EXPLICIT AND IMPLICIT GEOLOGICAL MODELLING METHODS ON RESOURCE DEFINITION AND RESOURCE UTILISATION – SISHEN IRON ORE DEPOSIT CASE STUDY

Jacques Deacon
(Student number: 747848)

School of Mining Engineering
University of the Witwatersrand
Johannesburg, South Africa.

Supervisor:

Prof. RCA Minnitt

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Abstract

Technological advances make geological modelling easier and more intuitive than ever before. There is a clear shift in the mining industry concerning the needs of the geological model and its function. Geological modelling is one of the first steps in the resource evaluation process; its primary function is to define the orebody's physical properties and characteristics. It can, therefore, be argued that the geological model has a commanding impact on the entire resource evaluation process. Although many publications exist regarding modelling conventions, few truly compare the explicit versus implicit approaches and document the observed differences.

This case study on the Sishen iron ore deposit shows that modern implicit modelling techniques can create geological models comparable to those created using traditional wireframing techniques. In many aspects, these implicit models are superior to their explicit counterparts due to their increased modelling speed and multiple data source inclusion. The implicit modelling process delivered a geological model with modelled ore volumes equivalent to those of the traditional explicit geological model. However, spatial reconciliation between the explicit and implicit versions of the Sishen geological models showed substantial discrepancies due to fundamental differences in geometry and connectivity, and modelling conventions. These differences in the geological models are manifested in considerable change in the final, defined Sishen resource.

This case study for the Sishen iron ore deposit confirms that geological models are critical to the entire resource definition and extraction process. Any resource evaluation and planned extraction activity is only as accurate as the geological model used to define the resource originally. This study also shows how critical it is to test geological model performance through the entire mining value chain. Basic volumetric comparisons or tonnage reconciliations can mask the effects of geological modelling approaches on resource definition and extraction.

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Declaration

I declare that I am familiar with the School of Mining Engineering's policy on plagiarism, that the work contained in this project report is my own unaided work, that it is written in my own words, and that all sources of material contained within this report have been suitably acknowledged.

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1. INTRODUCTION

1.1. Research Background

With technological advances, geological modelling techniques have improved dramatically in recent times. Modelling methodologies are migrating from a physical, *explicit* model creation procedure which entails the manual creation of points, lines and surfaces of a geological model. New intuitive, *implicit* model-building methodologies are now employed. Input data is evaluated against a mathematical function and a realistic geological model created by following rules and parameters set up by the user for a specific geological setting. New implicit modelling methodologies have many advantages over traditional explicit modelling techniques; foremost speed, which can expedite the resource evaluation process exponentially.

Geological modelling is one of the first steps in the resource evaluation process; its primary function is to define the orebody's physical properties and characteristics. It can, therefore, be argued that the geological model has a commanding impact on the entire resource evaluation process. It is therefore imperative to use the most accurate modelling technique possible.

The question, however, remains whether a model produced by modern implicit techniques can service a complex resource definition and utilisation process like that required for Sishen to the same standard as the traditional modelling process.

1.2. Background Context

The Sishen iron ore deposit developed in a unique geological setting. Its size also commands a range of very challenging geological settings, which are difficult to interpret and model. Over the years, geologists at Sishen have produced timely, robust explicit wireframe geological models, which served to guide mining activities. The increases in production scale and mining tempo over the last couple of years have, however, created a scenario where geological models lag behind the exposure of ore, as it simply cannot be explicitly updated effectively within the turnaround time required for mining activities. This leads to poor scheduling and reconciliation of mining activities, negatively affecting the entire mining value chain. Mining in areas where the geology is not fully understood (and modelled) also creates significant business risk.

To address these shortfalls, the construction of an updated geological model using modern implicit modelling methodologies was commissioned. An independent consultant (Tect Geological Consulting) with extensive knowledge regarding implicit geological modelling was tasked with the creation of this model to ensure that industry best practice was followed. With continuous communication, knowledge-sharing and collaboration between consultant and site, a high quality implicit geological wireframe model of the Sishen orebody was delivered on 10 October 2016. The model is currently in the testing phase before full integration can commence.

These developments make Sishen an ideal case study to evaluate the impact of implementing implicit geological modelling to a complex existing mining value chain, and how this compares to the traditional explicit wireframe based process.

1.3. Research Motivation

Although many publications exist regarding modelling conventions, few quantitatively evaluate the explicit versus implicit approaches and express their tangible differences. How does a model built by a computer compare to a model built by a human being? To what extent can the intuition applied by an experienced geologist during geological modelling be replicated by an automatic computation process? How do these differences in geological models affect the resource utilisation (mining) process?

An opportunity presents itself to draw an extensive comparison between the two modelling techniques with the Sishen case-study. The author is of opinion that such a report can act as a reference point for other mining sites and professionals tussling with geological modelling, a very relevant aspect of today's mining industry.

1.4. Aims of Research

The aim of this research is primarily to develop, test and apply techniques and analysis to effectively measure and quantitatively compare the performance of different geological modelling methods.

Subsequently, how geological models fundamentally affect the defined resource can be quantified and comprehended. The Sishen orebody is well understood and an effective explicit geological model serving the mining process well is available as a baseline for this study. What impression the newly proposed implicit model will have on the current Sishen resource evaluation process should be comparatively tested. Sishen has an exhaustive resource definition procedure for optimal resource classification and utilisation. Many factors such as geology, grade and beneficial potential are built into this proficient resource definition process. The geological model, however, remains the first-order control on the resource definition matrix, as it is the foundation of all geological and resource knowledge. Understanding how comparative geological models influence the Sishen material classification will be an insightful study.

The research aims to ultimately understand and demonstrate the impact geological models have on the resource evaluation process, expectantly showing how geological models critically affect the entire mining value chain, although it is one of the first steps in the resource definition process. Performing this analysis on a dynamic mining value chain such as Sishen offer a phenomenal opportunity to show the importance of the geological model, and how vital it is in the extended mining value chain, not just the resource definition process.

2. LITERATURE REVIEW

2.1. Geological Modelling Review

The Oxford dictionary defines a model as: 1) *"A three-dimensional representation of a person or thing or of a proposed structure, typically on a smaller scale than the original.* 2) *A simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions"*. Ronald (2017) defines the geological model as *"a computer based three-dimensional (sometimes 2D) wireframe model that is the culmination of interpreted geoscientific data for a particular area of interest or deposit"*. These definitions articulate import aspects of modern geological models.

In geo-sciences we are faced with an enormous scale difference between the volume being sampled and the sample volume. To model an exact copy of the geological body with only a fraction of information available is impossible. In the mining industry the term "All models are wrong, some are useful" is often used. This quote should be a reminder that it is not about getting the model "right" (Ronald, 2017). The focus for geological modelling should rather be to build useful fit-for-purpose models that represent the current geo-scientific understanding of the deposit. Ronald (2017) gives fundamental considerations to enable successful geological modelling:

1) What will the model be used for?

The model should be constructed with a clear purpose in mind. A model to be used for high-level application like greenfields exploration planning do not need to be as detailed as a model used during the eventual mining process.

2) Understand the deposit

Geological models must be valid representations of the geological processes that formed the deposit. Modelled rocktypes must adhere to rational geochronological sequences, and any deformation or alteration features should comply with fundamental geology and physics laws.

3) Incorporate all (trusted) data

The main data used for geological modelling is drillhole intersection data, as it provides exact location information concerning the deposit. Modern geological modelling techniques and software can use auxiliary sources of data like geophysics, geomorphic analysis and mapping to improve the interpretation and modelling of the orebody. It is however important to have confidence in the data. Quality control of data in important to determine to what degree data can be applied.

4) Get to know the fundamental data

Exploratory data analysis (EDA) should be performed before any modelling can commence. By understanding the data better, appropriate groupings or domains for the data can be formulated. Considering also the purpose of the model, the optimum data domains can be identified and modelled.

5) Think regionally first, then model down to deposit scale

Geological models for mining or prospecting purposes often only consider the local-scale interpretation. The mining or prospecting area is however but a small fraction of a much larger geological process. Geological models should include and comply with the larger-scale geological setting, as it often represents the early order controls on geometry, mineralisation and alteration in the deposit.

6) Start with structural "skeleton"

Geological model should be based on the understanding of the structural regime. By modelling the structural network or "skeleton" first will improve the interpretation of the stratigraphy, mineralisation and alteration in the deposit, producing more fundamentally sound models.

7) Keep it as simple as it needs to be

Ore forming processes is geologically very complex. In modelling terms, a verified simple interpretation is more effective than elaborate sophisticated interpretations. Considering the purpose of the model, if a geological feature or process has no utilisation impact, it should not be modelled.

8) Don’t forget the waste!

Often times in exploration or mining, the focus is on the orebody, with waste only modelled as a derivative of the target. For the geological model to be un-biased, no particular unit should not be preferentially sampled, interpreted or modelled. To be fundamentally sound the geological model should be a fair representation of the entire geological setting.

9) Reconcile your shapes in 3D

The geological model should be evaluated in three-dimensional space to ensure that it is a realistic interpretation of the geological setting. In especially elongated orebodies, a cross-section connection approach is often followed where individual two dimensional cross-sections is constructed and connected to create a three-dimensional model. When the model is viewed perpendicular to the direction of the cross-section interpretations, it often shows a poor representation of the geological interpretation. Geological models should be true three-dimensional representations of the proposed object, the orebody, to be considered fundamentally sound.

2.1.1. *Explicit Geological Modelling*

Cowen *et al*. (2003) defines the traditional wireframing modelling process as an "explicit" modelling method. The outlines of the orebody are manually digitised, as individual geological cross-sectional interpretations, through the full extent of the orebody and subsequently joined to create final wireframes. The geological model is thus a direct function of manually-constructed surface elements and their arrangement. Cowen *et al*. (2003) give their view on the limitations of explicit modelling:

- Manual digitisation is very time-consuming.
- The final model is essentially a product of the individual geologist's own interpretation, with almost impossible reproducibility between different geologists.
- Any edits or additions to the model require complex, time-consuming manipulation of the model, leading to models that are not continuously being updated.
- Models cannot automatically be updated as new or different information becomes available.

Birch (2014) also acknowledges these limitations, emphasising the time-consuming nature and the reproducibility aspect of the explicit modelling technique.

As an experienced explicit geo-modeller, the author concurs with these limitations of traditional wireframing from own personal experience. Furthermore, the author is of opinion that technological advances in computer technology will allow optimisation of the modelling procedure, similar to the advances made in the resource estimation field with the development of advanced grade estimation and simulation technologies.

Cowen *et al*. (2003 & 2011) investigated the possibilities of wireframe-free geological modelling where the input data (drillhole data) is directly used to populate a block model by means of a mathematical estimation function, called "direct-to-block" modelling. The direct-to-block modelling concept can be regarded as the precursor concept to geological modelling without "explicit" controls, producing a model "implicitly" from the data, by means of an estimation function.

2.1.2. *Implicit Geological Modelling*

Cowen *et al*. (2003) define implicit geological modelling as a process where the model is rendered by evaluating an input dataset by means of a mathematical function through space. As an example, Cowen et al. (2003) used a sphere with a unit radius function [$f(x,y,z) = c$; where x,y,z are the spatial coordinates and c a constant] of such a mathematical function. They observed that these functions are very complex for the purpose of generating a modelling surface and that they are far too computing-intensive to be practically applied to "real-world" examples. With the paper published in the year 2003, it can be concluded that no realistic geological modelling solution other than wireframing existed at the turn of the millennium.

With further development in mathematical interpolates, "smarter" functions were developed that offered plausible solutions for effective implicit modelling. Today the most commonly-used function for implicit modelling is the radial-basis-function (RBF).

RBF represents the creation of the volume function as a sum of *basis* functions, with a linear weighting method exactly the same as dual kriging (Cowen et al. 2003). RBF is a global interpolant, and requires the use of the entire dataset to compute the weighting function, which severely limits its practical use on large datasets; >40 000 data points according to Cowen et al. (2003). FastRBF was subsequently developed to address the limitations of ordinary RBF. FastRBF works in the same way as RBF, the only difference being that infinite precision regarding the weighting calculation is not required, since the coefficients are only computed to within a pre-determined accuracy, introducing a dramatic increase of computation speed (Cowen et al. 2003). The Leapfrog Geo® modelling software is powered by FastRBF, with a claim of utilising >1 000 000 data points "incredibly quickly" on an ordinary computer (Maloney, 2014).

In the publication, *Practical Implicit Geological Modelling*; Cowen et al. (2003) give a pioneering showcase of the application of modern implicit modelling technologies like the FastRBF function. Their case studies include:

- Near-mine exploration and targeting (Cosmo Howly gold deposit)
- Ore boundary definition for resource definition (Saratoga gold deposit)
- Geological modelling – kimberlite pipe delineation

In conclusion, Cowen et al. (2003) give their preliminary impressions of the potential advantages implicit modelling offer over traditional wireframe modelling:

- Generating complex geological objects of any shapes;
- Ability to process large datasets on a personal computer;
- Rapid speed of modelling;
- Modelling iso-grade directly from drillhole data without domaining and variography;
- The ability to create multiple, reproducible models that are conditional to the data itself, not modelling intuition;
- Rapid update of implicit models, keeping models dynamic and up to speed with data acquisition.

After the publication of Cowen et al. (2003)'s pioneering work, implicit modelling went from strength to strength. Greeted with much appreciation, the mining industry embraced the technology and the advantages implicit modelling offers. In 2014, ARANZ Geo Limited published an insightful document *Unearthing – 3D Implicit Modelling* as a celebration to its Leapfrog software's 10 year anniversary. This publication serves as a valuable source to gauge the current state of geological modelling in the industry.

A single explicit geological model (*one model syndrome*) is regarded as a substantial risk in the modern day resource evaluation process, as alternative modelling hypotheses cannot be tested (Hollenbeck, 2014). Implicit modelling enables the rapid generation of multiple realisations of the orebody from the same dataset. These stochastic realisations can be evaluated and the most risk-averse version ultimately used in the resource evaluation process.

Geological modelling is changing from a purely explicit ore domaining exercise to the effective modelling of the *geological process* controlling the mineralisation mechanism of the orebody. If the mineralisation control and style of the orebody is well defined and understood, it can be used as a parameter in the implicit geological process. These "smart" models are superior to their explicit wireframe rivals, as they can create detailed and complex models that are impossible with traditional wireframing.

Implicit modelling enables the use of secondary data sources in addition to drillhole intersections in the geological modelling process. These datasets include regional - and downhole geophysics, hyperspectral drill sample and mine face scans and "monitor-while-drilling" (smart bit) data (Hodkiewicz, 2014). These secondary datasets combined with implicit modelling can deliver vastly detailed models with an unprecedented understanding of the orebody.

Literature review indicates that the concept of judging whether a geological model is "good" is also evolving. Whether the model is *fit for its intended purpose* should rather be established. Implicit modelling enables the rapid creation of multiple models with different final purposes, from greenfields exploration models (large scale) to final grade-control models (small scale).

Developments in implicit modelling also led to the furthering of subsidiary research areas such as the structural control of orebodies. Implicit modelling enables the effective and rapid modelling of complex, structurally-deformed orebodies. Ground-breaking work it this field include Vollgger *et al*. (2012, 2015) where they illustrated the successful modelling of the structurally-complex Navachab – Namibia VHMS orebody implicitly (Figure 1). Basson *et al*. (2016) also showcased the ability of implicit modelling to model the structurally complex, high-grade host rocks to the Venetia kimberlite diatremes (Figure 2). As many of the world's most valuable orebodies have strong structural controls, this field of study promises much value in the future.

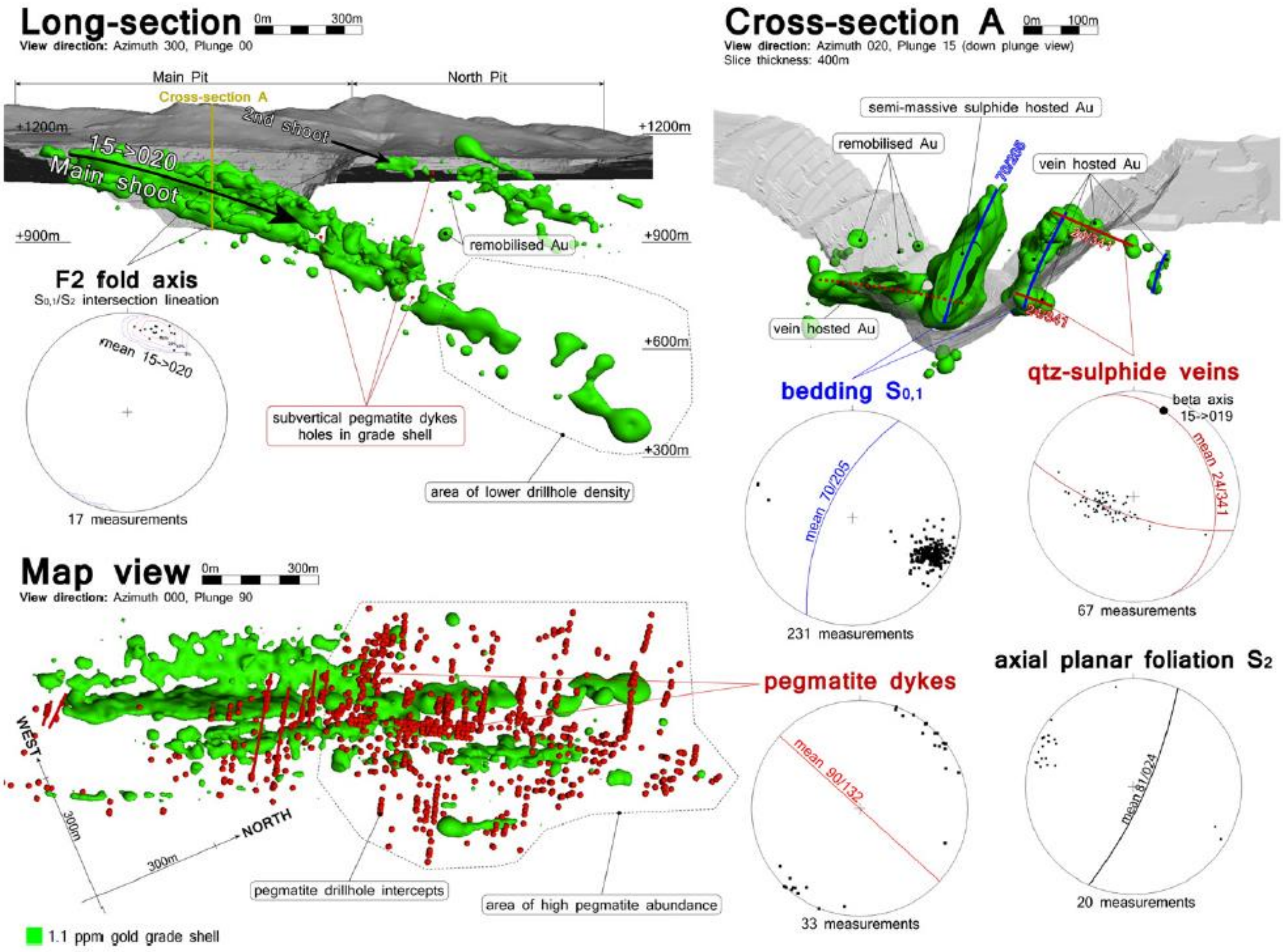


Figure 1 - The implicitly-created geological and grade shell model of the Navachab deposit (Vollgger *et al,* (2015).

