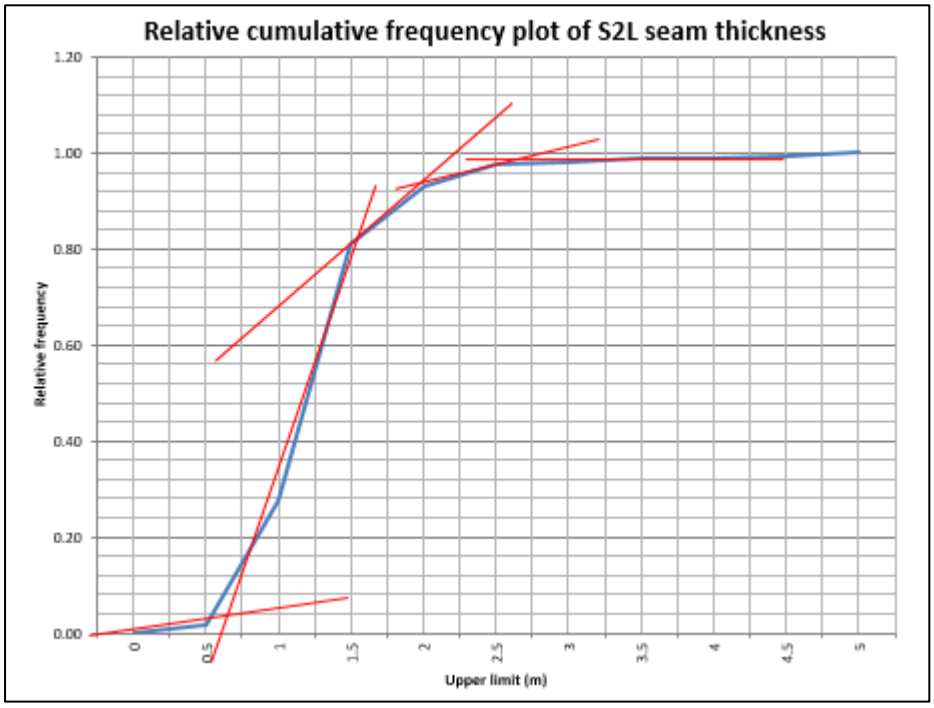

***Figure 24**: A cumulative frequency plot is used to establish natural inflection points,*

A plan view of the spatial distribution of the seam thickness, based on these five classes, was then generated (Figure 25). The seam thins toward the edges of the deposit, as is to be expected for coal seams deposited within fluvial depositional environments. Based on the map there was no need for zonation.

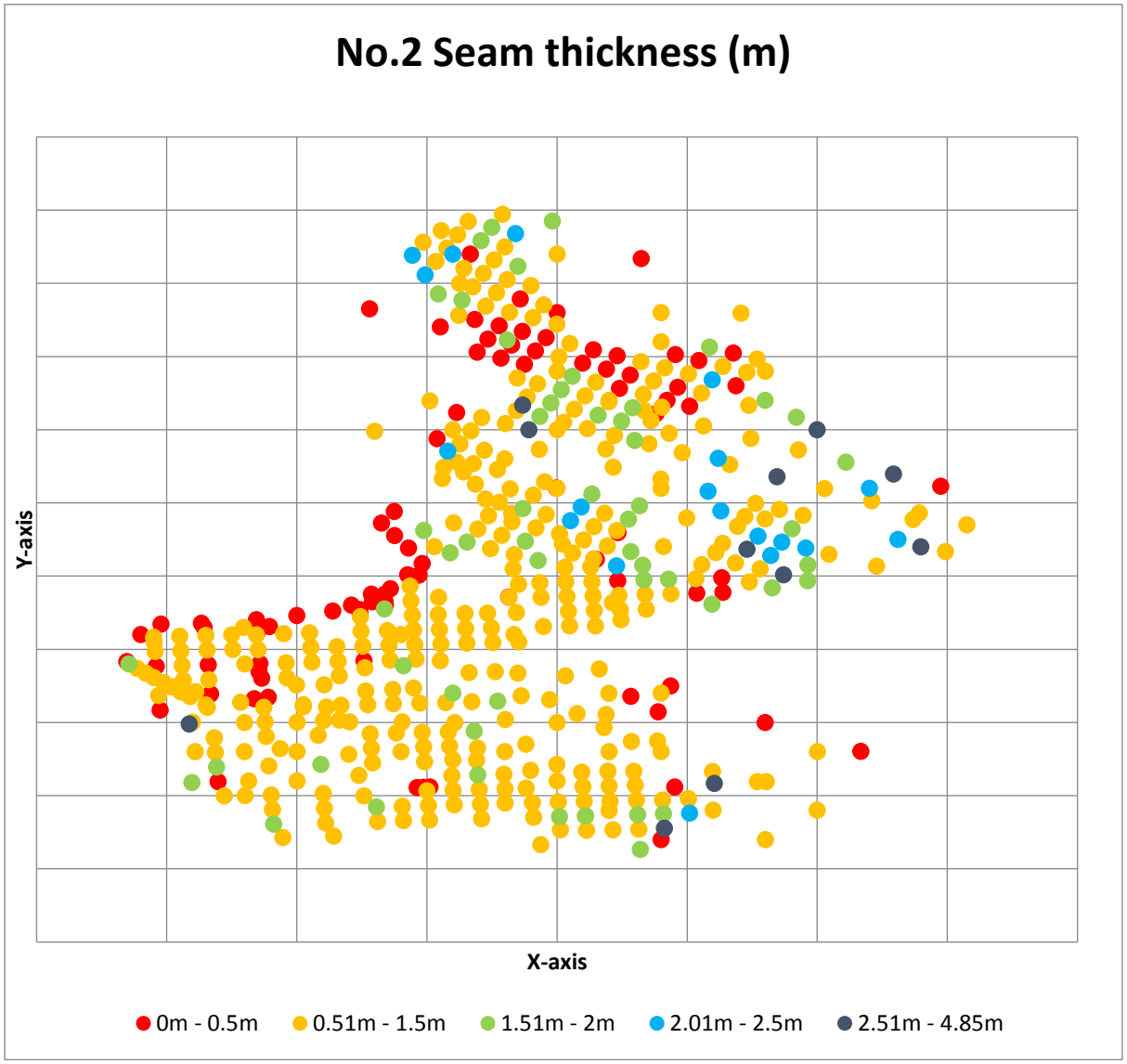

Figure 25: *Seam thickness plot of No.2 Seam on plan view*

The next step is to evaluate the spatial correlation or variography of the data, this was done in Minex (Figure 26). The four variograms displayed were drawn in the four dominant directions, namely 0°, 45°, 90° and 135°. The number of pairs associated with each point on the variogram is displayed to give an indication of which points can be disregarded due to

insufficient pairs. This variogram is typical for coal seam thickness, where the variogram shows a clear direction of highest continuity and geometric anisotropy. The direction of highest continuity correlates with the orientation of the valley in which the seam was deposited.