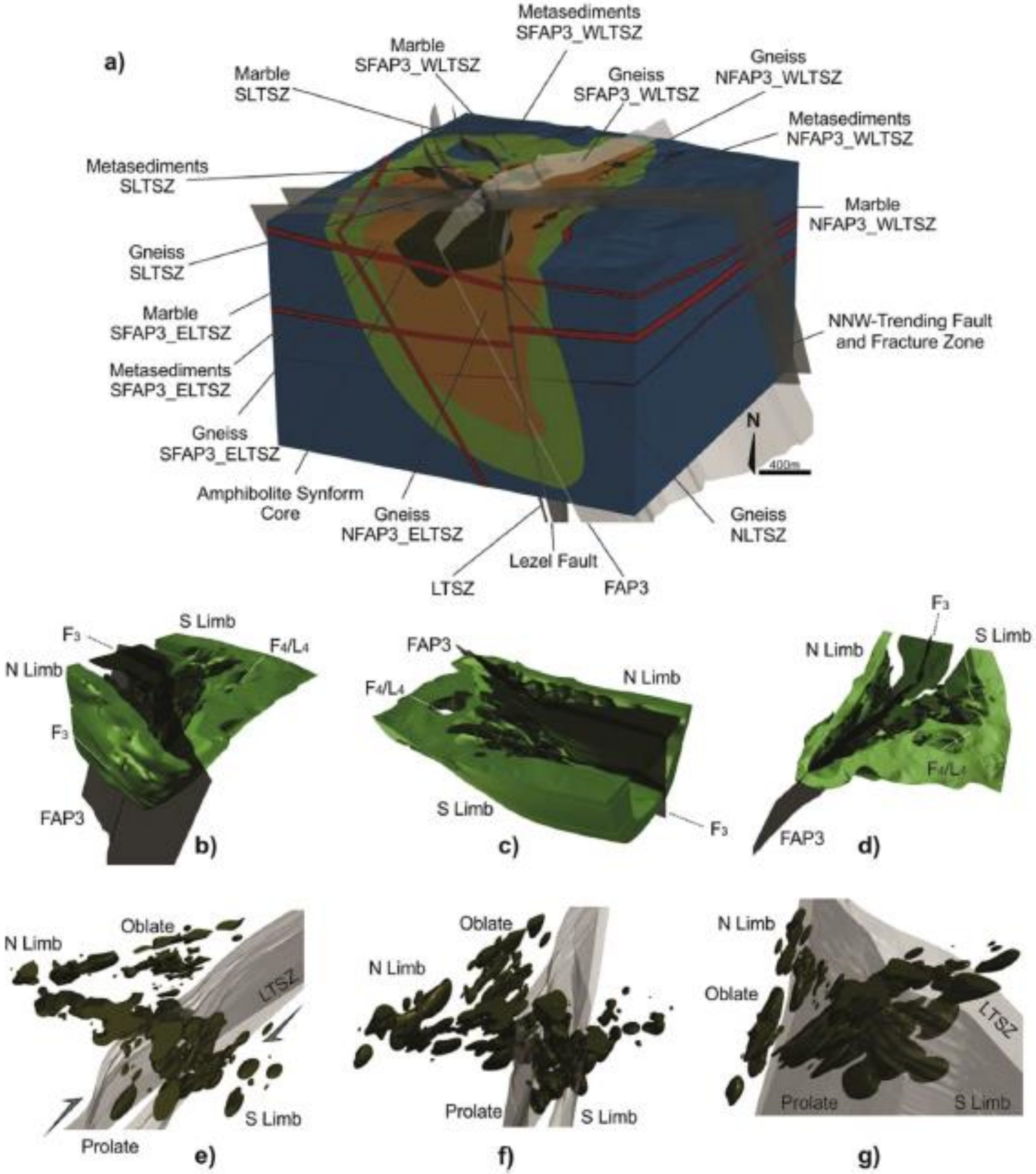


Figure 2 - The implicit geological model of the Venetia high grade host rock complex (Basson *et al,* 2016).

2.1.3. Model Validation

Melker (2014) reiterates the fact that the geological model is virtually the base of all the resource extraction (mining) decisions. Every downstream process in the mining cycle is only as good as the base geological model. It is therefore imperative that a fit-for-purpose geological model that conform to the data and represent the understanding of the orebody is used as the starting point for all mining decisions.

Morley *et al*. (1999) identified geological interpretations as a key performance area in the mining value chain. According to their research, geological models contribute a great deal to resource and reserve uncertainty and therefore have a direct financial impact on the mining operation. Morley *et al.* (1999) identified key performance areas for geological interpretations (Table 1), which can be applied as a validation protocol for geological models.

Table 1 – Key performance areas for the validation of geological models (Morley *et al*, 1999).

Geological interpretation key performance activities	
Key performance activity	**Task**
Database management	Merging survey, Assay and Geological databases
Create digital terrain model	Modelling surfaces in 3D
Geological modelling	Lithological and structural modelling
Geostatistical analysis	Analyse and define spatial relationships in data
Define domains	Identify controls on mineralisation

Traditional wireframe validation usually entails verifying the intuitive (human) aspect of the modelling process. Traditional validation rarely extends beyond the checking of basic controls such as verifying that the model honours (snaps to) drillhole contacts. Validating whether sensible interpolation distances were applied when the model was connected and if the model "appears" to be a realistic interpretation of the orebody are also subjective validation.

Table 2 - Risk contribution factors in the geological modelling process (Steward, 2014).

SOURCES OF UNCERTAINTY AFFCTING THE '**QUALITY**' OF IMPLICIT MODELS:			
SOURCE	**CAUSE**	**DESCRIPTION**	**COMMENTS**
Intrinsic variability		Variability of the phenomenon of interest at all scales from sample support, to block support, to domain.	*Magnitude depends on the phenomena itself and the scale of the measurement and estimation. For some phenomena (e.g. precious metal grades) this may be high, for some variables (e.g. seam thickness) low.*
Physical data errors	**LOCATION**	Measurement errors in collar and downhole survey measurements, errors in mark-up, etc.	*Magnitude of error depends on the capability of the instruments used - this should be appropriate for the requirements of the job.*
	LOGGING (SUBJECTIVE)	Inconsistency in logging, mis-identification.	*Logging is a subjective process. In the future, it is likely that much logging will be replaced by quantitative measurement.*
	SAMPLING AND ANALYTICAL ERRORS	Primary sample recovery, sampling errors during sample preparation, analytical errors.	*Must be actively managed and quantified.*
	MISTAKES	Errors in identification, recording, transcribing, retrieving, attribution. For example, sample swapping, wrong collar.	*Errors of this type commonly result in RADICAL errors in models. Frequently the only way to detect such errors is by cognitive processes. Such errors CAN be eliminated. Doing so should be a major focus of data quality management.*
Data adequacy	**SAMPLE SPACING, DISTRIBUTION AND ORIENTATION**	Orientation of drilling with respect to key structures, sample spacing relative to volume of interest (SMU), spacing relative to important geological features/grade distribution.	*May not be known until after the fact. Often decided by comparison with analogue deposits. High value in obtaining close spaced data at early stages.*
	OBSERVATION BIASES, KNOWLEDGE GAPS	Whether relevant data is recorded.	*As above, relevance may only become clear after time.*
Geological interpretation	**APTITUDE AND EXPERIENCE OF GEOLOGIST**		*The ability to create coherent explanations from sparse observations is the key differentiating skill that geologists bring to the mineral industry. The magnitude of uncertainty due to interpretation may be large.*
	COGNITIVE BIASED AND HEURISTIC ERRORS	Representativeness, anchoring, availability, concreteness, proximity, escalation of commitment.	*This is a real source of risk to the mining industry. Risk may be mitigated by fostering active contemplation of alternative (e.g. by external input) and adequate resourcing.*
Geometric modelling	**CHOICE OF MODEL**	Intrusion vs vain vs contact surface, choice of drift model, global vs structural trend.	*There is no objective method for guiding these choices. The decision is usually a pragmatic assessment of which choices produce the best looking result.*
	CHOICE OF PARAMETERS	Compositing rules, anisotropy ratio, orientation of anisotropy, range of continuity ect.	*You would generally expect these choices to be at least partly influenced by the data. In praxi, the same pragmatism as described above applies.*
Grade estimation	**CHOICE OF DOMAIN TO ESTIMATE**		*A subjective decision guided by the patterns observed in data, the notion of statistical homogeneity, and scale (splitting versus lumping).*
	CHOICE OF PARAMETERS	Compositing rules, nugget/ range of continuity mode, anisotropy orientation and ratio. Choice of drift model.	*These choices should be at least partly influenced by the data. In praxi, the same pragmatism as described above applies.*

As modern implicit models are conditional to the data and rules used to create them, the validation of basic controls in the modelling process becomes absolute. Steward (2014) proposes that the quality of an implicit model is primarily controlled by the quality of the input data and the hypothesis followed during the modelling proses. He suggests that the sources of uncertainty be reviewed when models are validated (Table 2).

2.2. Sishen Iron Ore Deposit – Review

2.2.1. Geology

Regional Geology

The Sishen orebody is hosted in the Transvaal Supergroup, with the main orebody occurring as ferruginous Banded Iron Formation (BIF) of the Asbestos Hills Subgroup and ferruginous shales and conglomerates of the Gamagara Subgroup. The deposit is classified geotectonically as a Proterozoic Lake Superior-type banded iron-formation, due to its age (2.4 – 1.9 Ga) and formation genesis in passive margin sedimentary rock successions (Beukes *et al.* 2003) (Cairncross and Dixon, 2005). Being located adjacent to a large, distinguishable regional anticline structure, tectonic events affected the orebody strongly. The Sishen deposit is hosted in the northern extremity of this large-scale structure, named the Maramane Anticline (Van Schalkwyk and Beukes, 1986) (Figure 3).

Local Geology

The Sishen orebody strikes North-South and consists of multiple isolated orebodies hosted in graben, half-graben and folded structures (Van Schalkwyk and Beukes, 1986) (Figure 4 to Figure 6). Large scale sedimentation and mineralisation occurred in basins formed by multiple tectonic events of different scales. Low-angle thrusting of waste rock over the main orebody host rock preserves the mineralisation and sees the orebody dipping west at an average of 11 degrees (Anthonissen *et al,* 2016) (Figure 4 to Figure 6).

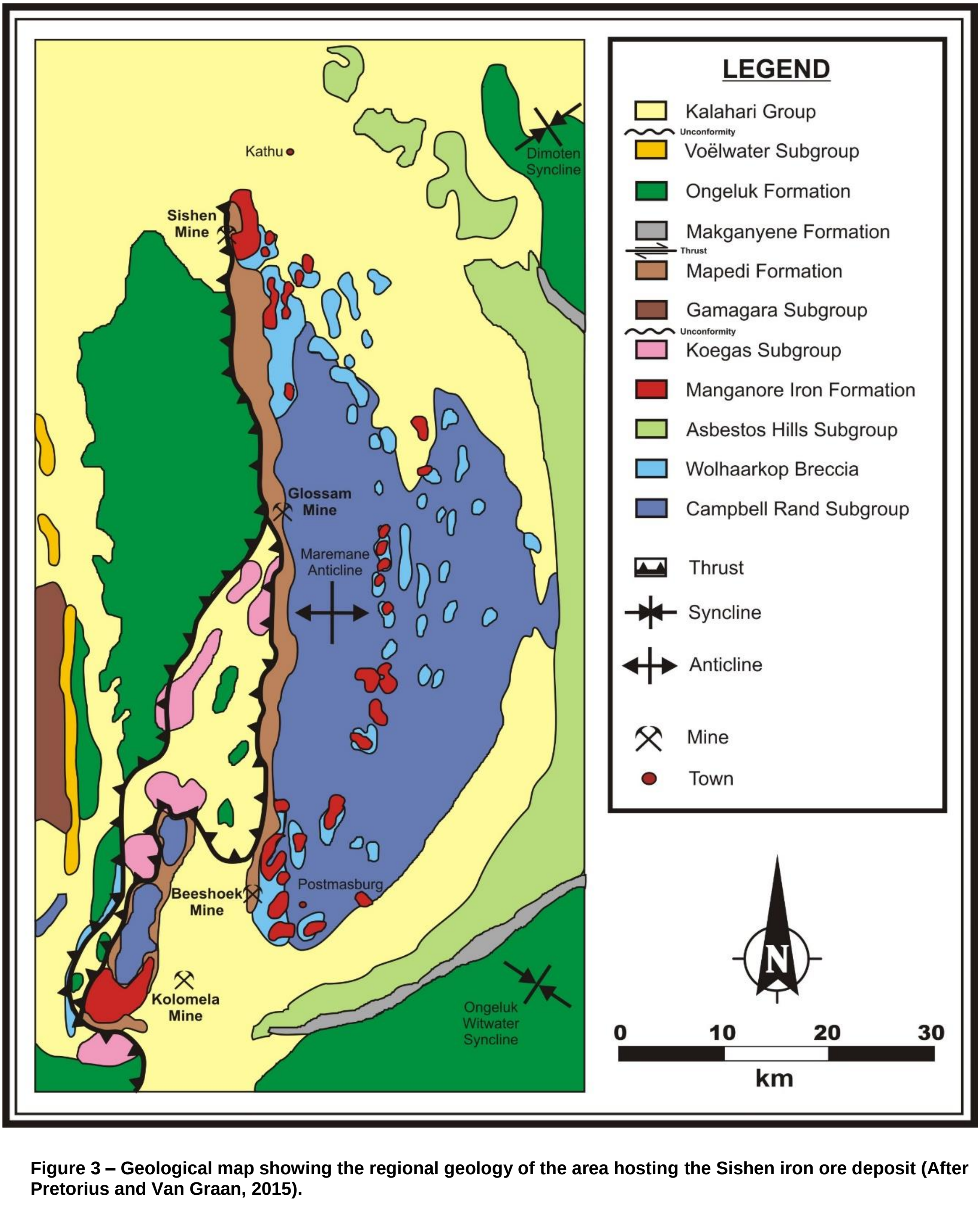


Figure 3 – Geological map showing the regional geology of the area hosting the Sishen iron ore deposit (After Pretorius and Van Graan, 2015).

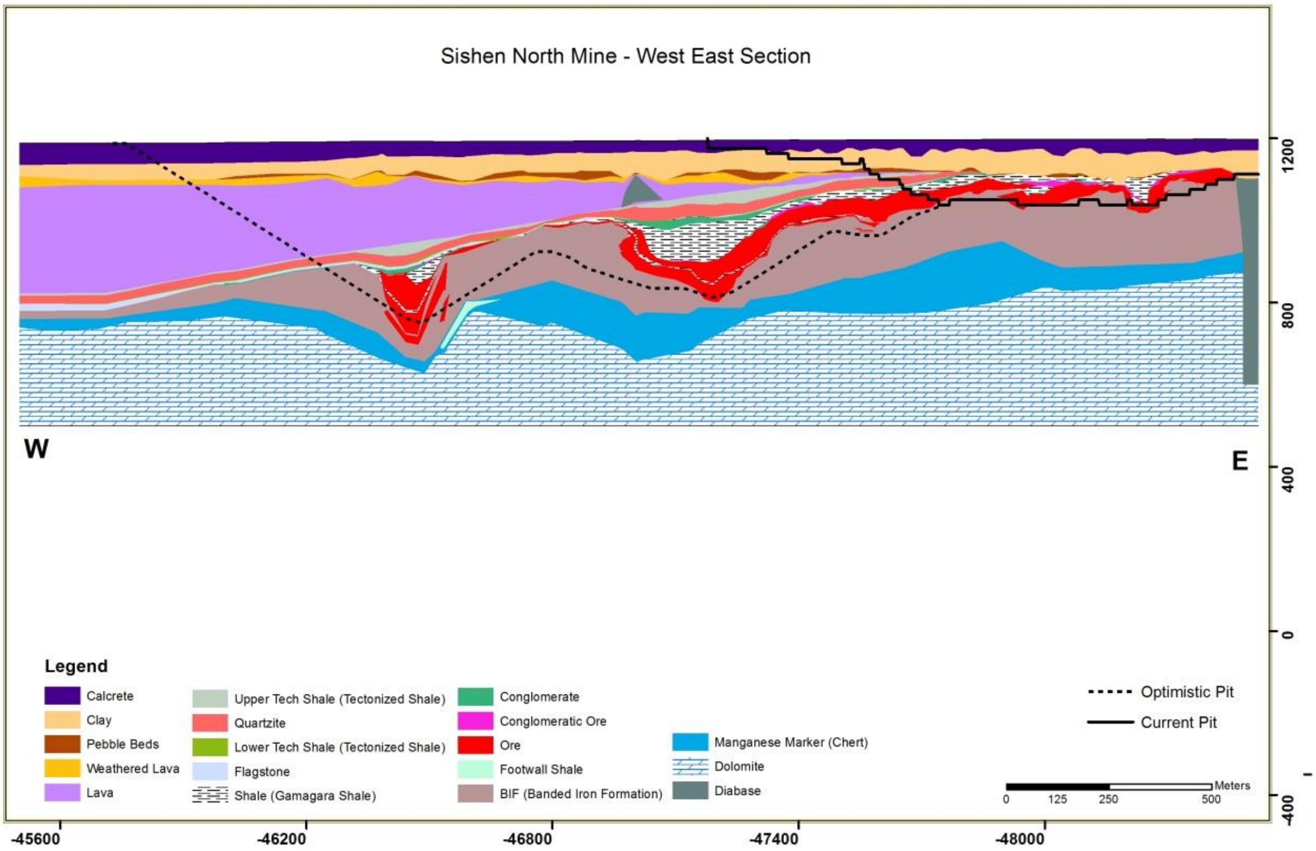


Figure 4 - W-E cross-section through Sishen North Mine (Pretorius and Van Graan, 2015).

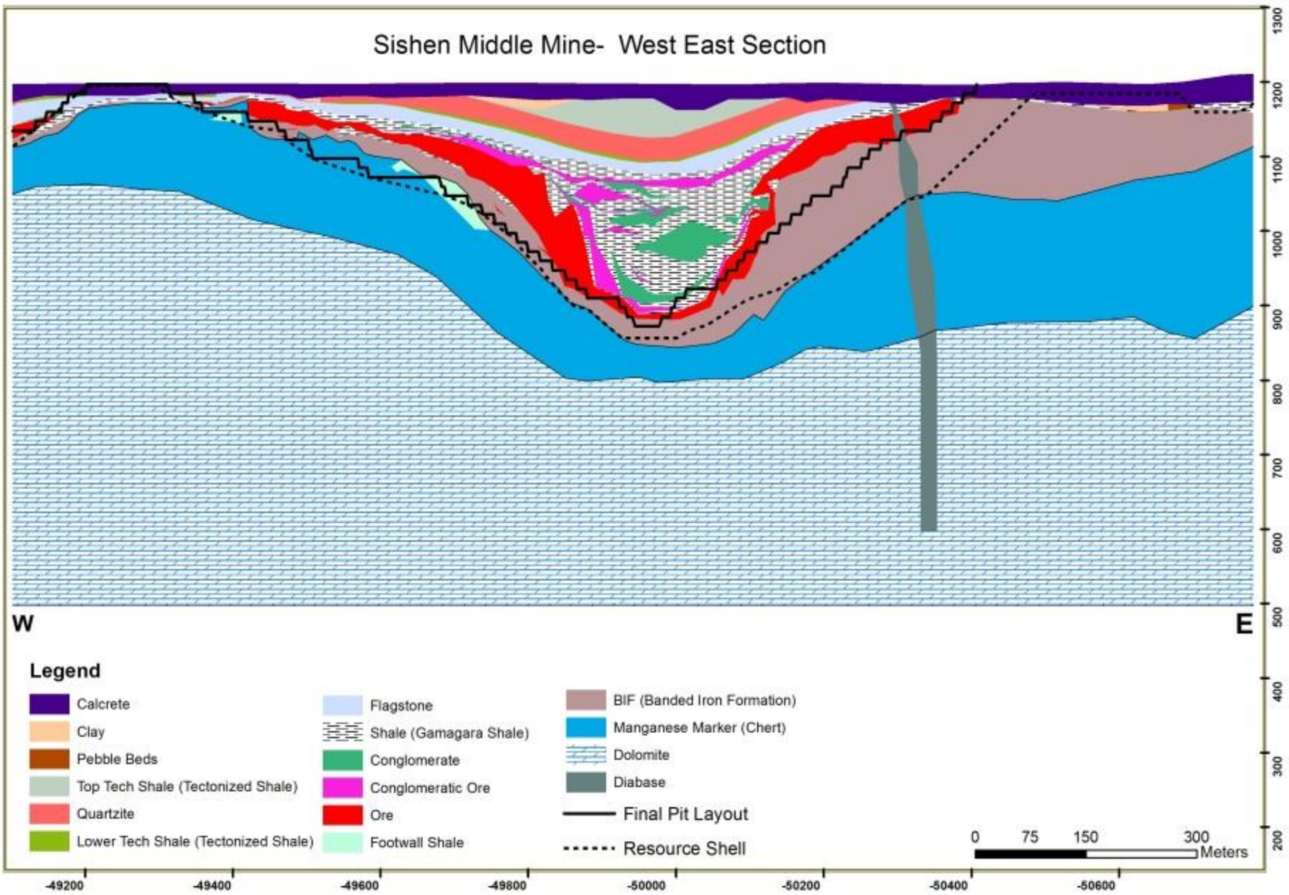


Figure 5 - W-E cross-section through Sishen Middle Mine (Pretorius and Van Graan, 2015).