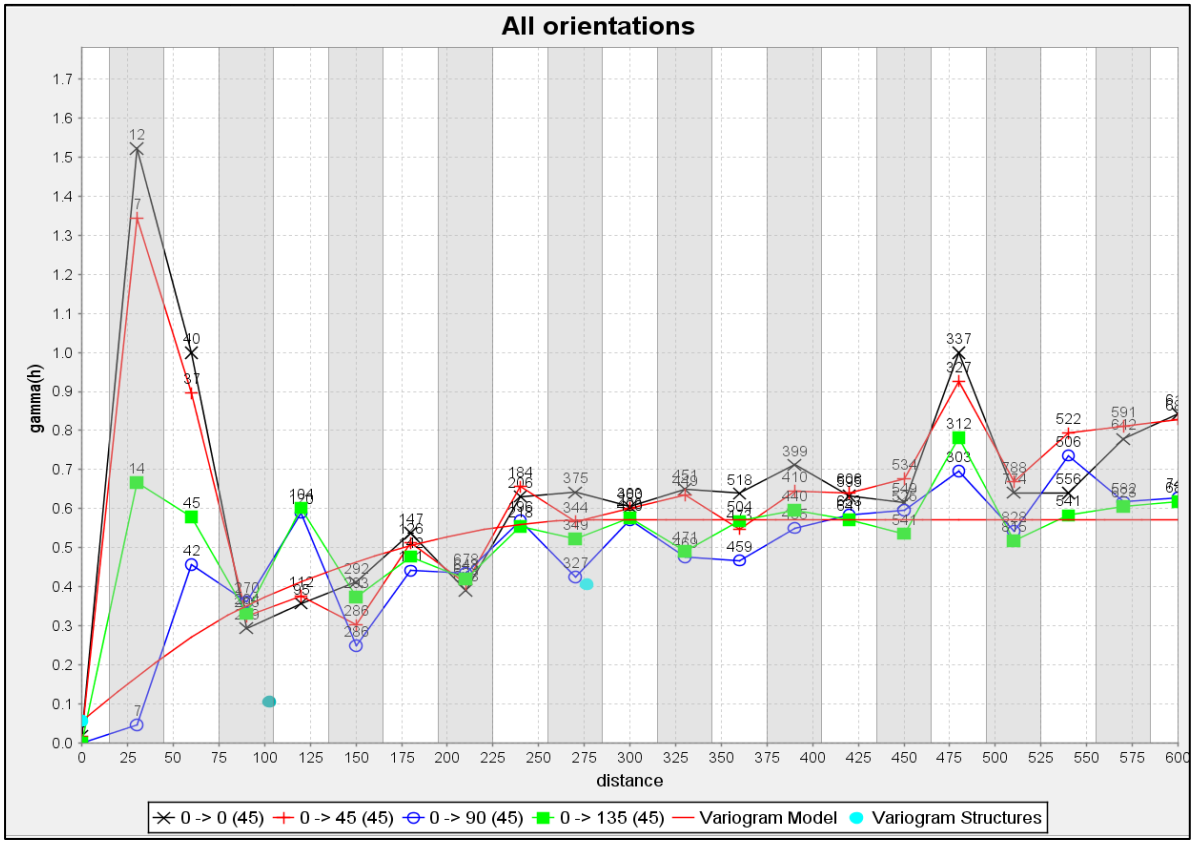

***Figure 26**: Variograms in four main directions for the No.2 Seam thickness.*

There is a clear indication of geometric anisotropy, with different sills being reached in different directions. The direction of highest continuity is in the 135º direction which was also identified in Figure 25.

A spherical model was used (Figure 27) with a sill of 5.8, nugget of 0.06 and range of 275m. The nugget effect in coal is usually in the region of 10% or less, like that of the modelled variogram. The number of pairs associated with the first two data points are low and therefore these two points were disregarded when the variogram model was fitted.

For DHSA the estimation variance needs to be calculated for a range of different block sizes increasing at regular intervals. The sizes of the test blocks used usually range from 10% to 200% of the range (Williams, et al., (2015)).

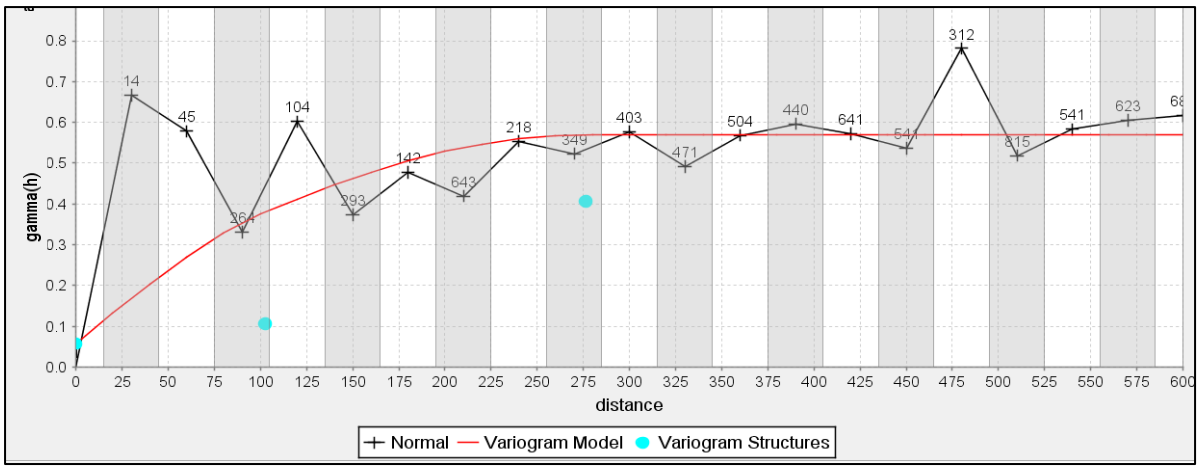

***Figure 27**: Spherical variogram model fitted to the No.2 Seam thickness data with a total sill of 0.56, nugget of 0.06 and range of 275m.*

For this case the estimation variance was calculated for 2D test block sizes, with one sample per block, ranging from 10m x 10m up to 200m x 200m using 10m increments. Effectively an equivalent drilling grid was generated for this range as every block had one sample in the centre of the block. In the estimation 2 x 2 discretisation was used for every block. The next step in the DHSA is calculating the GEV from the estimation variance by determining the number of test blocks capable of fitting within the area being evaluated. In this study one years' worth of mining was investigated. The higher the number of blocks (N) capable of fitting into the study area, the lower the GEV, coinciding with a denser drilling grid. A larger N can be achieved by reducing the test block size, which makes intuitive sense as a smaller drillhole spacing should result in a smaller GEV.

Once the GEV has been calculated it is converted into a relative percentage error by the following formula:

$$\boldsymbol{Relative\ percentile\ error} = \frac{\boldsymbol{\sigma_{ET}}}{\boldsymbol{\mu_{Z^*}}}$$

Where σ_{EST} is the standard deviation of the estimation variance and μ_z^* is the estimated seam thickness (Table 5).

Table 5: *Relative percentage error for an area equating to one year's mining activity in a mid-sized coal mine.*

Grid dimensions	Relative percentage errors Mean = 1.26m Area: 70 000m^2
10	5.37
20	10.44
30	15.17
40	19.64
50	23.62
60	27.41
70	30.86
80	33.94
90	36.62
100	38.88
110	40.68
120	42.59
130	44.12
140	44.44
150	45.00
160	46.04
170	45.61
180	45.82
190	44.15

The relative percentage error is then plotted against the block sizes, representing the drilling grid. The plot represents at what drillhole spacing a specific relative percentage error is reached, yielding the corresponding classification distance on the vertical axis (Figure28).

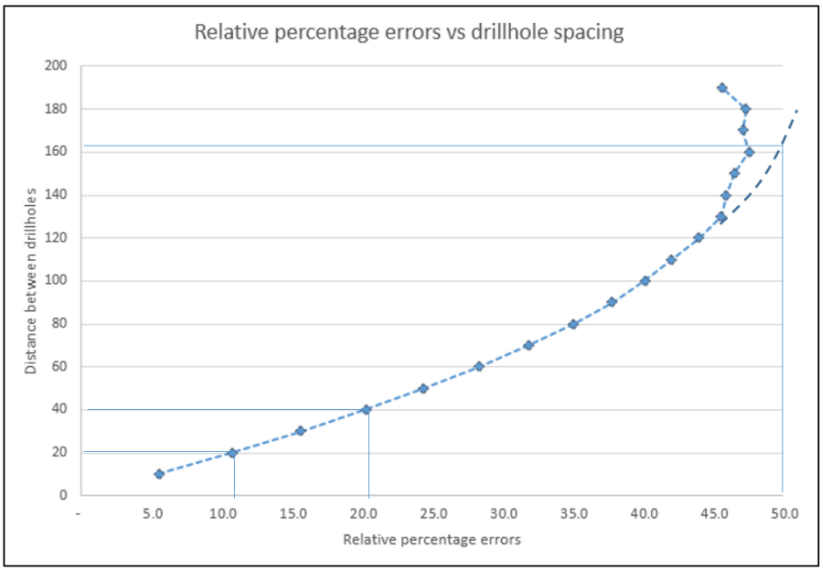

Figure 28: *Relative percentage error vs. drillhole spacing plot for seam thickness of a mid-sized coal mine within western portion of Witbank coalfield. Statistics applied over a 1 year mining period with a mean thickness of 1.26m and an area of 70 000m^2.*

There is a sharp inflection point before the graph reaches the 50% relative percentage error, marking the point where the number of blocks within the area of investigation exceeds the test area size, consequently increasing the global estimation variance. For this reason, the trend line is projected beyond the inflection point and a theoretical value read from the vertical axis.

Based on the above analysis, assuming a Measured Resource category at 10% relative percentage error, an Indicated Resource category at 20% and Inferred Resource at 50% the drillhole spacing for Coal Resource Classification should be 20m, 40m and 160m consecutively. A drillhole spacing of 20m is impractical in the coal environment from a bulk mining point of view as well as from an economic point of view, the cost of drilling at such a close spacing is practically not possible.

This GEV method has a few pitfalls which cannot be avoided. The first and most important is the size of the area being investigated. The norm is to evaluate an area equating to the area that would be mined over a period of 5 years, which may be interpreted differently by different mining operations depending on the size and rate of mining. If for example the same data is applied over the entire LOM area (Table 6) the graph looks very different (Figure 29).

The inflection point where the number of blocks within the area of investigation exceeds the test area size remains at around 130m but the relative estimation error is much less.

***Table 6**: The influence of a change in area on the relative percentage errors if different mining horizons were used.*

Grid dimensions	Relative % errors Mean = 1.26m Area: 70 000m^2	Relative % errors Mean = 1.26m **Area: 700 000 000m^2**
10	5.37	0.17
20	10.44	0.33
30	15.17	0.48
40	19.64	0.62
50	23.62	0.75
60	27.41	0.87
70	30.86	0.98
80	33.94	1.07
90	36.62	1.16
100	38.88	1.23
110	40.68	1.29
120	42.59	1.35
130	44.12	1.40
140	44.44	1.41
150	45.00	1.42
160	46.04	1.46
170	45.61	1.44
180	45.82	1.45
190	44.15	1.40

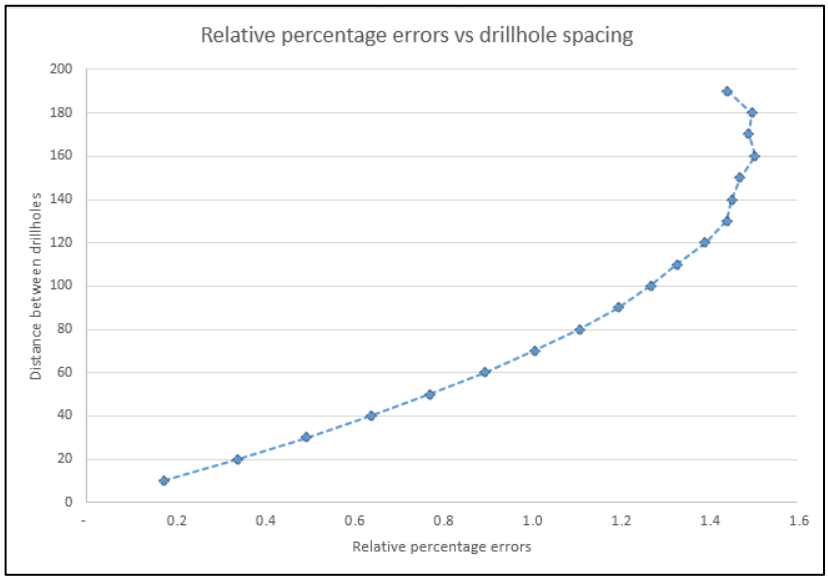

***Figure 29:** Relative percentage error vs. drillhole spacing plot for seam thickness of mid-sized coal mine within western portion of Witbank coalfield. Statistics applied over the total LOM.*