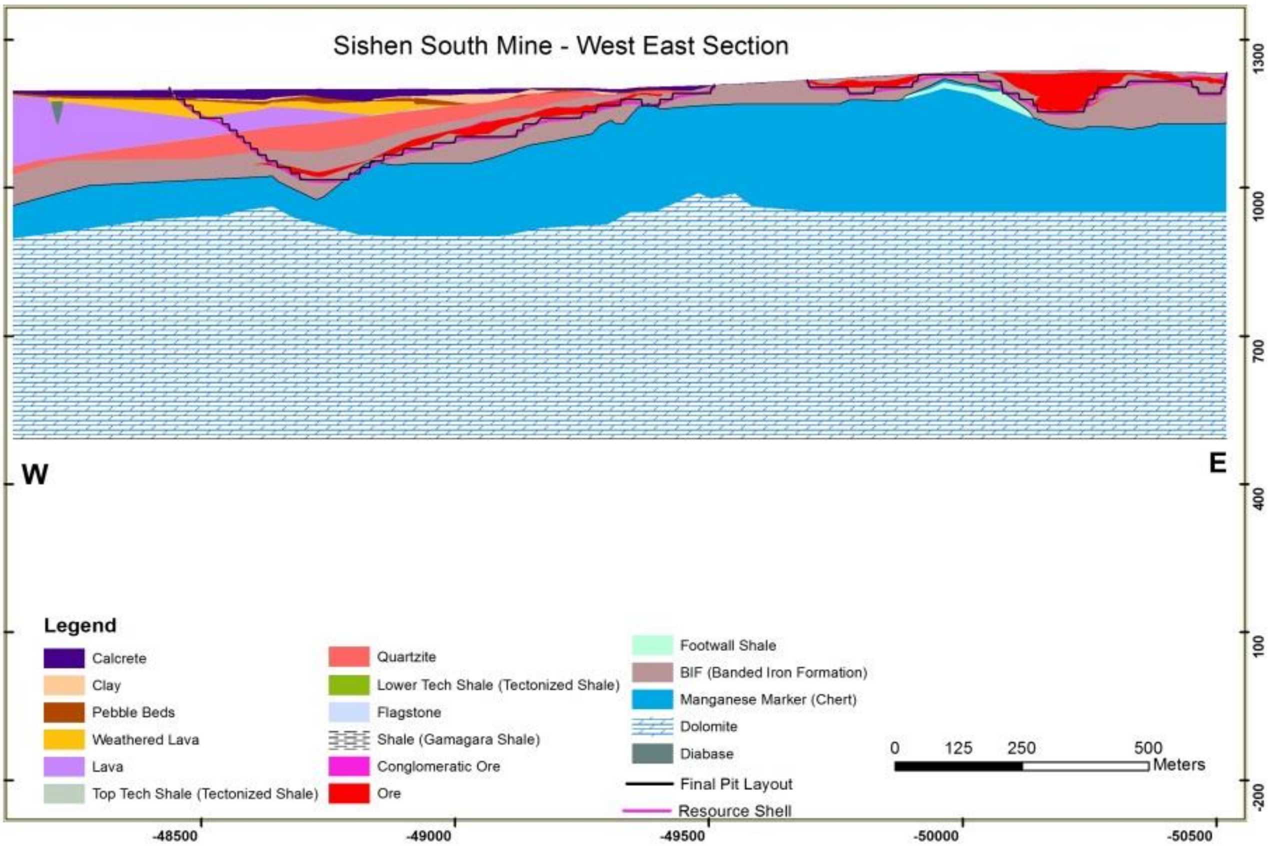


Figure 6 - W-E cross section through Sishen South Mine (Pretorius and Van Graan, 2015).

Genesis of High-Grade Hematite Iron Deposits

Most of the world's largest high-grade (60 – 70 wt per cent Fe) hematite deposits are the product of enrichment of Precambrian banded iron-formations (BIF) (Beukes *et al.* 2003). Iron ore deposits have a monomineralic composition, making it difficult to establish the exact process responsible for the enrichment (Beukes *et al.* 2003). Many deposits also have strong deformation and chemical weathering overprints that obscure the primary ore forming process (Taylor *et al.* 2001).

Three general genetic BIF-hosted iron mineral ore types are currently recognised, namely ancient supergene, hydrothermal and supergene-modified hydrothermal deposits (Beukes *et al.* 2003). The ancient supergene deposits, like the Sishen-type deposits in South Africa (Figure 7), is characterised by a downward grade profile into the unmineralised banded iron-formation host, and occur immediately below a major erosional unconformity.

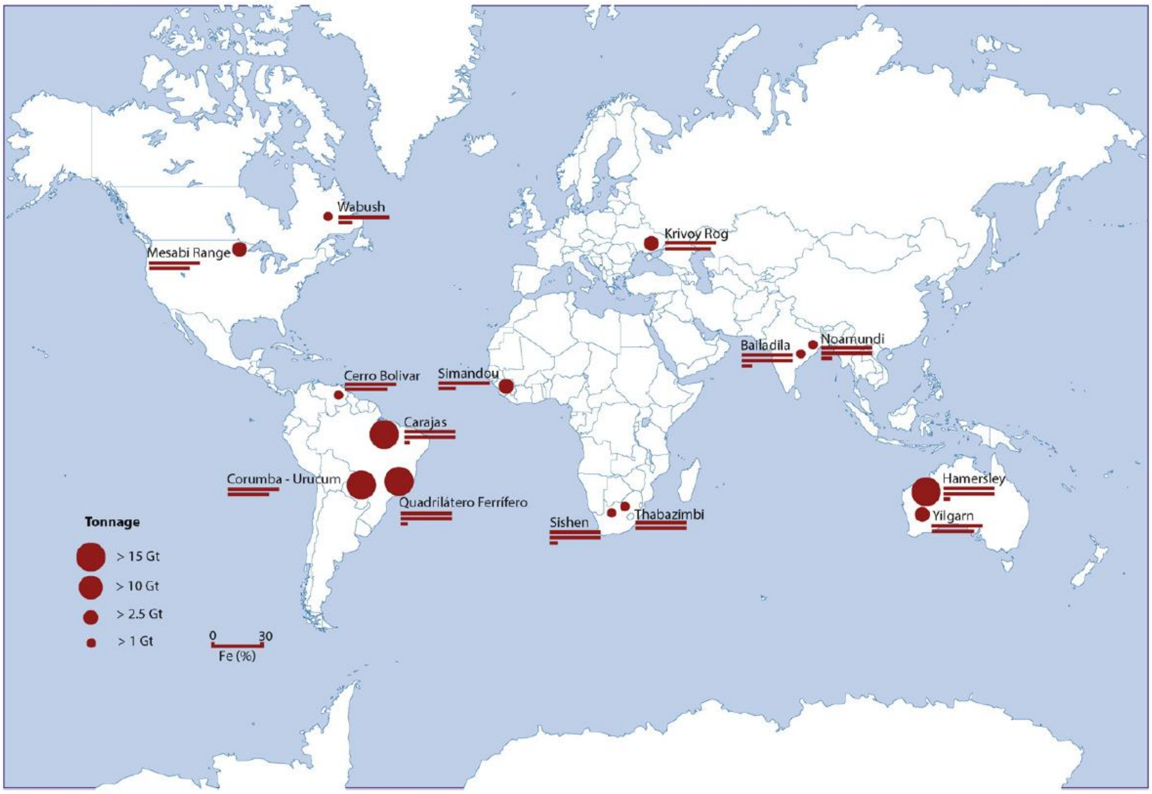


Figure 7 - Location of significant BIF-hosted iron ore districts and deposits. The size of the position indicator shows the tonnage size of the deposit. The cumulative length of the bar graphs beneath each locality indicates the Fe grade (Hagemann *et al,* 2016).

In contrast, the Thabazimbi deposit in South Africa and the Tom Price, Mount Whaleback, Paraburdoo and Newman deposits in Australia (Figure 7), have upward grade profiles with no association with any unconformity. These deposits are classified as hydrothermal ores (Beukes *et al.* 2003). Supergene-modified hydrothermal ores resemble large volumes of friable saprolitic ores that are derived from supegene enrichment of earlier hydrothermally altered iron-formation, next to hard high-grade hydrothermal hematite orebodies. Some of the best examples of supergene-modified deposits are the Quadrilátero Ferrifero and Carajas districts in Brazil and the Noamundi and Dalli-Rajhara districts in India (Figure 7) (Beukes *et al.* 2003).

The size of the deposits can vary considerably from super-large to small, depending on the geological setting and erosional preservation (Beukes *et al.* 2003) (Figure 7). Supergene-modified hydrothermal ores represent the largest deposits, with up to 13 billion tonnes of in-situ ore in the Carajas district. Ancient supergene ore deposits can also be very extensive, as in the case of the Sishen deposit which contain up to 2 billion tonnes of in-situ ore (Van Schalkwyk and Beukes, 1986). Hydrothermal ore deposits tend to be somewhat smaller, containing 0.9 – 1.4 billions tonnes of ore, a typical size of the Australian deposits of this type (Taylor *et al.* 2001).

Sishen Ore Genesis

The Sishen operation exploits four main textured high-grade, hematite ore types; massive, laminated, brecciated, and conglomeratic (Figure 8). The generally accepted model for mineralisation is supergene Fe-enrichment of the banded iron-formation hostrock, forming the high-grade laminated and massive ore types. Over millions of years, oxygen-rich surface water seeped down through the BIF, leaching the silica bands and replacing it with the iron-oxide mineral hematite (Figure 9) (Van Schalkwyk and Beukes, 1986). This process is evident in the occurrence of mineralisation being most prevalent in the upper part of the BIF, and mineralisation grade decreasing gradually downwards towards the footwall.

The conglomeratic ore horizon formed due to subsequent deformation processes of erosion and re-deposition of the massive/laminated ore horizon in tectonic activated graben, half-graben and basin structures (Figure 8) (Van Schalkwyk and Beukes, 1986). Lower grades of mineralisation are hosted in the footwall BIFs, and the Gamagara sediments of shale, conglomerate and flagstone.

A recent publication by Hagemann et al. (2016) emphasises the structural control on mineralisation in BIF-hosted iron mineralisation systems. Large-scale faulting and folding was essential for the creation of pathways for hypogene and supergene fluid movement, which are paramount for the enrichment process of the proto-BIF host to high-grade iron ore deposits such as Sishen (Hagemann *et al.* 2007, 2016).

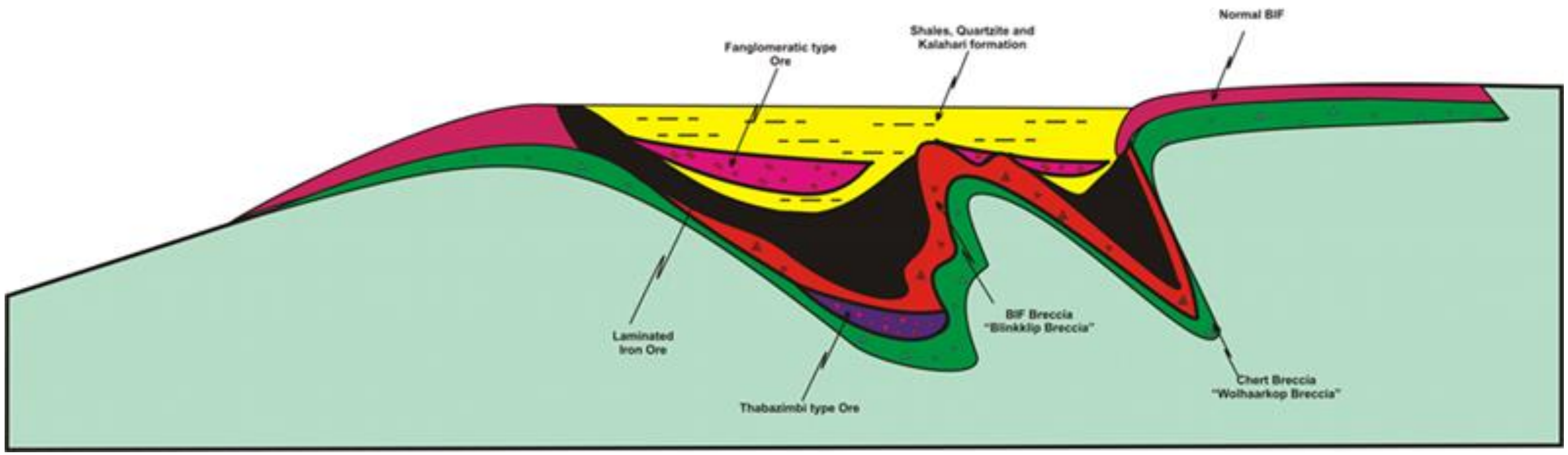


Figure 8 - Illustration showing the emplacement of the Sishen ore types (After Van Schalkwyk and Beukes, 1986).

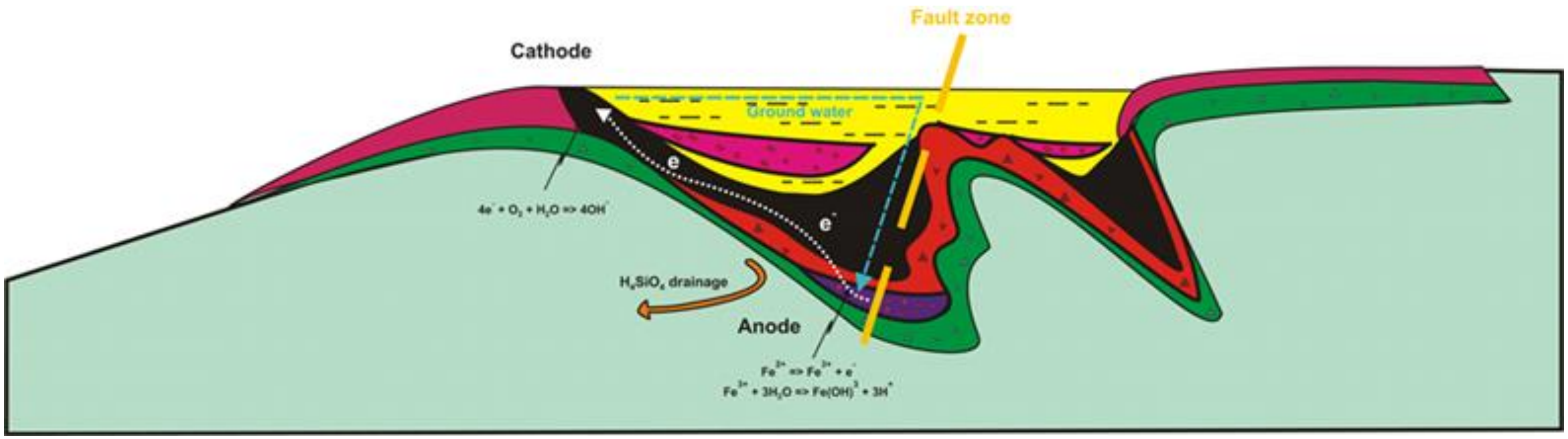


Figure 9 - Illustration representing the Sishen ore genesis (After Van Schalkwyk and Beukes, 1986).

Stratigraphic Sequence

The Sishen deposit is stratigraphically hosted in the Transvaal Supergroup. The floor rock consists of the Campbellrand Subgroup dolomites, which is overlain by a chert breccia known locally as the Wolhaarkop breccia, formed by karstification and paleo-sinkhole formation in the floor carbonates (Figure 10). After transgression of an inland sea, the Asbestos Hills Subgroup banded iron-formation (BIF) was deposited in a shallow sea environment. Later multiple tectonic episodes deformed the unit extensively, producing a brecciated and folded rock package, more so towards the footwall of the unit (Van Schalkwyk and Beukes, 1986). A mafic intrusive unit appearing as a sill, known locally as bostonite, intruded into the BIF, often being intersected at the contact between the main ore mineralisation and the BIF footwall. Although appearing in highly altered form as part of the Sishen deposit, there seems to be some correlation between this unit and the more extensive gabbro intrusive body at the Kolomela Mine, 80km south of Sishen (De Kock, 2013).

After chemical sedimentation ceased, clastic sedimentation processes deposited the Gamagara Subgroup, comprising of shale, conglomerate, flagstone and quartzite (Van Schalkwyk and Beukes, 1986). These stratigraphic sequences are buried by overthrusted andesite (locally referred to as lava), with lenses of diamictites at the thrust surface. Thin diabase dykes hosted within north-south trending normal faults intersects all the stratigraphic units up to and including the andesite.

Finally Karoo Supergroup sediments of Dwyka tillite and shale, and recent Kalahari Group units of pebblebeds, clay and calcrete form the rest of the Sishen orebody overburden (Van Schalkwyk and Beukes, 1986) (Figure 10).

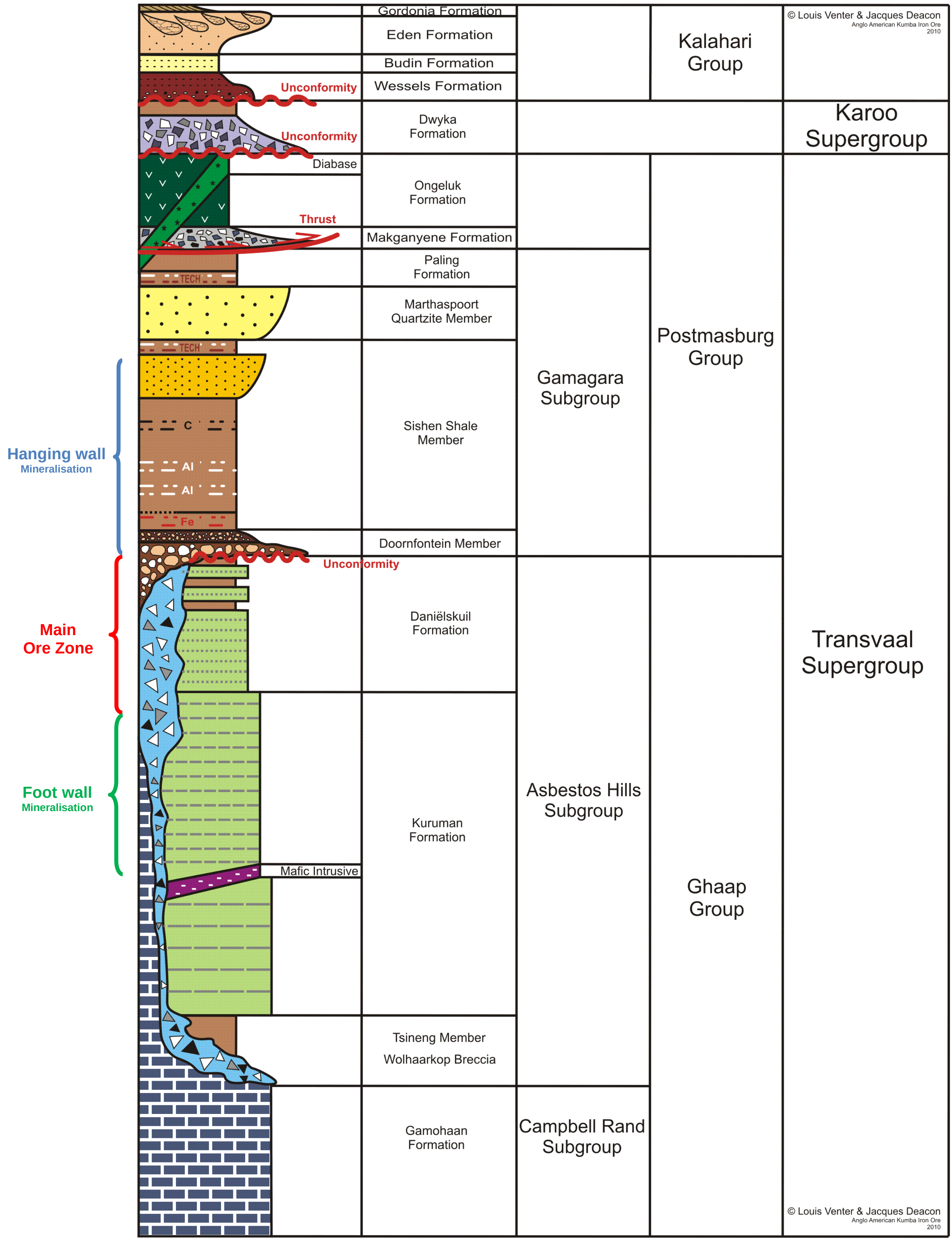


Figure 10 - Stratigraphic sequence of the Sishen deposit (Deacon, 2011).