Similarly, if the same data is applied with a larger mean (Table 7), say 3m (instead of 1.26m) the graph again changes (Figure 30). The reason for this is that the variogram is independent of the mean, but the GEV is a function of the estimate of the mean.

***Table 7**: The change in the relative percentage errors if a larger mean were to be used.*

Grid dimensions	Relative % errors Mean = 1.26m Area: 70 000m^2	Relative % errors **Mean = 3m** Area: 70 000m^2
10	5.37	2.26
20	10.44	4.38
30	15.17	6.37
40	19.64	8.25
50	23.62	9.92
60	27.41	11.51
70	30.86	12.96
80	33.94	14.25
90	36.62	15.38
100	38.88	16.33
110	40.68	17.09
120	42.59	17.89
130	44.12	18.53
140	44.44	18.67
150	45.00	18.90
160	46.04	19.33
170	45.61	19.16
180	45.82	19.24
190	44.15	18.54

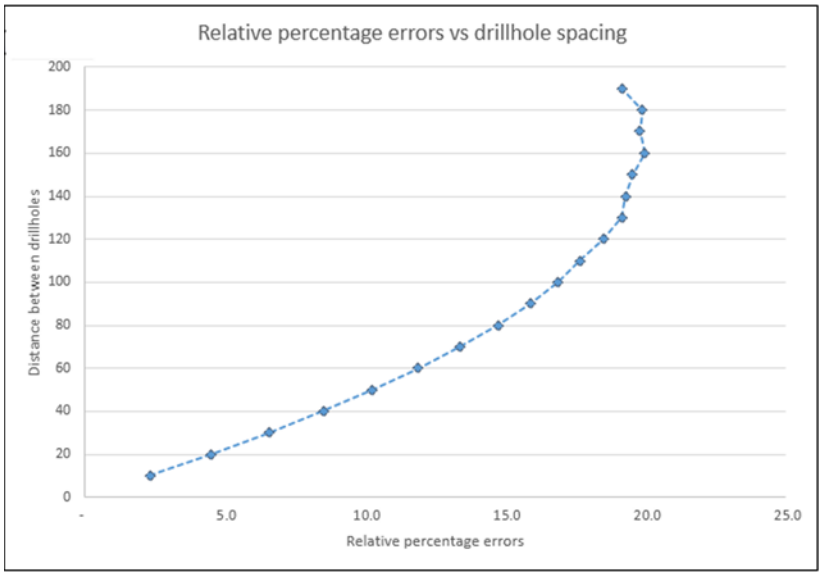

***Figure 30:** Relative percentage error vs. drillhole spacing plot for seam thickness of mid-sized coal mine within western portion of Witbank coalfield. Statistics applied over a 1 year mining period. A larger mean is utilised as part of the relative percentage error calculation.*

Therefore, the DHSA method needs to be applied with caution and not accepted blindly. There are plenty small loopholes which can significantly skew the conclusions drawn from such an analysis. Even though the DHSA is less complex than the previous two methodologies it is again not suggested for use in calculating reliable drillhole spacing for Coal Resource Classification purposes as the method is not robust as was shown in the above examples.

5.5 Conclusion from the statistical & geostatistical analyses

Statistics/geostatistics should confirm the geology, if there is a discrepancy between the mathematical conclusion and what is practically seen in the field, the geology should take precedence. Statistics and geostatistics are however, valuable tools for assisting in the understanding the mineralisation at un-sampled locations within deposits and for improved Coal Resource modelling.

The starting point of all geostatistical evaluations should be data validation and EDA. The importance of evaluating the central tendencies, spread and shape of the distributions prior to embarking on geostatistical analysis are of utmost importance for understanding the shape of the data distribution.

Geostatistics is the only method able to give quantitative estimates of confidence, this should not contradict the importance of other factors, such as EDA and geological knowledge. Geostatistical methods are not without problems when applied to coal data.

Geostatistics is heavily reliant on the spatial continuity of data being evaluated, the variogram displays the spatial continuity in terms of variation as a function of distance. This is a useful tool and forms the basis of most geostatistical estimations. Each estimate based on the variogram has an associated estimation variance, kriging minimises the estimation variance, which is known as the kriging variance of the estimate, resulting in the smallest standard error and narrowest possible confidence intervals. Although kriging results in smoothed estimates it is often used for Coal Resource modelling within the mining industry. The estimated kriging standard errors, only reflect the sampling and block configurations used in estimation and do not fully capture the deposit variability. It however, remains a valuable tool for determining the reliability of estimates. It provides an indication of the confidence to be associated with the estimation methodology in classification methods.