2.2.2. Mining and Beneficiation

Sishen is an exclusively open-cast operation. The pit-layout extends for about 12km North-South and 3km East-West (Pretorius and Van Graan, 2015). Mining takes place in multiple smaller mining pits, with the main mining areas being referred to as North Mine, Middle Mine and South Mine (Figure 11).

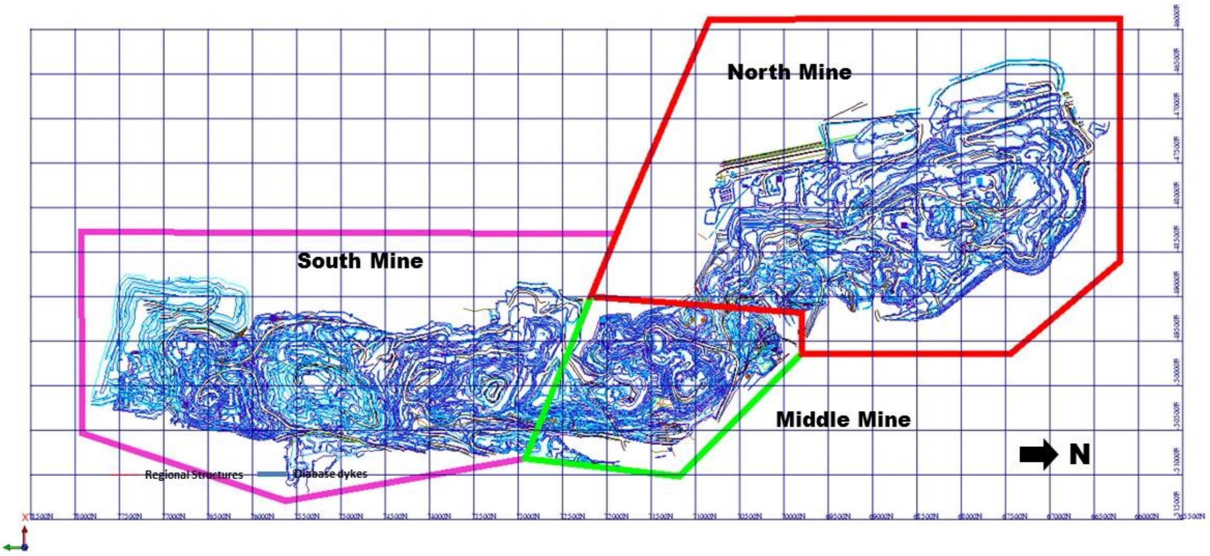


Figure 11 - The Sishen mining pit, subdivided in North Mine, Middle Mine and South Mine.

The open-cast mining process entails topsoil removal, drilling and blasting of rock (ore and waste) and hauling of material out of the pit. Waste rock is hauled to the nearest waste dump or back-filled in areas where no further mining will take place. Ore material is hauled directly to the beneficiation plants or stockpiled in accordance with the direct blending needs of the beneficiation plants.

Beneficiation of ore material takes place in two plants, namely the DMS plant and JIG plant. After the material is crushed, washed and screened in different size fractions, the lower-density waste component of the ore material is removed by either suspension within a high-density medium (ferrosilicon) in the DMS process or by segregation principles in the JIG process (Pretorius and Van Graan, 2015).

Different size fraction and grade products aligned with client requirements are produced. The individual production beds are stockpiled before being reclaimed and loaded on freight trains for transport to the local steel mills or internationally via the Saldanha port (Pretorius and Van Graan, 2015).

Sishen currently aims to produce 28.5Mt of product in 2017, with roughly two-thirds (2/3) being produced from the DMS plant and one-third (1/3) from the JIG plant. Two modules for Ultra High-Density Medium Separation (UHDMS) beneficiation are also currently being tested on the JIG discard material to determine the effectiveness of this beneficiation technique on lower Fe-grade run-of-mine (ROM) material not currently utilised in either the DMS or JIG plant.

2.3. Sishen Resource Definition

2.3.1. Geological Data

Drilling Data

The main source of data used for resource definition at Sishen Mine is drilling data. Sishen Mine commissions various phases of drilling to ensure appropriate drill data coverage for resource confidence at the specific stage of the project (Figure 12).

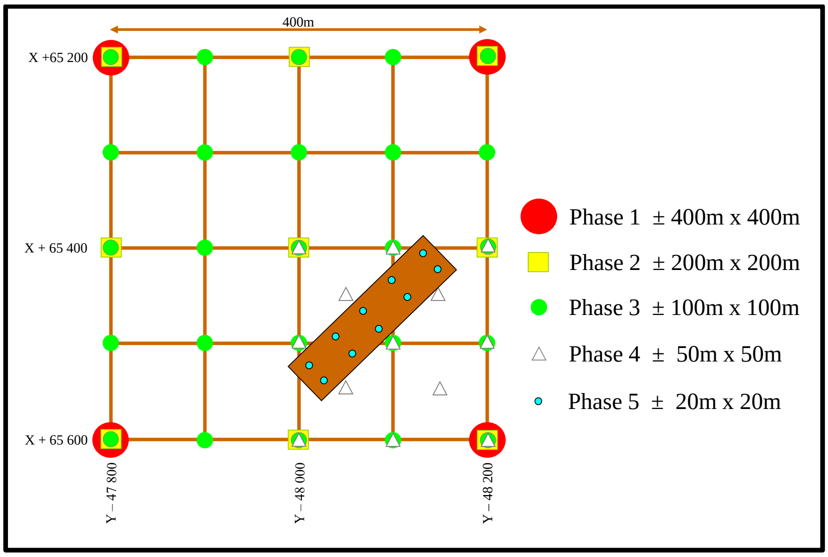


Figure 12 - Drilling phase grids employed at the Sishen operation (Pretorius and Van Graan, 2015).

As can be seen in Figure 12, the drill grid spacing decreases with subsequent drilling phases. Phase 1 exploration drilling is the first grid size, used to identify new orebody targets. It is also used for geotechnical stability surveys for planned infrastructure development such as waste dumps, road, rail and building structures. Subsequent, infill exploration drilling with decreasing grid sizes, through phases 2-4, deliver more extensive data coverage on the identified orebodies. For resource definition requirements, the aim is to maintain a phase 4 drilling density over the planned reserve shell area (final pit design), and phase 3 or 2 drill density for the extended resource shell (optimistic pit design). Phase 5 infill drilling is regarded as a grade control function, taking place within the active pit area to provide additional data for mining activities at the production stage.

Drilling Method

Phase 1 – 4 exploration drilling (Figure 12) is performed from surface. Each new drillhole is piloted through waste rock lithologies by percussion drilling until the Gamagara quartzite or shale marker units is reached. Subsequent diamond drillcore drilling then commences, producing a representative drillcore sample of the orebody intersection. This practice increases the rate of drilling and saves costs, as the waste rock is quickly traversed while still maintaining the best drilling and sample quality through the orebody intersection.

Current protocol dictates the complete intersection of the orebody; with drilling only ceased once the chert breccia - or dolomite floor rock is reached. Many historic drillholes however were drilled under other protocols with different purposes; like intersecting only the high-grade ore or drilling to a pre-determined length below the high-grade ore footwall before drilling is terminated. These practices created risk concerning the displacement and grade characteristics of the low-grade footwall units, especially in the BIF unit.

To ensure the correct geo-location of orebody samples (drillhole intersections), current protocol dictates the comprehensive surveying of the drillhole path of all exploration drillholes longer than 250m or which have intersected more than 3m of high grade ore. Unfortunately many historic drillholes were not surveyed; with the drill path of these drillholes reduced to a straight trace line from its surveyed drill-collar starting position to final depth.

Phase 5 infill drilling (Figure 12) is performed by reverse circulation method, which has a high penetration rate, essential as these drilling activities take place within the active mining pit.

Logging and Sampling

The logging of drilling material (percussion rock chips and diamond drillcore) takes place continuously as new data are generated. To prevent logging and sampling errors, data capturing takes place directly into a geological database (AcQuire), using standardised codes for lithological units, weathering/alteration and structural features.

Sampling protocol of drillcore entails the splitting of the material by means of diamond blade saw cutting, subjecting one-half of the material for chemical analysis, with the other half being archived. Sample intervals may not extend over clear lithological contacts or where the core material is lost during drilling. Samples should have a maximum and minimum length of 3m and 0.4m, respectively. Sampling should cover the complete orebody, which may extend from the flagstone to BIF. Waste rock contact samples should be taken on either side of the mineralised zone, or if the sampling was intermittent. Percussion rock chip samples are compiled as 3m composite samples, provided no change in lithology is observed.

Historic sampling was biased towards the high-grade ore material and where clear Fe mineralisation was visible. This selective sampling practice led to the sampling populations of lithological units to be utilised as low-grade run-of-mine (ROM) material being unrepresentative and biased towards a higher-grade. To mitigate this risk, an extensive resampling process was launched (Deacon, 2011), which entailed the sampling of all low-grade archived drillcore available at Sishen mine.

Geochemical Analysis

For the iron-based orebody, an element suite of Fe, SiO_2, Al_2O_3, K_2O, P, Mn, MgO, TIO_2, S and V_2O_5 are analysed for. Prior to 2010, the analysis of exploration samples took place on-site by means of X-ray fluorescence (XRF) from a pressed pellet prepared sample, while the RD (relative density) was determined by means of a minidens technique. Historically (pre-1990), RD was not measured, but determined by means of a formula, based on the assumption that RD is a function of the degree of mineralisation of the heavy element Fe.

Since 2010, the analysis of exploration drilling samples is performed by the Anglo Research Lab, using the X-ray fluorescence (XRF) analytical technique from a fused bead prepared sample. The RD (relative density) for each sample is determined by the use of a pycnometer.

Phase 5 grade control and blast-hole samples are analysed on-site by the automated Robolab system ensuring a quick turnaround time for mining production needs.

Quality Assurance and Quality Control

For QA/QC purposes, batches of samples subjected for analysis to the lab include random control samples, comprising a blank, duplicate and standard reference material sample. After analysis these control samples and validated against set specifications, determining whether the entire batch's analyses can be accepted or rejected. Rejected batches are re-analysed, while accepted batches' individual samples are subjected to sample-based QA/QC. The responsible exploration geologist will validate each analysis against the geologic log. If a clear discrepancy between the chemical analysis and logged geology is observed, it might indicate an analytical error of the sample and it is re-analysed. Once all the analysis for a particular drillhole is received and validated, the drillhole is signed off as completed.

2.3.2. *Other Geological Data*

Geophysics

Multiple regional geophysical surveys were compiled over the years for Sishen and its surroundings. This data indicates large-scale structures and intrusive bodies which impact the emplacement of the orebody. Figure 13 indicates how structurally complex the Sishen prospect is. These structures may have played a major role in the mineralisation process and orebody preservation (Basson *et al*, 2017). It is thus of paramount importance to include this information in the geological modelling and resource evaluation processes. Effective modelling of structurally complex orebodies using traditional wireframing is very challenging. Currently, interpretations of geophysical survey data are only used as guidance during the geological modelling process.

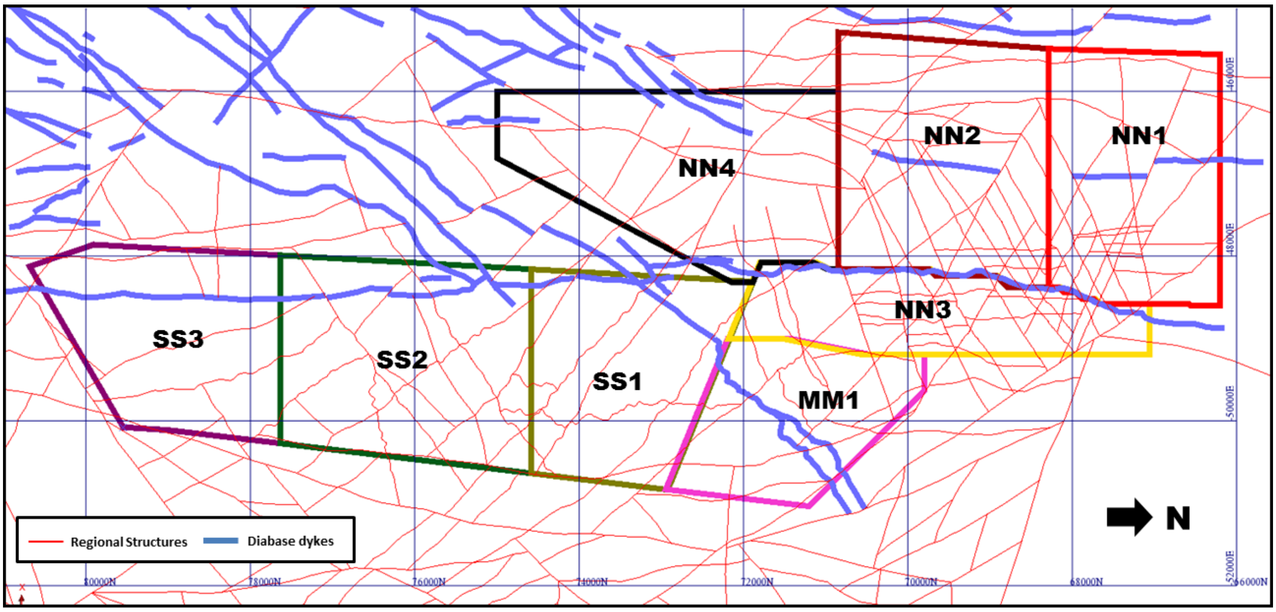


Figure 13 - Interpretation of geological structures (faults) and intrusive bodies (diabase dykes) from regional geophysical survey data (modified after Basson *et al,* 2017).

Geological Mapping

Mapping data has different applications at Sishen Mine. Geotechnical pit-mapping is critical to ensure high-wall safety. Geological bedding dip and dip direction, as well as geological structures (faults) locality and orientation (Figure 14), play a major role in defining the risk associated with the open pit mining process (Figure 15).

Pit mapping is exclusively used during the grade control process for the effective production blast block demarcation process. Figure 16 shows the geological composition of a typical mining bench at Sishen. Notice the emplacement and orientation of the geological contacts on the mining face. The insert on Figure 16 shows how these geological contacts dictate the final resource definition of the production blast block. Because the scale of mining is the all-inclusive mining bench, different types of material and the relative fractions of ore versus waste on the mining bench command the final classification of the ore material for optimal resource utilisation.

From this example, it is clear just how important accurate prediction of geological contacts are. The geological model should be locally representative of these geological controls at mining scale. The Sishen resource definition is hugely dependent on accurate, high density geological data and an efficient, dynamic geological wireframe model which can support such a process.

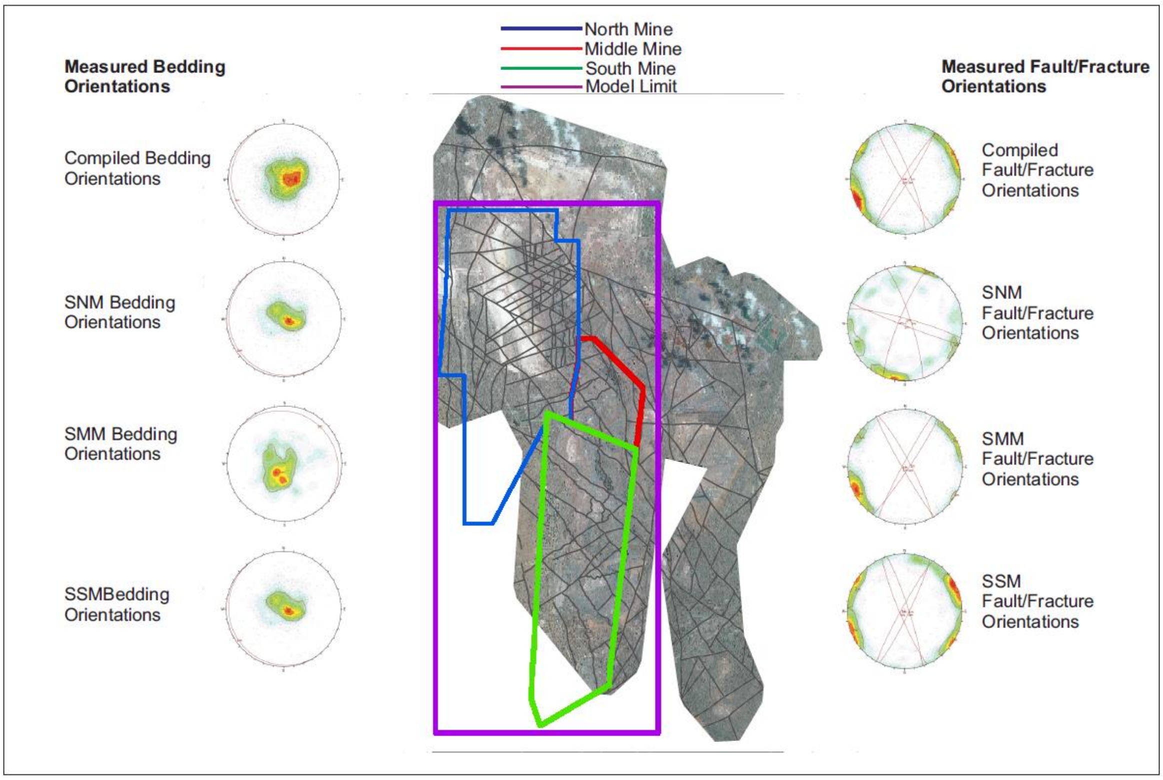


Figure 14 – Geotechnical map showing the geological emplacement characteristics and the orientation of main structural features of the Sishen pit area (Anthonissen *et al,* 2016).

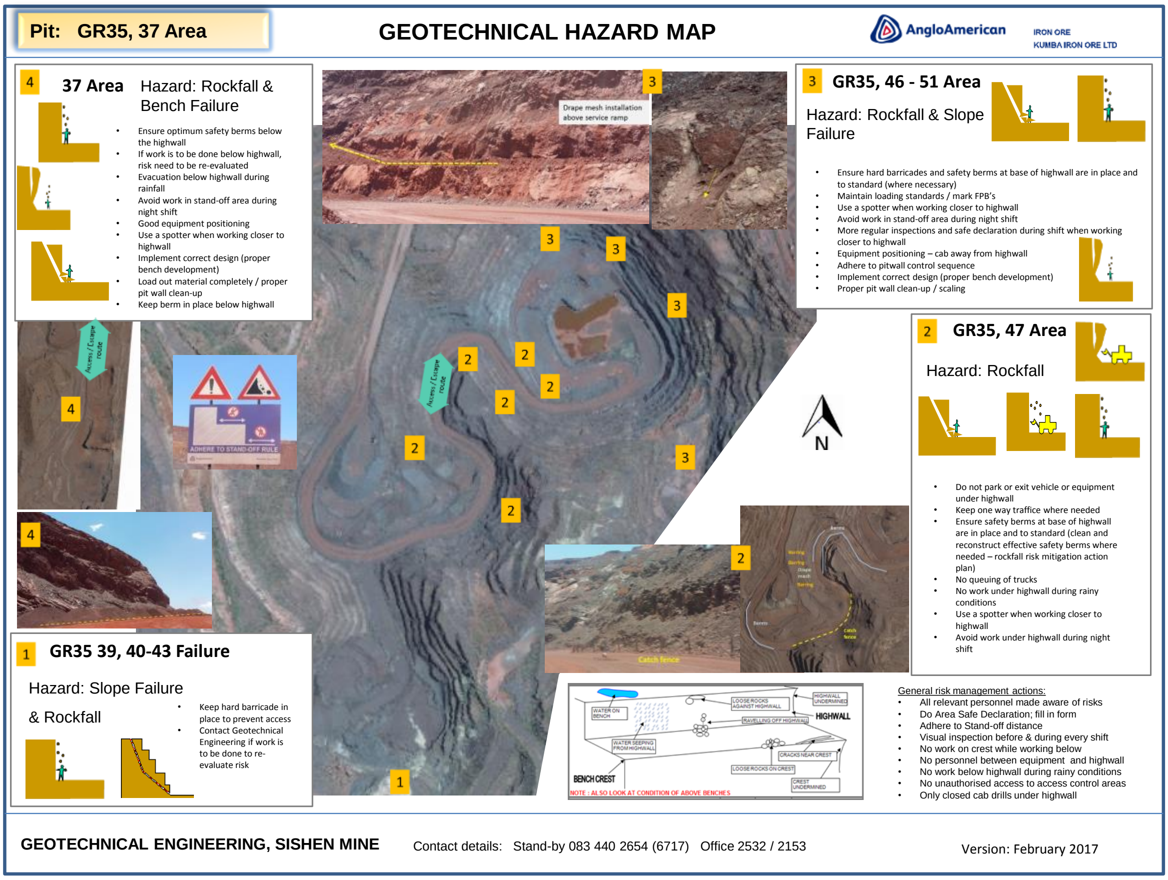


Figure 15 – Geotechnical risk map of Sishen Middle Mine (Carey, 2017).