A key assumption in geostatistics is that of stationarity, i.e. a random function that is homogeneous and self-repeating in space. Most features within the coalfields are not stationary but can be corrected for by; modelling the trend, finding a trend free direction and using the variogram in this direction, ignoring the trend, identifying domains that are more similar in thickness or quality than the surrounding domains.

Even if the distributions are homogeneous, Gaussian distributions with no trend, there are still sources of errors that can have a large effect on the reliability of the estimate. These sources include understanding of elements such as connectivity of the mineralisation, information effect, support effect and the regression effect. The CP needs to be aware of these effects and their influence on the reliability and therefore confidence in the estimates made.

The purpose of utilising set drillhole spacing radius for Coal Resource Classification purposes is to give an indication of reliability of the estimate. Three mathematical approaches to quantify the reliability and uncertainty of these estimates have been considered, namely; the non-linear Discrete Gaussian Model (DGM) framework, Conditional Simulations(CS) and the Global Estimation Variance (GEV).

The non-linear estimation approach is based on the DGM framework, few datasets in their original units adhere to multi-Gaussian properties, therefore the data sets need to be transformed into Gaussian Values. Due to the mathematical complexity, this method was not further pursued as a solution to an improved Coal Resource Classification methodology.

Conditional Simulation (CS) was also reviewed, this methodology is based on the generation of possible realisations compatible with the available data, yielding probability distributions of the elements investigated. All branches of statistics rely on the probability distribution for an assessment of uncertainty, relevant information can be gathered from a probability distribution as calculated by CS, that is more precise, more universally understood and richer in information than the four categories widely used for Coal Resource Classification. This approach is informative and useful for developing exploration drilling strategies and assessing the risks present due to variability but has the disadvantage of being labour intensive, CS was not further developed in this study.

Lastly the Drillhole Spacing Analysis (DHSA) method was investigated and a practical example was produced. DHSA is reliant on the Global Estimation Variance (GEV) which is a geostatistical measure calculated from the variogram. It can be used to calculate the theoretical optimum drillhole spacing for a deposit with a prerequisite statistical confidence interval. A disadvantage is that not all variables are spatially correlated therefore a variogram cannot be constructed. In the case of coal quality data where there are linear relationships between the calorific value, volatile matter and the ash content, this drawback can be sufficiently mitigated. The GEV measure gives a good indication of relative errors which are expressed as a percentage of the mean value. The relative percentage errors are plotted against the test block sizes, which in turn can be used as Coal Resource Classification distances of Measured, Indicated and Inferred respectively.

The DHSA method of characterising uncertainty was applied to the thickness of the No.2 Seam of a mid-sized coal mine located in the western portion of the Witbank coalfield. From its analysis, it was concluded that the DHSA method used for uncertainty characterisation is not ideal for use within a national reporting code system. The reason for this is that the method is not robust and data can be manipulated in such a way that is misleading to the general investing public. Although this method can and does add value it needs to be applied with caution and not without the due consideration of geological factors.

The use of standard error maps and CS provide a good indication of uncertainty and the application of uncertainty theories are not to be underestimated.

6. ALTERNATIVE METHOD FOR COAL RESOURCE CLASSIFICATION

As previously mentioned, the value of onsite practical geological knowledge and information should not be underestimated and the geostatistics should always confirm the geology. For this reason, a purely mathematical approach to Coal Resource classification would be a gross over sight. Therefore, a combination of geological factors should be used for reliable Coal Resource classification.

A score card method for Coal Resource classification in the Witbank Coalfield, with associated weights for specific elements to be considered, is proposed as an improvement over the SANS10320 standard to Coal Resource classification method see Table 8.

Table 8: *Proposed scorecard for Coal Resource Classification, incorporating geological factors, geostatistical analysis as well as drillhole spacing analysis. Scorecard must be read in conjunction with Figure 17*