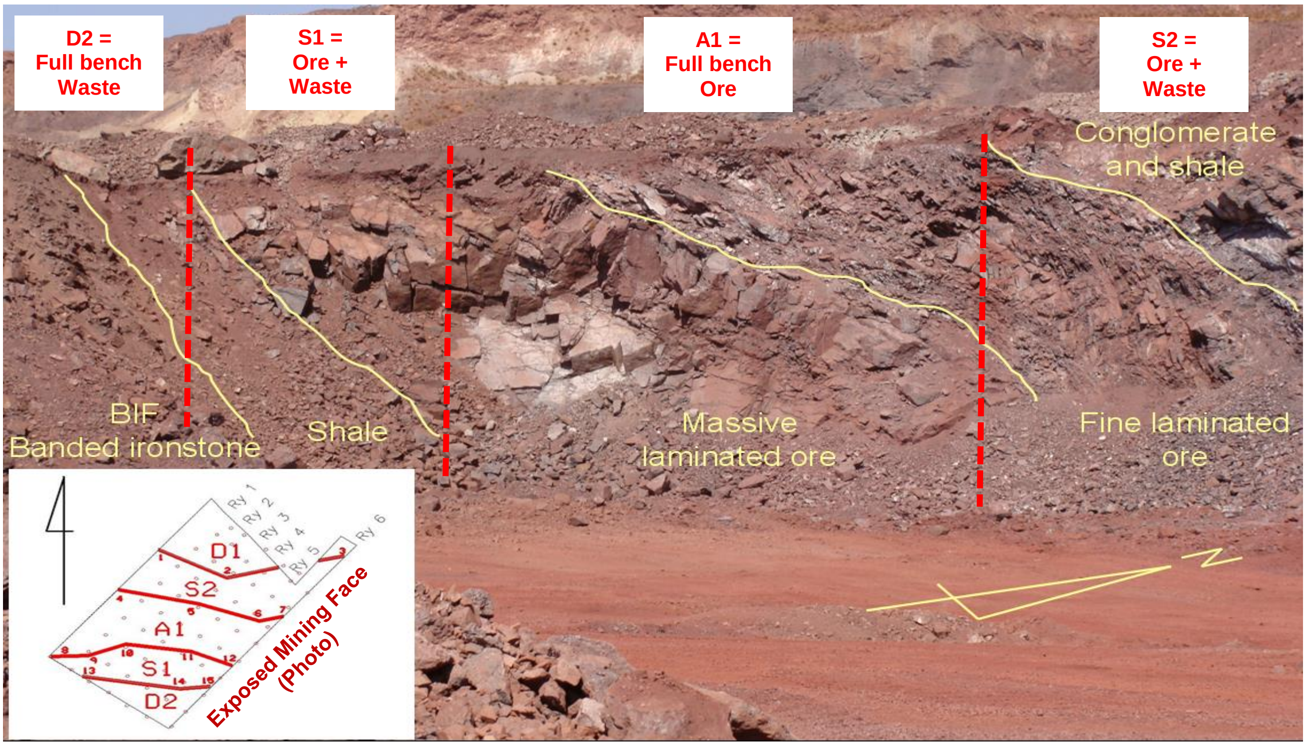


Figure 16 – Application of geological pit mapping and resource definition at Sishen Mine. Insert show the resource classes defined on the blast block (after Vorster, 2011).

2.3.3. Geological Modelling

Traditional Explicit Wireframe Geological Model

The geological wireframe models for the Sishen deposit are constructed explicitly in Geovia Surpac®. For resource estimation and reporting purposes, the complete model is revised and updated on an annual basis. The update process entails reviewing new drillhole information and reinterpreting the geology in the locality of new information. The wireframes are deconstructed and the new drill contacts added as new surface elements before the model is manually interconnected to create an updated geological model. For practical modelling, the stratigraphic sequence is subdivided into 18 distinguishable modelling units (Figure 17).

Sishen Geologiese Segment Indeling - Geological Segment Division				
Seg -	Kode	Gesteentenaam -	Material type	Geological codes (acQuire/Surpac View)
19 -	lug	Geen inligting -	No Information	NI ; SCR
3 -	kk	Kalkreet -	Calcrete	CC ; FER ; GRV ; LIM ; SLT ; MDS ; MUD ; SD ; SL ; LST
4 -	kl	Klei -	Clay	CL ; TAL ; TUF
5 -	rol	Rolsteen -	Pebblestone	PEB
6 -	lav	Lawa Verweerd -	Lava Weathered	LAW
7 -	law	Lawa -	Lava	LAV ; AGL ; DMT ; SHD ; TIL
11 -	skb	Skalie bo Kwartsiet -	Shale above Quartzite	SH ; SHT
8 -	kwt	Kwartsiet -	Quartzite	QTZ ; SST ; VQ
16 -	sko	Skalie onder Kwartsiet -	Shale below Quartzite	SH ; SHT
9 -	pe	Plaveisteen -	Flagstone	FLS
17 -	sk	Skalie -	Shale	SH ; SHA ; SHC
10 -	kgt	Konglomeraat -	Conglomerate	CGT ; CGB ; GRS
2 -	ekg	Konglomeratiese erts -	Conglomeratic ore	HC ; HG
1 -	ert	Erts -	Ore	HB ; HD ; HL ; HM
12 -	ly -	Lintyster -	Banded Iron Formation	BIF ; BIB
18 -	skv	Vloer skalie -	Floor Shale	BOS ; SH ; SHF
13 -	mm	Mangaanmerker -	Manganese Marker	MN ; CBR ; CH ; CHM ; FEM ; SHM ; WAD
14 -	dol	Dolomiet -	Dolomite	DOL
15 -	di	Diabaas -	Diabase	DI ; DIO ; DLT ; GAB ; SDT
20 -	xx	Struktuur interpretasies	Structural intepretation	FFF

Figure 17 - Geological units modelled in the Sishen wireframe model (Pretorius and Van Graan, 2015).

Current modelling convention entails that models of the continuous, stratiform units such as BIF, shale and quartzite, are built as digital terrain models (DTMs) surface wireframes at the footwall of the unit. Erratic, discontinuous units such as conglomerate beds and ore units are built as enclosed, solids object wireframes (3DMs) as shown in Figure 18.

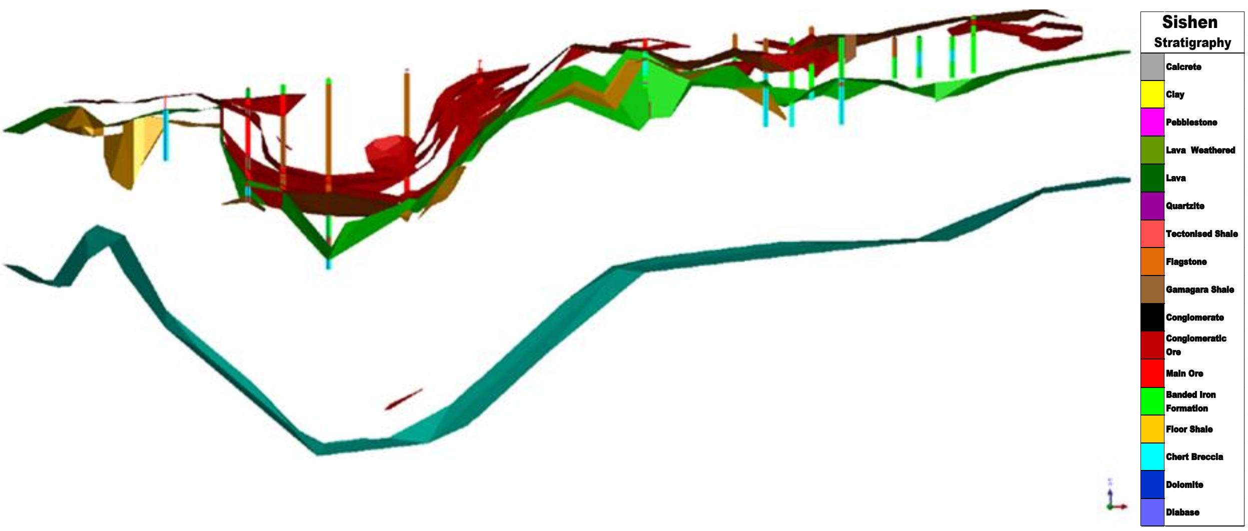


Figure 18 - A typical W-E cross-section through the Sishen explicit geological wireframe model.

The current Sishen geological explicit wireframe model has limited structural interpretation. Models are manually offset and constrained locally where structures are inferred from input drillhole data, or where regional structural data are indicative of such features. The geological structures such as faults are however not categorically created as surface objects during the modelling process, with no subsequent explicit effect on the geological model (Figure 19). As discussed earlier in this report, implicit modelling shows the ability to model structural complexity more efficiently.

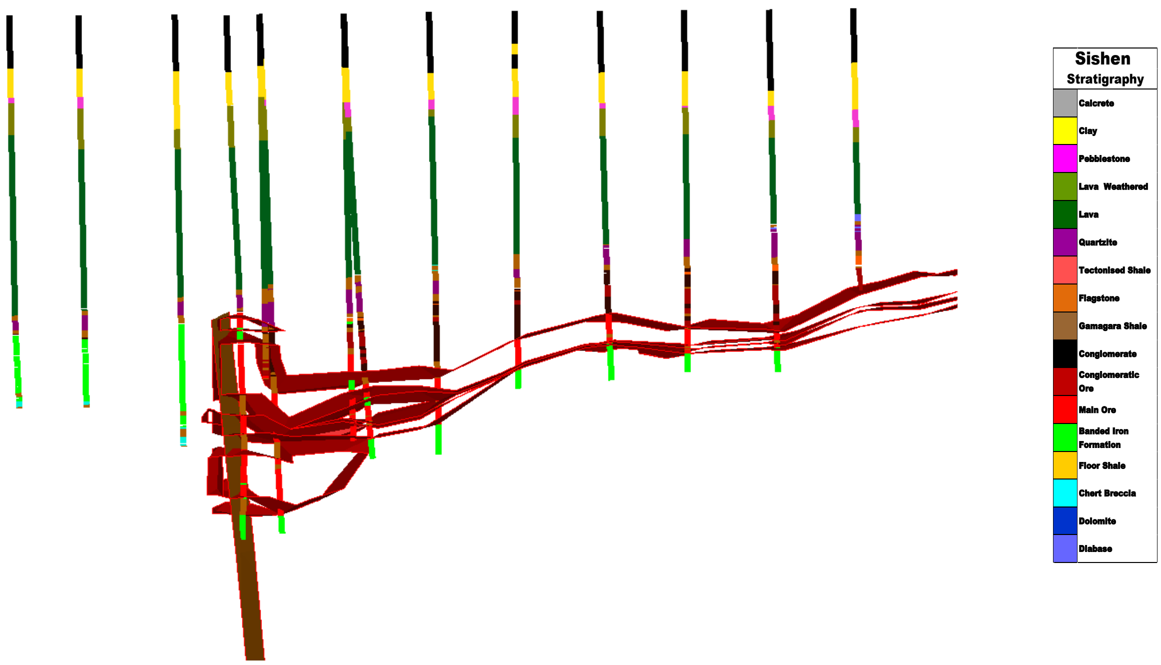


Figure 19 – Cross-section indicating how the main orebody (red) is locally constrained to a large geological structure (fault) derived from regional geophysics (brown).

The current Sishen explicit geological modelling procedure follow basic ore-modelling focused guidelines (Cloete, 2017). No ore interpretation is to be extended further than 50m beyond current supporting borehole information, unless geological continuity can be confirmed (e.g. geological mapping) and interpretations can be extended up to 200m. Ore above the 25 meter horizon (imaginary horizon 25m below the lower boundary of the main orebody) with a thickness of 3 meters or more has to be modelled. Ore below the 25 meter horizon with a thickness of more than 6m has to be modelled. Any waste inside the ore body has to be modelled, except if the waste intersection is isolated (no connectable unit within a 50 m radius parallel to intersection).

To maintain the quality of the geological model and to evaluate changes and additions made during the updating period, new model versions are subjected to a peer-review panel on-site (Figure 20). The final accepted version is signed-off by the panel and competent person before use in the resource definition process.

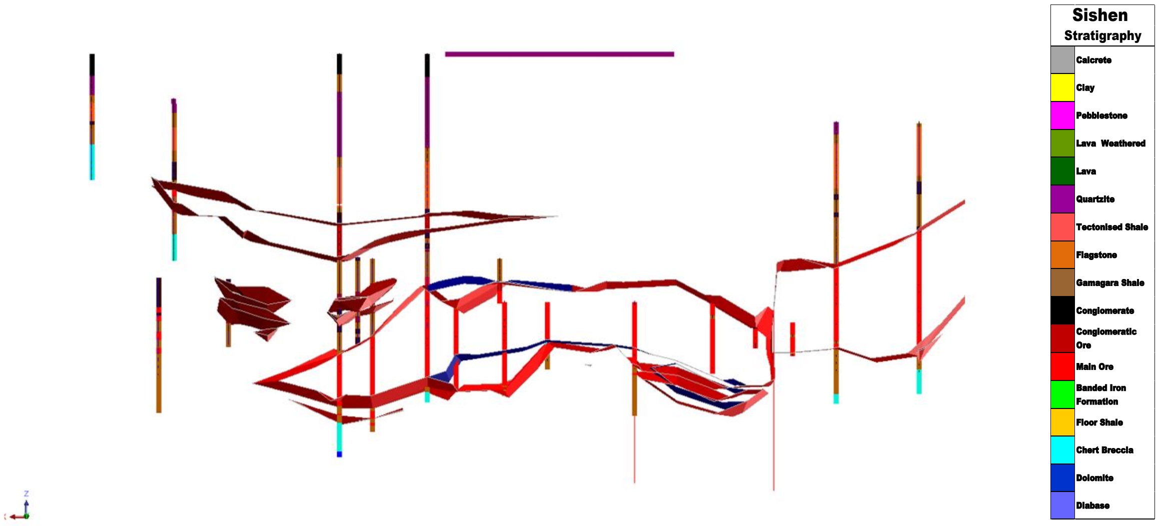


Figure 20 – Cross-section indicating how the geological ore model was updated from the previous version (blue) to the new proposed version (red) as a function of the additional drilling data (Middle Mine area).

Implicit Geological Model

To overcome the shortcomings of the traditional wireframe model, Sishen commissioned the construction of a Leapfrog Geo® implicit model by an independent consultant (Tect Geological Consulting). The Sishen orebody is structurally very complex. These structures have a strong control over mineralisation. Emphasis was thus placed on establishing the structural framework of the deposit through rigorous structural mapping (Figure 21) and digital fault-network construction (Figure 22). This structural framework defined discrete domains (fault-bounded blocks – Figure 23) for the implicit geological model. The lithological succession was subsequently constructed in each domain from the available drillhole information. This type of geological model based on first order structural modelling (*tectonostratigraphic modeling)* can be categorised as a fully-constrained litho-structural geological model (Anthonissen *et al,* 2016).

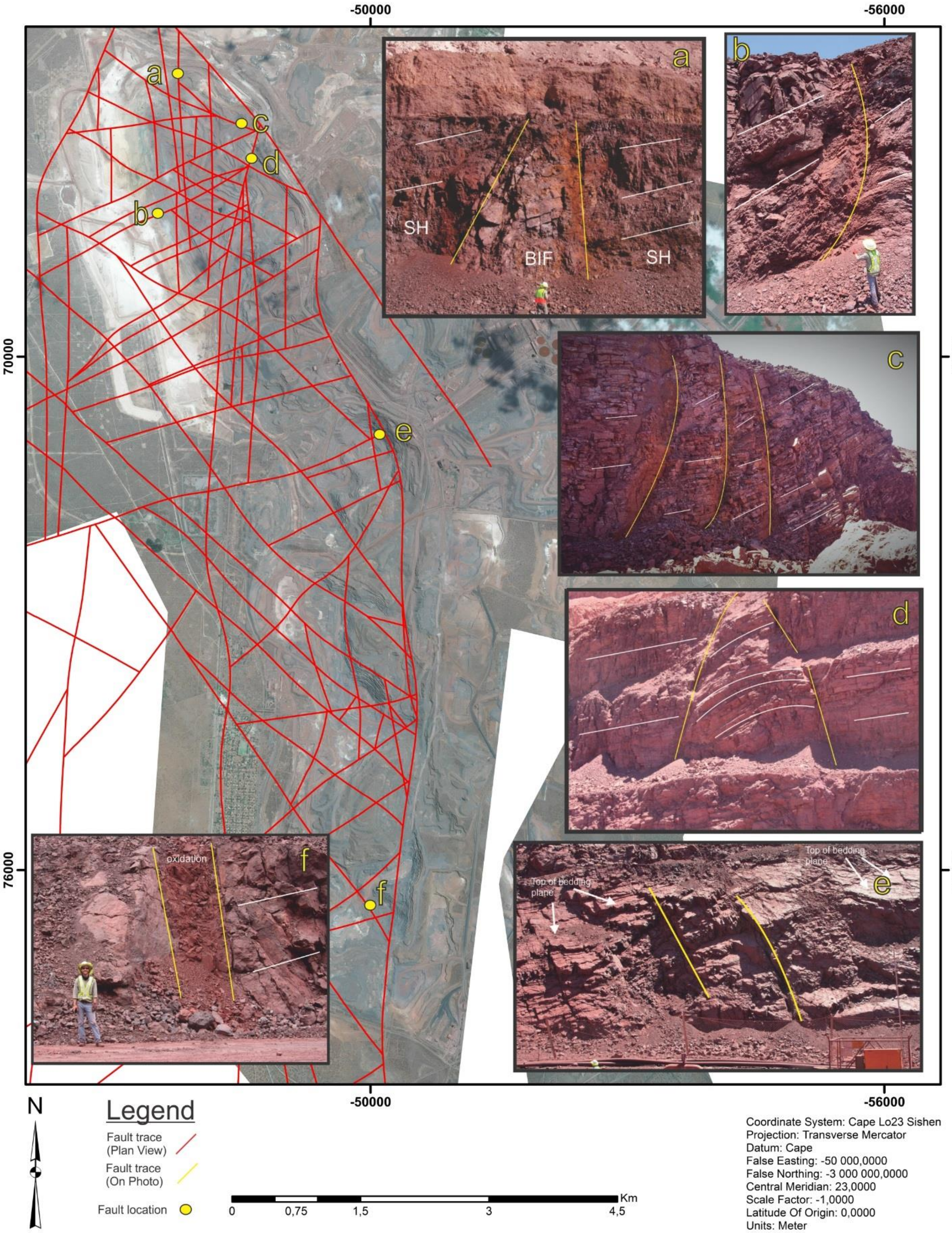


Figure 21 – Structural pit mapping and fault network of Sishen Mine (Anthonissen *et al,* 2016).

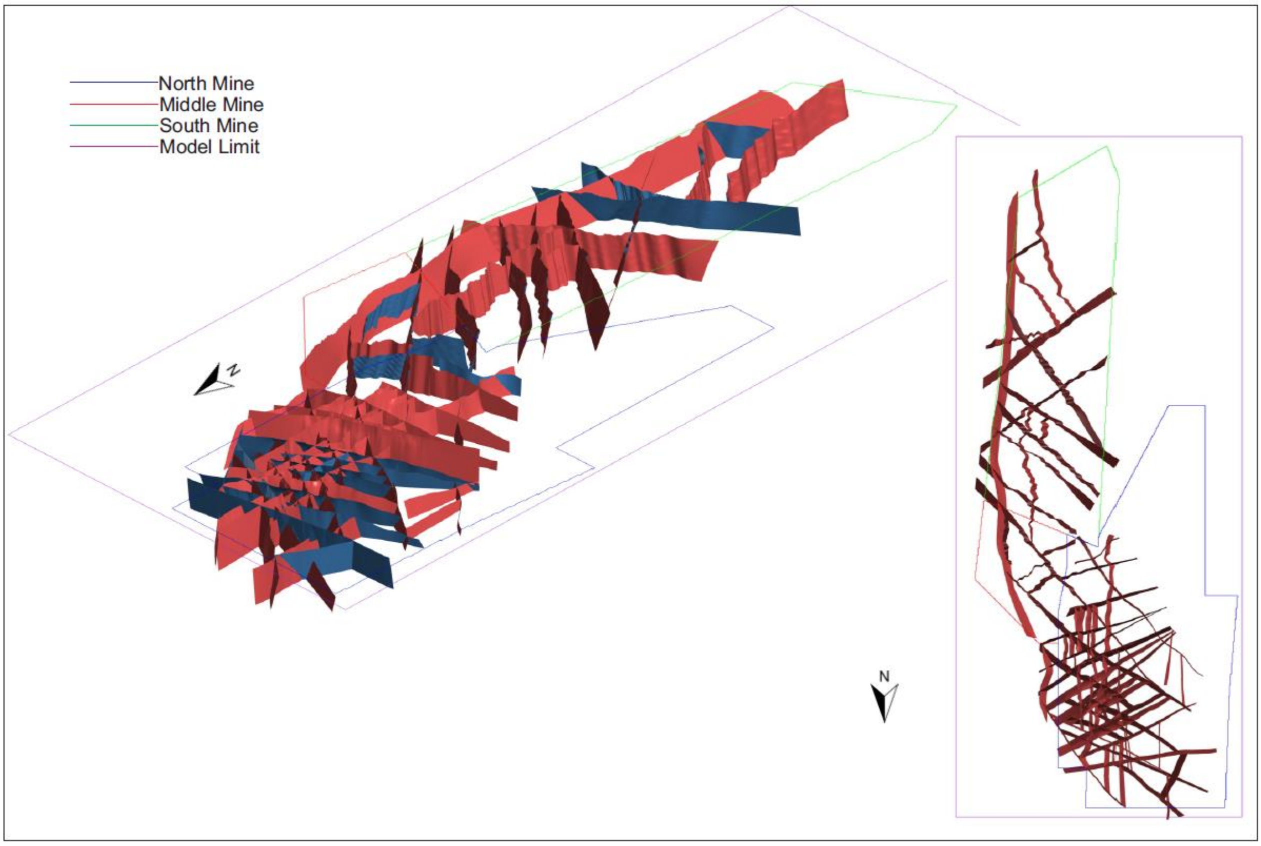


Figure 22 - The digital structural framework of the Sishen iron ore deposit (Anthonissen *et al,* 2016).

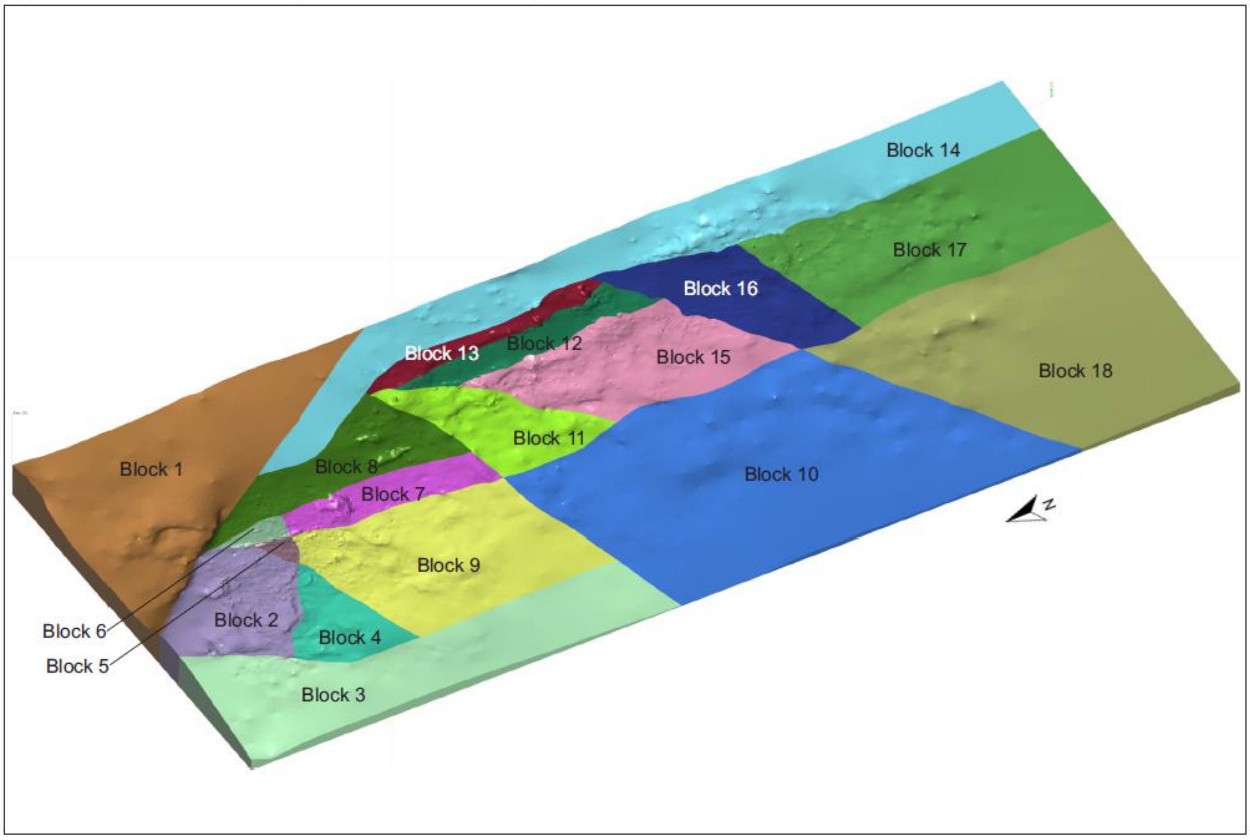


Figure 23 - The fault bounded block system created for Sishen Mine (Anthonissen *et al,* 2016).

For the implicit model, the original modelling scheme was adapted from the Sishen explicit modelling stratigraphic sequence discussed in the previous section (Figure 17). To facilitate the implicit modelling process two lithological groupings were created. The first grouping (Figure 24, PLithofiacies_Mod_Primary) represents the main stratigraphic sequence of the deposit. The second grouping (Figure 24, PLithofacies_Mod_Secondary) acts as further refinement and sub-division of the primary grouping in the various geological units (rock-types) (Anthonissen *et al,* 2016). This process allows the effective modelling of "non-unique" geological units, which carry the same logging code but belonging to multiple stratigraphic units. An example of this is the shale rock type of the Sishen deposit, which can belong to the either the Tectonized Shale unit, Gamagara Shale unit or Floor Shale unit, based on its stratigraphic position (Anthonissen *et al,* 2016).

Not unlike the explicit model, the stratiform units such as the BIF, shale and quartzite were built with *deposit* - or *erosion* lithological "geometries" (Surface system - Leapfrog Geo®) to facilitate the continuous nature of these units in the implicit model. Discontinuous units such as conglomerate beds, diabase dykes and ore units were built as *intrusion* "geometries" (Surface system - Leapfrog Geo®) to represent their intermittent nature.

Modelling parameters were aligned with the criteria used for explicit modelling, specifically interval selection. Ore and waste solids were modelled with a consistent downhole geological compositing interval of 2.99m. This ensured that intervals of waste less than 3m in the ore was ignored and included in the ore, and vice versa for insignificant ore intervals in the waste. To mimic the tabular nature of the orebody, strong ellipsoid ratios were used for the ore volumes, typically 5:5:1 (x:y:z orientation). Waste lithology volumes were modelled with a general 3:3:1 interpolant ellipsoid. Ore volumes were assigned a non-parametric surface resolution of 1.5, enabling the creation of extremely detailed ore-volumes. Waste surface resolutions were assigned as 10 to produce smoother trends in the host rock (Anthonissen *et al,* 2016).

Due to the first order domaining of the orebody in primary fault-bounded blocks, the implicit model is effective in representing the strong control geological structures such as faults and folds have on the orebody. Figure 25 show how large-scale portions of the orebody are emplaced upwards or downwards (Basson *et al,* 2017). These displacements are also discerned by the relative position of the dolomite floor rock in the different fault-bounded blocks (Figure 25). The implicit model also shows the critical function geological structures have over the mineralisation of the orebody, clearly observable in the strong ore unit location and structural emplacement correlation (Basson *et al,* 2017) (Figure 25).

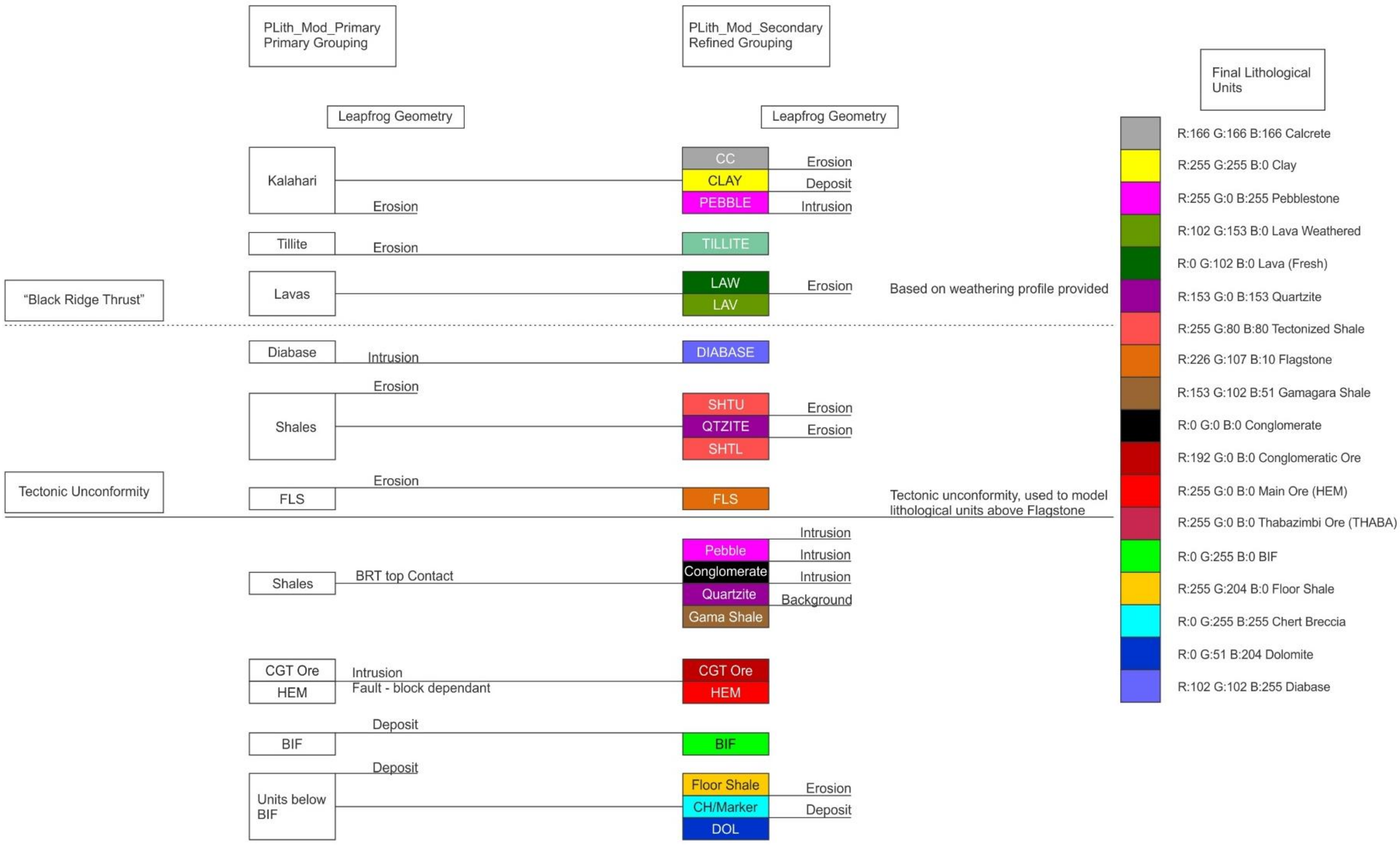


Figure 24 - Implicit modelling geological sequence schematic of the Sishen iron ore deposit (Anthonissen *et al,* 2016).

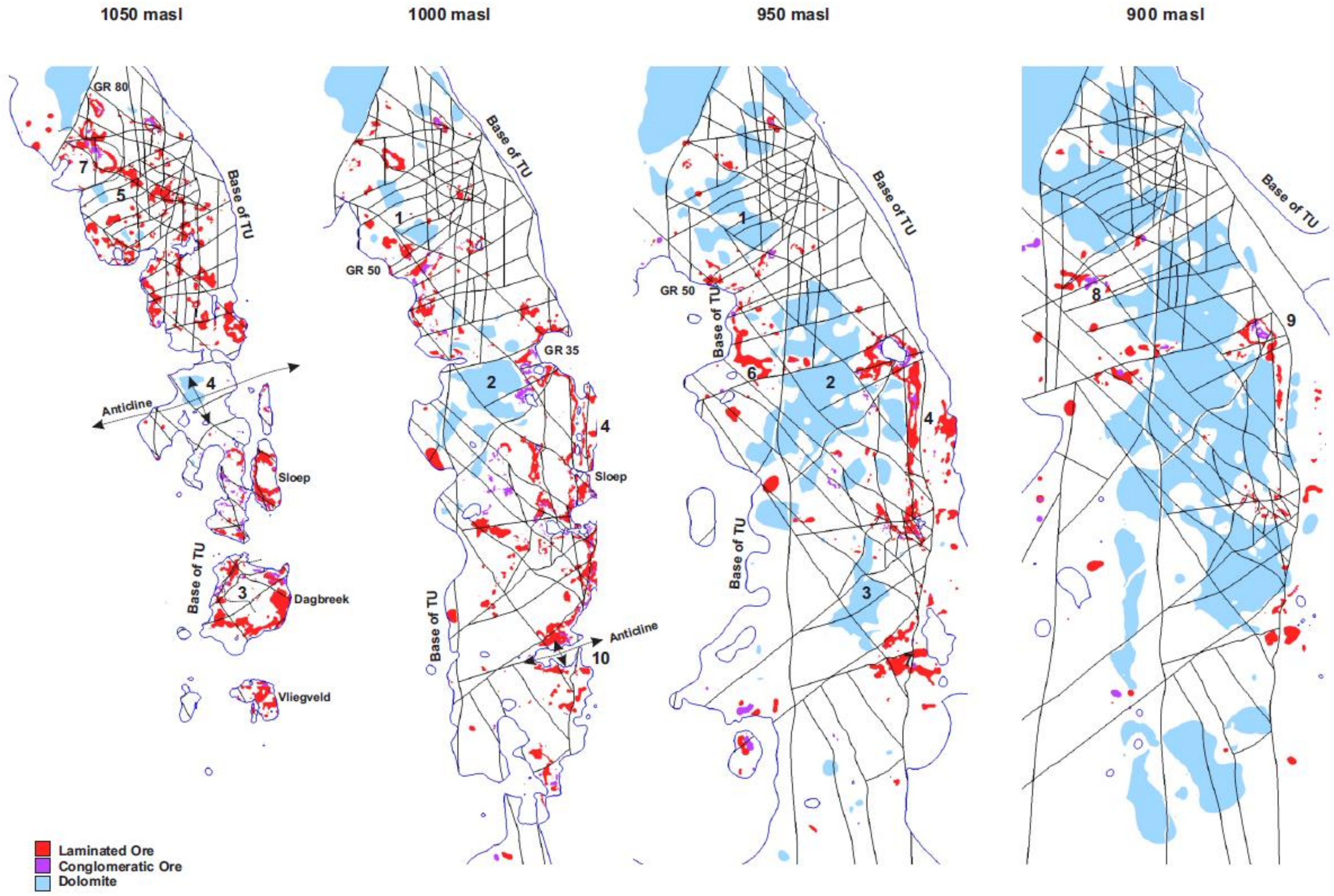


Figure 25 – The emplacement of key geological units in the implicit geological modelrelative to the main geological structures of the Sishen deposit (Basson *et al,* 2017).

2.3.4. Resource Estimation

For the Resource model, material type is allocated by intersecting the block model with the geological wire frame model (Pretorius and Hoffmann, 2005). Using the drillhole sampling database, geostatistical estimates of the chemical elements Fe, SiO_2, Al_2O_3, K_2O, P as well as relative density (RD) are calculated for each material type, within pre-defined domains, most which are structurally-controlled (Pretorius and Hoffmann, 2005). Co-Kriging is used as the grade estimation technique, as it results in the suite of chemical elements (grades) having the same spatial distribution characteristics after estimation (Figure 26).

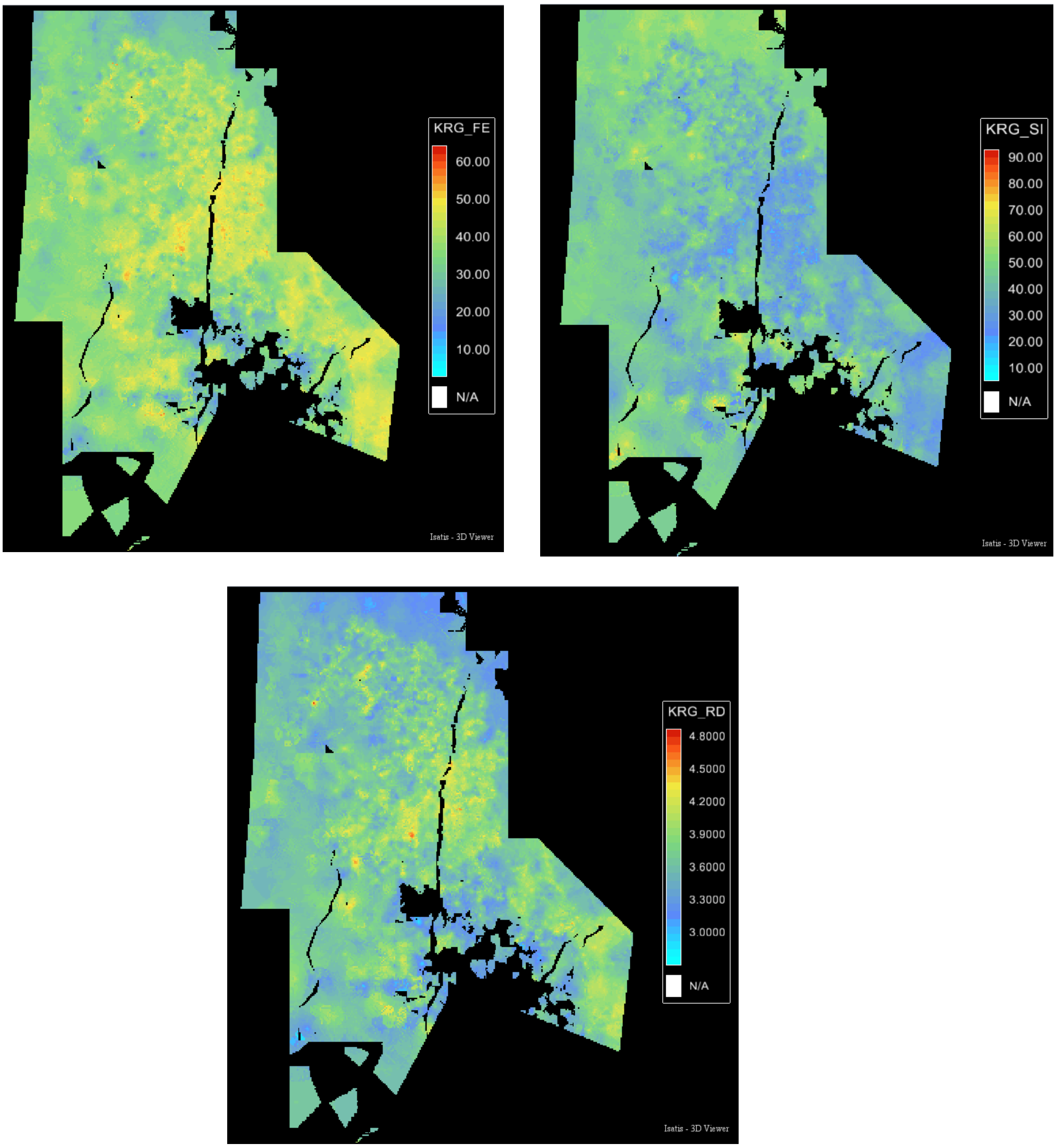


Figure 26 – Distribution of estimated Fe, Si, and RD grades in the Sishen North Mine BIF unit. Notice the high correlation in the spatial distribution patterns of grades as a result of the co-kriging process (Deacon, 2017).