Geological Occurrences	Description			Confidence factor	Weighting	Additional comments
Faulting	Unaffected by tectonic deformation			5	10%	Only known faulting, based on exploration drilling or geophysics, can be evaluated
	Affected by some extent of tectonic faulting, folds are open with long wavelengths and faults are uncommon			3		
	Severely affected by tectonic activity, folds are tight and over turned			1		
Weathering	Coal seams not affected by weathering			5	10%	The influence of weathering as a result of the limit of weathering or in the vicinity of faults/dykes need to be evaluated
	Coal seams mildly affected by weathering			3		
	Coal seams severely affected by weathering			1		
Intrusions	Unaffected by magmatic intrusions			5	10%	The influence of intrusions in terms of effect on coal quality and size of intrusions need to be considered
	Affected by some intrusions, coal in the vicinity of intrusions are less burnt and affected area is less than 1x the thickness of the intrusion			3		
	Severely affected by intrusions, coal in vicinity of intrusions are burnt and affected area is more than 1x the thickness of intrusion			1		
Floor undulations	Moderate floor undulations of less than 10º expected			5	5%	Floor rolls are common in the Witbank coalfield and causes difficult mining conditions, especially for underground workings
	Moderate floor undulations of less than 15º expected			3		
	Moderate floor undulations of more than 15º expected			1		
Geological variability	**Level of assurance**				**Weighting**	
Drill spacing providing geological confidence	Zone 1	Zone 2	Zone 3			As delineated in Figure 17 of this research report
	High: Drillhole spacing less than 100m	High: Drillhole spacing less than 200m	High: Drillhole spacing but less than 200m	5	30%	Please see proposed geological zones in Figure 17
	Moderate: Drillhole spacing greater than 100m, but less than 150m	Moderate: Drillhole spacing greater than 150m, but less than 200m	Moderate: Drillhole spacing greater than 200m, but less than 250m	3		
	Low: Drillhole spacing greater than 150m	Low: Drillhole spacing greater than 200m	Low: Drillhole spacing greater than 250m	1		
Quality of data	**Level of confidence**					
Assay data	High level of confidence, relevant and appropriate QAQC applied to all data			5	15%	
	Moderate level of confidence, QAQC applied, but not to satisfactory levels/standards			3		
	Low level of confidence due to historic data/labs or little or no QAQC applied			1		
Logging data	High level of confidence, relevant and appropriate QAQC applied to all data			5	20%	
	Moderate level of confidence, QAQC applied, but not to satisfactory levels/standards			3		
	Low level of confidence due to historic data/labs or little or no QAQC applied			1		
TOTAL					**100%**	

The scorecard includes geological occurrences and quality of data utilised for analysis. This approach is similar to those used internally within mining houses operating within the Witbank coalfield, and is aimed at managing variability. It provides the geologist with aspects that could warrant smaller scale mine wide zonation and offers an appropriate weighting to relevant aspects avoiding a one size fits all approach without being too prescriptive. The weighting and aspects included in the scorecard is up for discussion but a few non-negotiables are the influence of geological structures and the reliability of the data for Coal Resource modelling. These aspects form the basis for improved confidence in Coal Resource classification.

The scorecard comprises of three equi-important sections, regarding geological features, depositional environment and previously discussed proposed geo-zoning and the reliability of the data. This scorecard assists the CP with his/her judgement on confidence and is aimed at avoiding the "garbage in garbage out" practice or syndrome or view.

If the deposit is not affected by any geological disturbances and the CP has 100% confidence in all his/her estimations all aspects listed would be classified as a 5 and therefore a 100% rating, this is practically impossible and unrealistic. If the deposit is severely deformed and the CP has no confidence within his/her estimates a minimum rating of 20% can be achieved, although also improbable.

It is suggested that the confidence limits be divided as follows, in accordance to the scorecard proposed;

- Inferred: <40% confidence in estimate
- Indicated: 40% to 70% confidence in estimate
- Measured: 70%> confidence in estimate

In severely deformed areas where the aspects related to faulting, floor undulations, intrusions and weathering are all classified as 1, but the assay data, log data and drillhole spacing is satisfactory the deposit can be classified as a Measured Coal Resource. The reasoning behind this is that it is unlikely for the CP to be more than 70% confident in a thickness or quality estimate in severely deformed deposits.

The elements listed in the scorecard are those that are most likely to contribute to erroneous modelling, stemming not from erroneous modelling or estimation techniques but rather from increase variability that could not be quantified. A score card approach encompasses both geological confidence and statistically quantifies the expected variability. Another aspect that should be added, not as part of the score card, but as additional requirements to the governing codes is an indication per mining block of reliability or expected variability based on the results of the scorecard. Although such an approach is tedious and time consuming, the value of its use in production and as indication of confidence on a smaller scale cannot be overstated.

7. CONCLUSION

The problem statement set out at the beginning of this research report questioned the relevance of the Coal Resource Classification methods currently in use within the minerals industry of South Africa. The problem highlighted was twofold;

Not only do the coalfields vary from one to the other, but are also variable within the coalfields itself. The Witbank coalfield as example is not uniform in terms of seam geometry or quality characteristics. The variability of the qualities is due to the type of organic material constituting the coal seam, the nature of the hinterland and post depositional influences. There are several factors influencing geometry of the coal seams, the principle factors are; variable accommodation space, changing proximity to feeder channels, erosional cut out by overlying channels, shale-out into ponded deposits, differential compaction effects, interfingering into channel deposits and pinch out against topographic highs (Le Blanc Smith, (1980)).

Despite this, a blanket Resource Classification approach is often used to classify the Coal Resources into four categories based on fixed drillhole spacing.