The full estimation process extends beyond the scope of this report. In summary, the dataset for a unit of interest is firstly validated by an extensive Exploratory Data Analysis (EDA) process to ensure that only representative data is used for the geostatistical estimation. Three main processes are followed during the EDA process at Sishen.

Firstly, samples that are deemed to be of excessive length are removed from the dataset (Figure 27). A single geochemical analysis (sample) that extends over long geological intersections cannot be regarded as representative of the extended intersection. It can also be indicative of database errors. Secondly the Fe / RD relationship of the samples is verified (Figure 28). Samples should show a strong correlation between Fe (grade) and RD (weight) otherwise it is not a representative sample. Lastly, the total oxide (TOX) balance of the sample should be checked (Figure 29). It is a reasonable assumption that the summation of all the different elements analysed for in a sample should be close to 100%. When this is not the case, it can be indicative of a corrupted sample analysis, which is deemed not representative and should therefore be removed from the dataset.

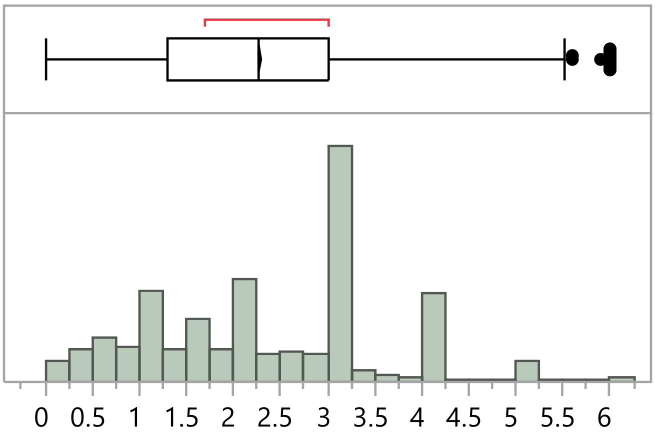


Figure 27 – Assay length (m) distribution. Sishen BIF analysis example. Excessively long samples are removed from the dataset as they are not representative (Deacon, 2017).

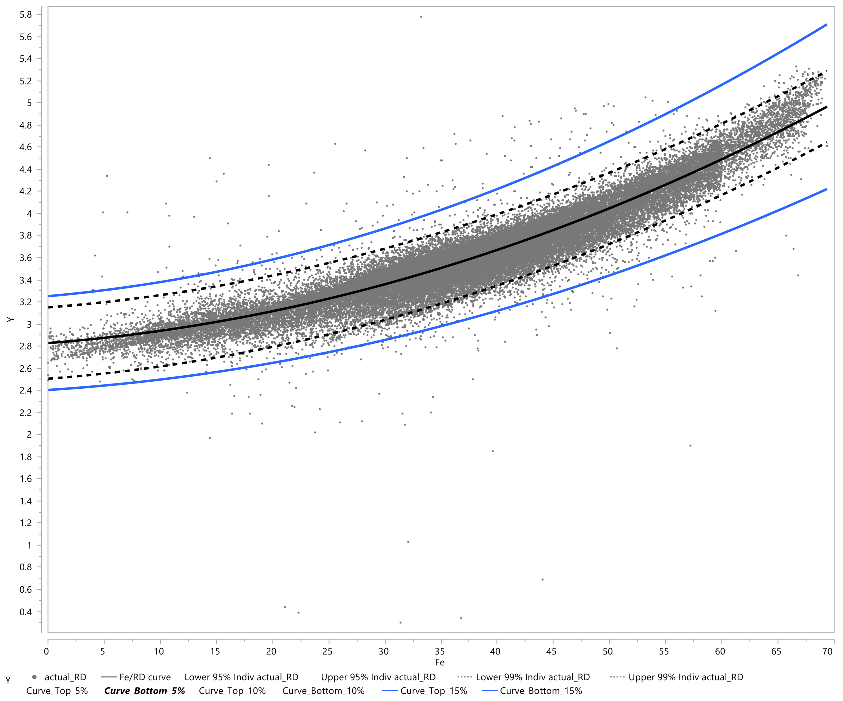


Figure 28 – Fe/RD multivariate verification for Sishen BIF assays. Samples that do not show strong Fe and RD relationship are deemed erroneous and removed from the dataset (Deacon, 2017).

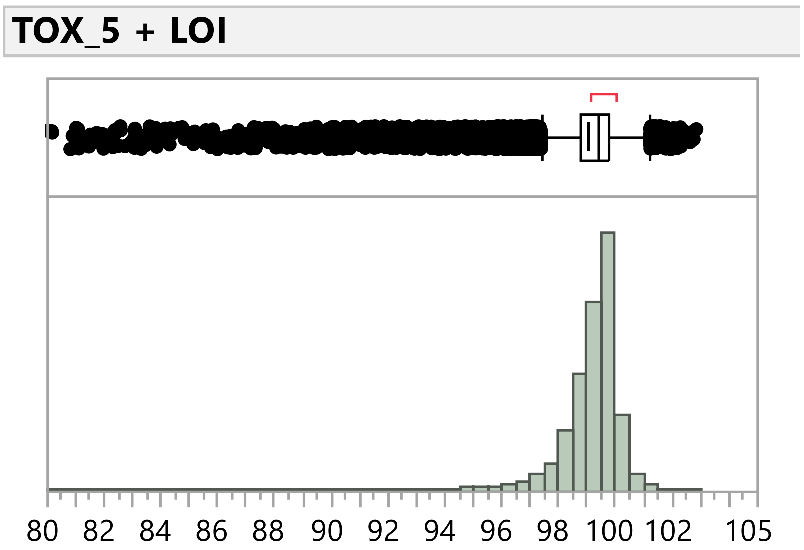


Figure 29 – Distribution of the total oxide (TOX) balance of the Sishen BIF assay dataset. Sample assays that do not add up to 100% can indicate a corrupted, unrepresentative assay (Deacon, 2017).

After data validation, the data is further analysed to understand the geo-spatial aspects of the grade distribution within in the geological unit of interest. The aim is to define discrete estimation domains which exhibit unique grade distribution characteristics with co-location. Sishen successfully applies a combination of clustering (hierarchical and k-means) analysis of grade values and spatial projection of the clustering result to identify domains to support the geostatistical estimation process (Figure 30).

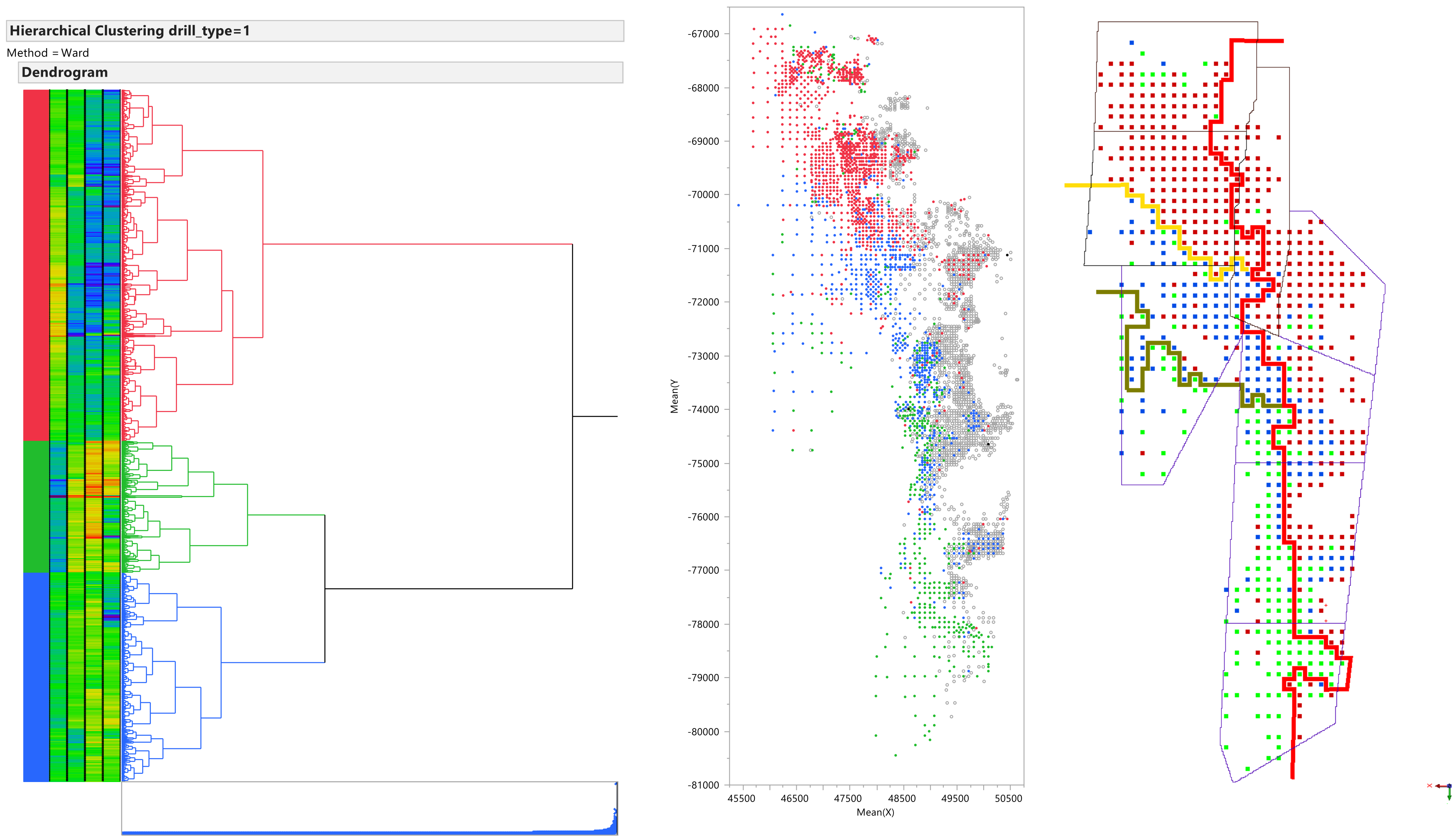


Figure 30 – Domaining of the Flagstone (zone 9) unit in domains which exhibit relative different multivariate grade distributions. The main processes utilised are clustering analysis of the multi-variant dataset (left) and the spatial projection of this result (middle) after which boundaries can be manually digitised (Deacon, 2015).

After the exploratory data analysis (EDA) process, the data is prepared for the geostatistical estimate. At Sishen the modelled orebody and dataset is unfolded (unit-unfolding - Geovariances Isatis®) before estimation. This unfolding process ensures that the estimate is performed in the unit's conceptual horizontal state as originally deposited before any geological deformation events disrupted the orebody locally (Van Zyl, 2014). After grade estimation the orebody is refolded, ensuring that the emplacement trends of the estimated grades follows the emplacement trends of the orebody (Figure 31).

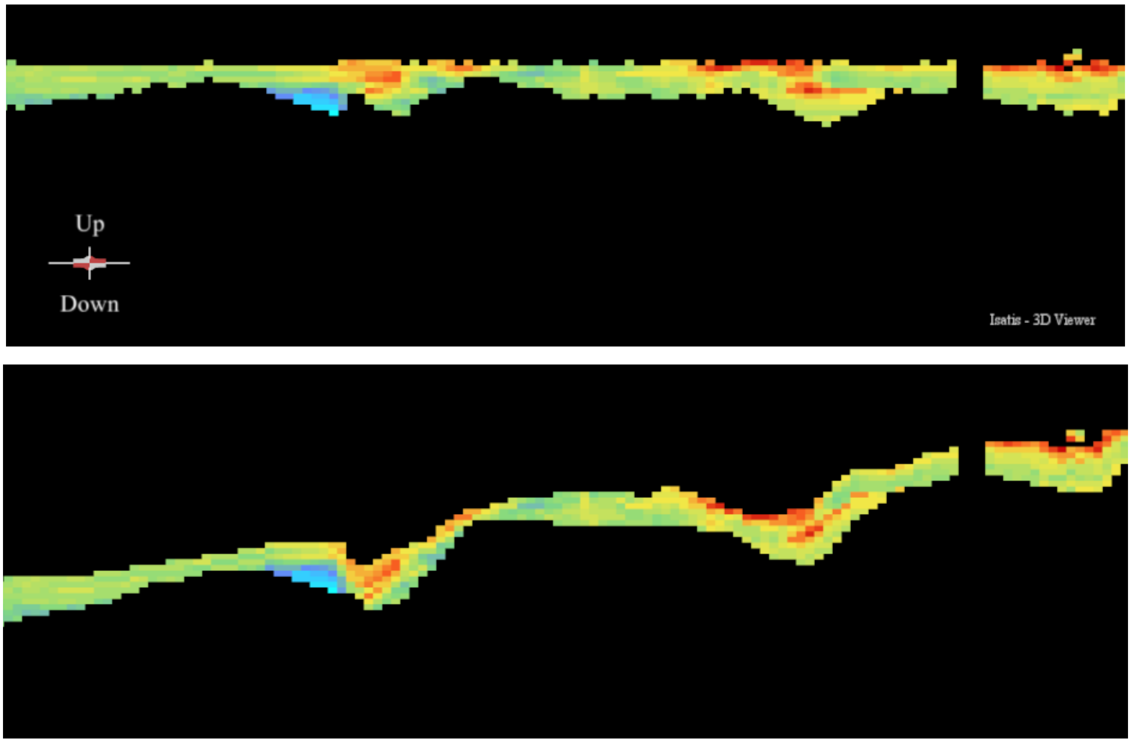


Figure 31 – The estimation of grades in unfolded position (top) facilitates accurate grade trending when the estimate is re-folded (bottom). North Mine BIF Fe grade example (Deacon, 2017).

Variography is then performed on the dataset. Co-variograms for the suite of grade elements are compiled for each discrete domain (Figure 32). During co-variography the same basic variogram, with analogous range and sill relationships, is fit to all grade elements. This ensures that the estimate of all grade elements will be correlated, thereby exhibiting the same distribution characteristics.

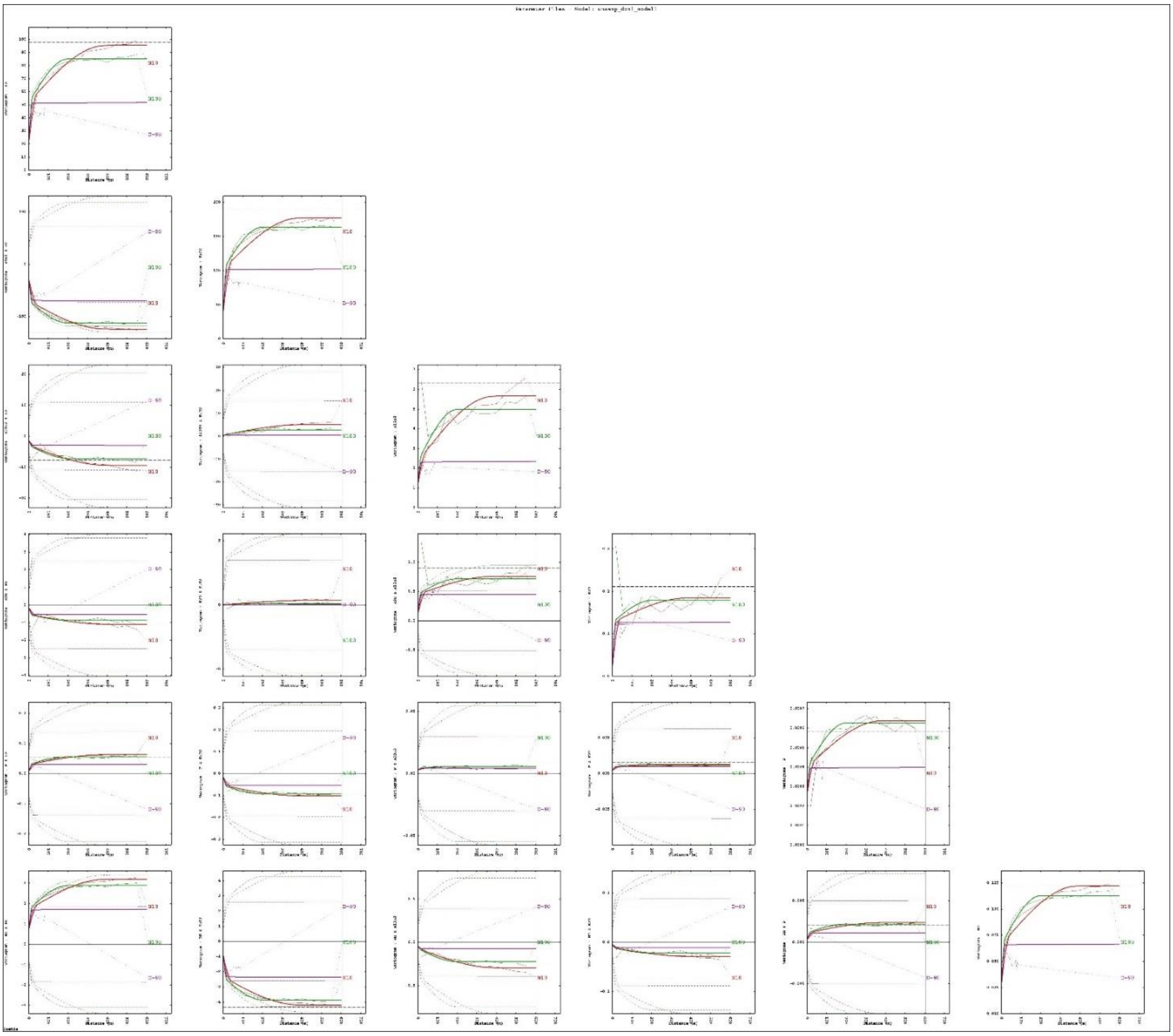


Figure 32 – A set of co-variograms used for the Sishen BIF grade estimate (Domain 2) (Deacon, 2017).

The modelled variograms are then used to determine optimal kriging parameters (neighbourhoods) for the estimation process. The Quantitative Kriging Neighbourhood Analysis (QKNA) (Vann et al, 2003) process is utilised, wherein multiple kriging runs are performed with a series of different neighbourhood parameters, including search radii and sample quantities.

The estimation parameters of these test kriging runs are compared, and the neighbourhood parameters with the optimal estimation results are ultimately used for the final grade estimate. At Sishen, the estimate is optimised for the slope of regression, percentage negative weights and standard deviation estimation parameters (Figure 33), by evaluating different vertical search distance, horizontal search distance and number of samples neighbourhood parameters (Figure 33).