Drillhole spacing only is an unsatisfactory method to assess the uncertainty associated with coal deposits. This method of classification fails to recognise direction of continuity and spatial fluctuations, failing to be a proxy for reliability, resulting in a false sense of security. It is unrealistic to assume that all coal deposits have similar variability or that every drillhole has a set radius of influence. Geostatistics is the only tool that can give a quantitative measure of uncertainty, for this reason statistical and geostatistical analyses should be conducted before statements regarding geological confidence can be made.

Coal Resource classification methods used elsewhere in the world were investigated as part of this study to establish what other methods of classification are available. The countries investigated were Canada and Australia as these countries, together with South Africa, are governed by CRIRSCO and the coal measures and depositional environments within these three counties resemble each other.

The base of the governing coal reporting codes in the three countries investigated rely on levels of increasing geological confidence. The South African code for Coal Resource

Classification is underpinned by the SANS10320 standard which relies on a minimum drillhole spacing dependant on two different coal seam deposit types, whereas the Australian Guidelines for Estimation and Classification of Coal Resources gives a guide as to which geological aspects need to be considered when classifying a deposit into the appropriate confidence category, but no fixed drillhole spacing is recommended. The Standardized Coal Resource/Reserve Reporting System for Canada differs from the afore mentioned standards in that it is prescriptive and is based on specific levels of geological complexity, which are governed by fixed parameters. None of the other codes use a broad sweeping set drillhole spacing to classify Coal Resources.

The Coal Resource Classification methodologies utilised on a more local scale were investigated to establish how mining houses practically manage the variability in their Coal Resources as the SANS10320:2004 standard best practise drillhole spacing for high-level of geological confidence is not sufficient. Fourteen mines operating throughout the Witbank coalfield were compared. For ease of comparison, only the No.2 Seam was investigated as part of this study. The drillhole spacing of the mines investigated was obtained information in the public domain or from personal communication with the CP. It was found that although Coal Resource Classification of the governing standard requires a 350m drillhole spacing for highest level of confidence, the mines drill to a much smaller grid for increased confidence yet, some still report on the SANS10320:2004 minimum code in the public domain.

An example of the Witbank coalfield was used throughout the study, the most economic and laterally continuous, No.2 Seam was used.

Appropriate geo-zones/domains were chosen based on the tectonic setting, basement paleo-topography, depositional environment, seam sequence and quality as well as major geological structures encountered within the coalfield. Four geo-zones were identified throughout the Witbank coalfield based on the aspects discussed. The classification methods used can therefore be tailored to suit the geological characteristics identified within each zone independently, and may differ between the zones.

Of the four zones identified, zone 1 is the most variable and would require the smallest drillhole spacing to be classified as a Measured Resource. Zones 3 and 4 are the least variable;

the only difference between the two zones being the coal quality and washability; resulting from different basement and hinterland compositions.

A map was created based on the average drillhole spacing drilled by the CP per mine. From this it was deduced that there are zones of higher variability which required a closer spaced drilling grid to be considered sufficient to provide confidence in the estimates. Based on these deductions four zones of comparable continuity/ variability was identified.

This brings us to the next question, how do the zones identified based on geological inferences compare with those obtained from drillhole spacing analysis? The zones correlate with the highest variability and smallest drillhole spacing located toward the western portion of the coalfield and the lowest variability with the largest drillhole spacing located toward the eastern portion of the coalfield.

Once the geo-zones have been established, the question "What alternative method of Coal Resource Classification could be suggested if not a fixed minimum drillhole spacing analysis?" was assessed. Coal Resource estimates are intrinsically uncertain because of its relative lack of data compared to volumes being investigated, due to this fact, characterisation of uncertainty is enormously important. Statistics can provide a measure of uncertainty and therefore reliability in the estimates without being influenced by human opinion or appetite for risk. For this reason, three methods of uncertainty and probability characterisation were investigated. Of the three, namely; the Discrete Gaussian Model (DGM) a non-linear estimation approach, Conditional Simulation(CS) and the Drillhole Spacing Analysis (DHSA) which relies on the Global Estimation Variance(GEV), the DHSA was deemed the most appropriate method. The DGM is mathematically complex, leaving too much room for error, the CS approach is labour intensive and requires specialised software packages. The third approach investigated, DHSA, is based on the calculation of a reliable global estimation variance. presenting its own set of problems which were highlighted and discussed in detail.

To address both the geological variability as well as provide a measure of uncertainty a scorecard approach is proposed in this research and it is deemed an appropriate and defendable alternative method for Coal Resource Classification.

The reason is that both the geological knowledge of the CP as well as the statistical expression or confirmation thereof supports the principles of the governing codes which are transparency, materiality and competence. The scorecard approach does not exclude the inputs or opinion of the CP yet it provides some quantitative measure of uncertainty that cannot be influenced by human perception or error.

In conclusion, no one technique is satisfactory for Coal Resource Classification primarily due to the variability of the coalfields within South Africa. For this reason, a one size fits all approach is not ideal and a standardised but versatile approach needs to be adopted for maximum efficiency in the classification methods chosen.

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