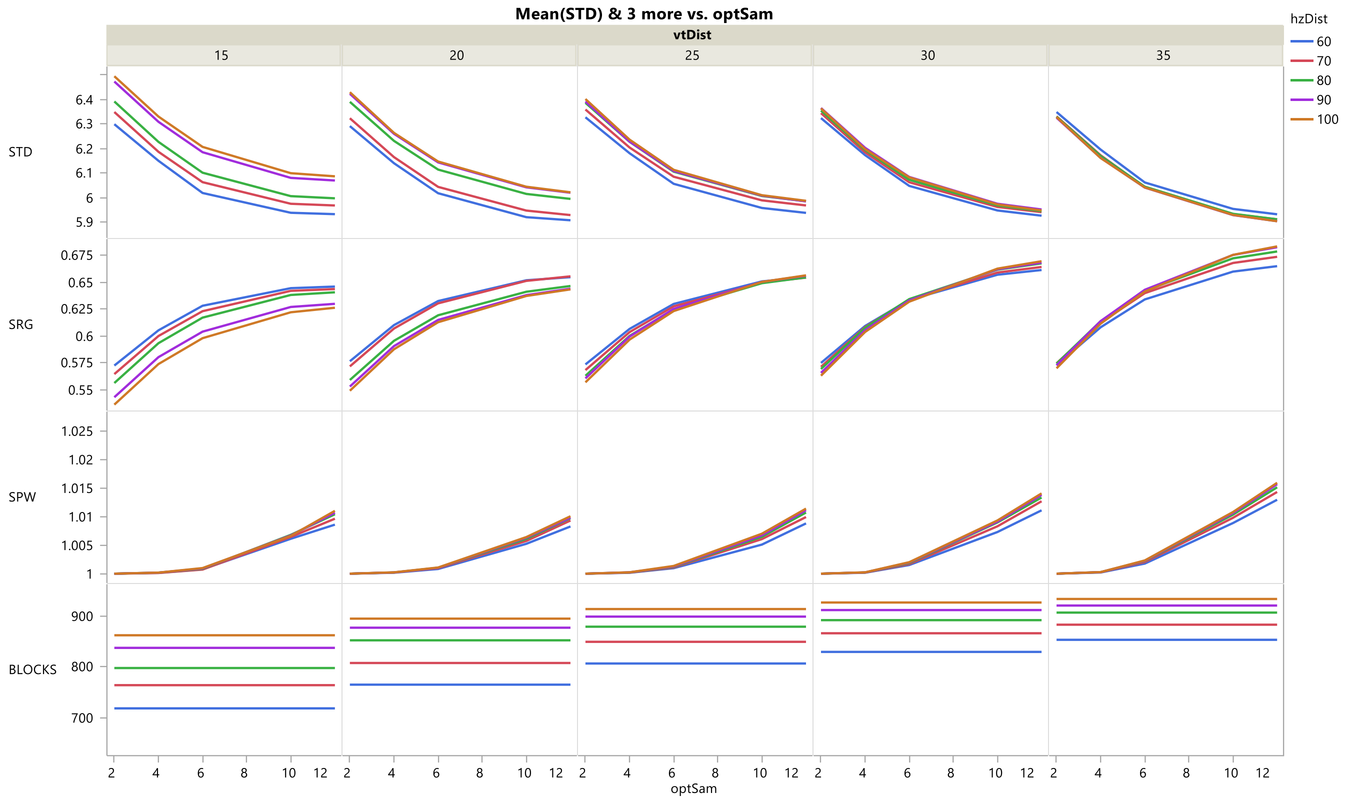


Figure 33 – The results of a Quantitative Kriging Neighbourhood Analysis (QKNA) showing how different search neighbourhood parameters affect the estimation parameters. Sishen BIF grade estimation example from Deacon, 2017. Estimation parameters: STD – standard deviation of grade estimate; SRG – slope of regression of estimate; SPW – sum of positive weights associated with estimate; BLOCKS – number of blocks estimated. Neighbourhood parameters: vtDist – vertical search distance; hzDist – horizontal search distance; optSam – optimum (maximum) number of samples in search definition.

The grades are estimated utilising the optimal defined neighbourhood by means of co-kriging. The estimate is validated by means of grade strip-plots (Figure 34).

Finally, a resource confidence classification is performed for the grades of the unit. Sishen utilises a balanced scorecard confidence classification process, catering for both geological and grade factors which affect resource confidence (Pretorius and Van Graan, 2015) (Figure 35). Grade factors include an estimation confidence parameter (slope of regression) and quality (QAQC) confidence parameters (drillhole type, total oxides balance, and actual/default sample indicators) of the data used to inform the grid node. Geology factors consider a data density parameter (distance to closest sample) and a geological complexity parameter (confidence score will be discounted in defined complex areas). A score value between 1 and 9 will be allocated to each parameter by applying set limits, after which a weighted average score will determine the node's final confidence index (Figure 35).

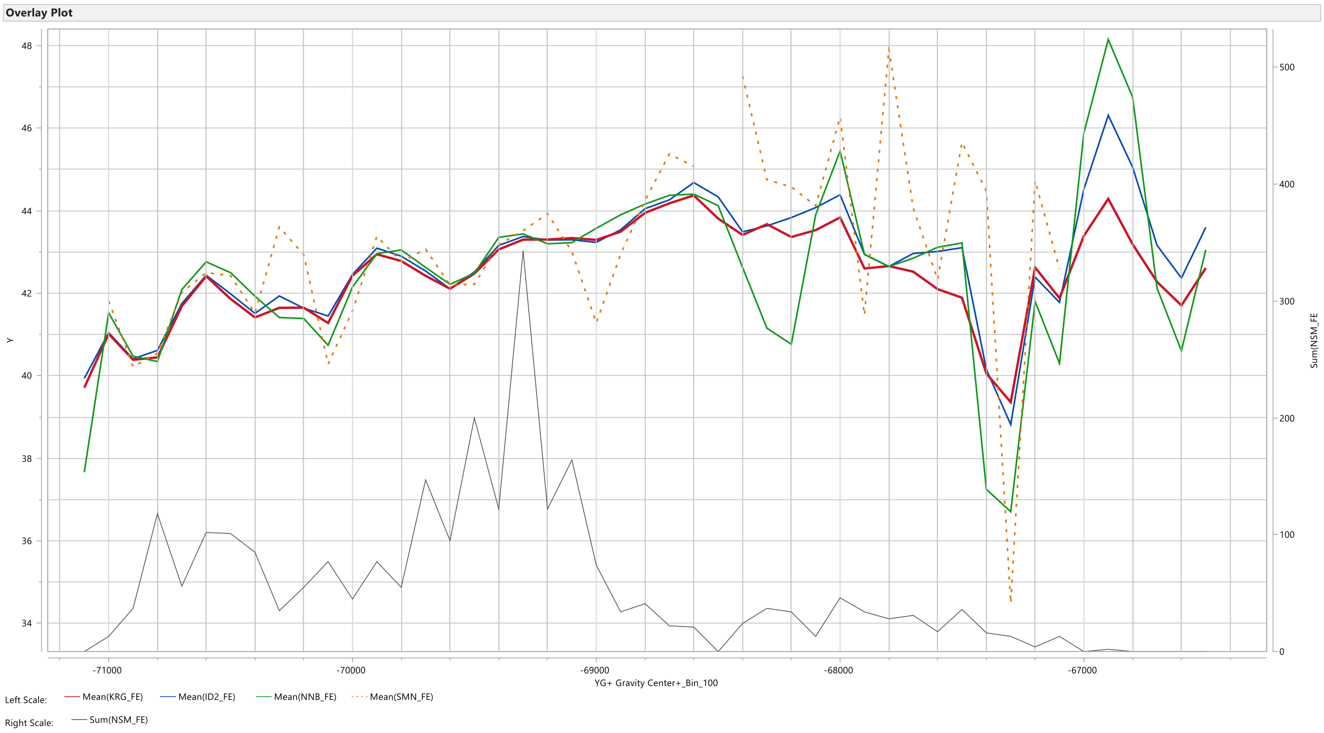
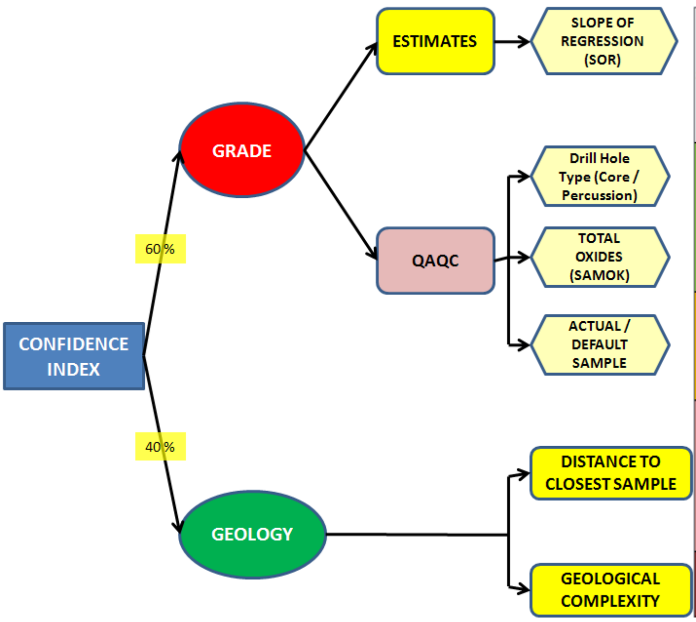


Figure 34 – A validation swath plot in Y direction for the in-situ Flagstone Fe grade distribution in the resource model (Deacon, 2015).



SCORE	CONFIDENCE	WEIGHT					
		60%				40%	
		ESTIMATION CONFIDENCE	QAQC CONFIDENCE			GEOLOGY CONFIDENCE	
		Slope of Regression (SOR)	Drill Hole Type (Core /	Total Oxides (SAMOK)	Actual/Default Sample	Distance to Closest Sample (m)	Complex Areas (inside Polygon)
9	Measured	≥ 0.95	≥ 0.90	≥ 0.90	≥ 0.90	< 10	-2
8		0.90 - 0.95	0.75 - 0.90	0.85 - 0.90	0.85 - 0.90	10 - 30	-2
7		0.80 - 0.90	0.60 - 0.75	0.80 - 0.85	0.80 - 0.85	30 - 60	-2
6	Indicated	0.70 - 0.80	0.50 - 0.60	0.65 - 0.80	0.65 - 0.80	60 - 80	-2
5		0.60 - 0.70	0.30 - 0.50	0.50 - 0.65	0.50 - 0.65	80 - 110	-2
4	Inferred 1	0.50 - 0.60	0.25 - 0.30	0.35 - 0.50	0.35 - 0.50	110 - 130	-2
3		0.30 - 0.50	0.20 - 0.25	0.20 - 0.35	0.20 - 0.35	130 - 160	-2
2						160 - 170	-2
1	Inferred 2	< 0.30	< 0.20	< 0.20	< 0.20	> 170	

Figure 35 – The balanced scorecard resource confidence classification matrix applied at Sishen (Pretorius and Van Graan, 2015).

2.3.5. Resource Definition

Cut-off grades

At Sishen iron grade (% Fe) is not the only factor controlling whether the material is regarded as ore or waste. Although it is the first indicator when determining the potential value of the material in terms of ore classification, it is by no means the only aspect of importance. Iron ore, as a bulk commodity, is beneficiated to a pre-determined Fe grade, but the contaminant chemical elements, including SiO_2, K_2O, Al_2O_3 and P, must also be considered in order to produce a product within set specifications. Failure in this regard will result in the saleable product being regarded as out of specification and a penalty fee will be applied to the set price. Cut-off grades for each chemical element should therefore be instated to mitigate the risk of financial loss due to producing product that is out of specification.

Multi-variant grade relationship

Everett (2011) however illustrates the potential ore loss when separate cut-off grades are applied to each of the individual grades. As a bulk commodity, run-of-mine material (ROM) from different areas in the mine, with different characteristics, can be blended (mixed) during beneficiation to create a final product with an average grade composition within set specifications.

A blending example is where a tonne of material that is rejected based on one grade criteria, i.e. K_2O being too high, can thus be blended with one tonne of material which is very low in K_2O, delivering 2 tonnes of material with an average K_2O grade that is within specification (Figure 36).

For optimum resource utilisation it is clear that the following aspects concerning cut-off grades should be understood:

1. The multi-variant relationship between chemical constitutes must be determined and understood (Figure 37, Figure 38).
2. The distribution and relationship between chemical constituents will differ from one material type to the next, so it is imperative that if more than one ore type

is utilised by the operation, the characteristics of each of these material types are understood (Figure 37, Figure 38).

3. How the chemical constitutes will behave during different beneficiation techniques must be determined and quantified, ensuring that the optimum beneficiation technique is used, guaranteeing that optimum value is extracted from the overall volume.

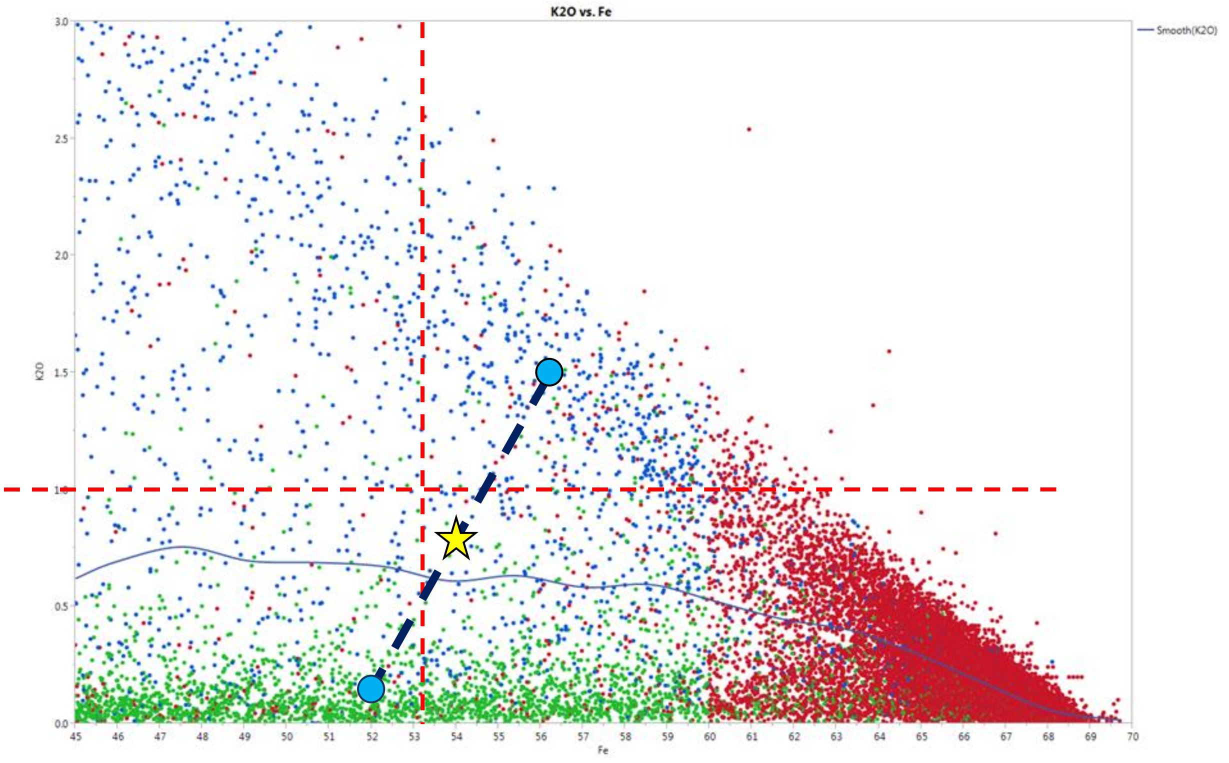


Figure 36 - Fe vs K_2O plot for Sishen high-grade ore material (Zone 1 – Main ore - red), Hangingwall material (Zone 17 – Shale - blue), and Footwall material (Zone 12 – BIF - green). Zone 1,12,17 sampling data points - 46000 records. Cut-off grades of Fe > 55 and K_2O < 1.0 applied. Blue markers and blue line illustrate that material outside separate cut-off grades can still be economical if blended to a final, average grade (star). Concept after Everett (2011).

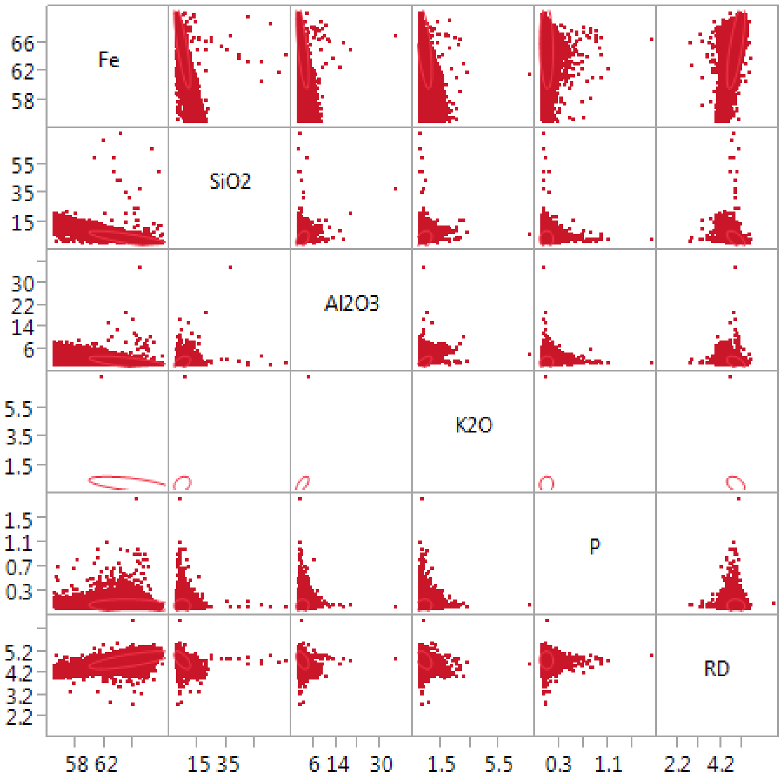


Figure 37 – Multi-Variant Relationship of the chemical constitutes in high-grade ore (Zone 1 – Main ore).

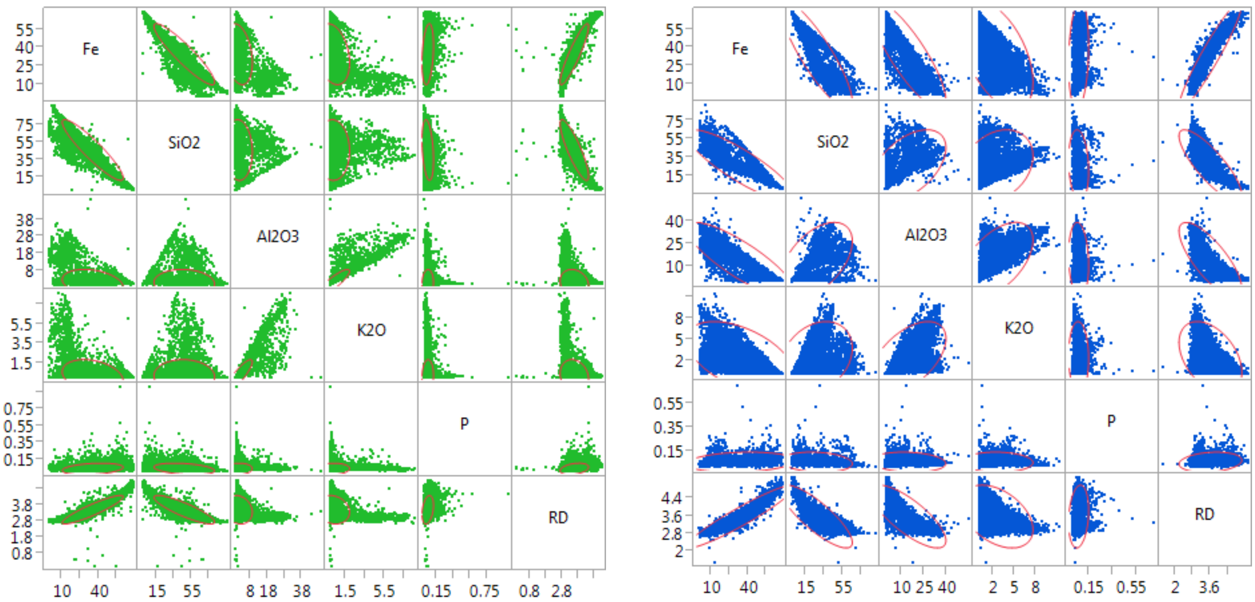


Figure 38 - Multi-variant relationship of the chemical constitutes in Footwall mineralisation (Zone 12 - BIF) (left) and the Hangingwall mineralisation (Zone 17 - Shale) (right).

For optimal resource utilisation, a material classification system was developed for the Sishen resource definition process to compute the in-situ as well as projected (beneficiated) value of the material, based on the factors listed above. This classification system also acts as a tool, assisting firstly; the decision-making process regarding how the material should be utilised for maximum value extraction, and secondly; quantifying the material's characteristics in a logical and structured fashion during the resource extraction process.

Methodology of the Sishen Material Classification Process

The Sishen Material Classification process is performed in the resource block models. The block model is populated with the geological wireframe model and each zone (geological unit) contain its assigned estimated grade information. Beneficiation algorithms are performed for each element of each material type, using the material type allocation and in-situ grade values for each unit cell (block). The beneficiation algorithms are mathematical functions derived from metallurgical test results of typical ROM material, obtained from bulk sample test work (Pretorius and Hoffmann, 2005). The algorithm will plot the input value (in-situ grade) on the relevant material type curve and output the expected beneficiated grade value. (Figure 38). A yield value, expressed as a fraction of 1, is also computed, which forecasts the fraction of product that will be obtained when the material is processed using the chosen beneficiation technique.

As a result, each unit cell (block) will have a material type allocation, in-situ grade values, projected beneficiated grade values and plant yield values. In the case of Sishen, the projected beneficiated values will be in duplicate: a set of grades for both the DMS and JIG processes.

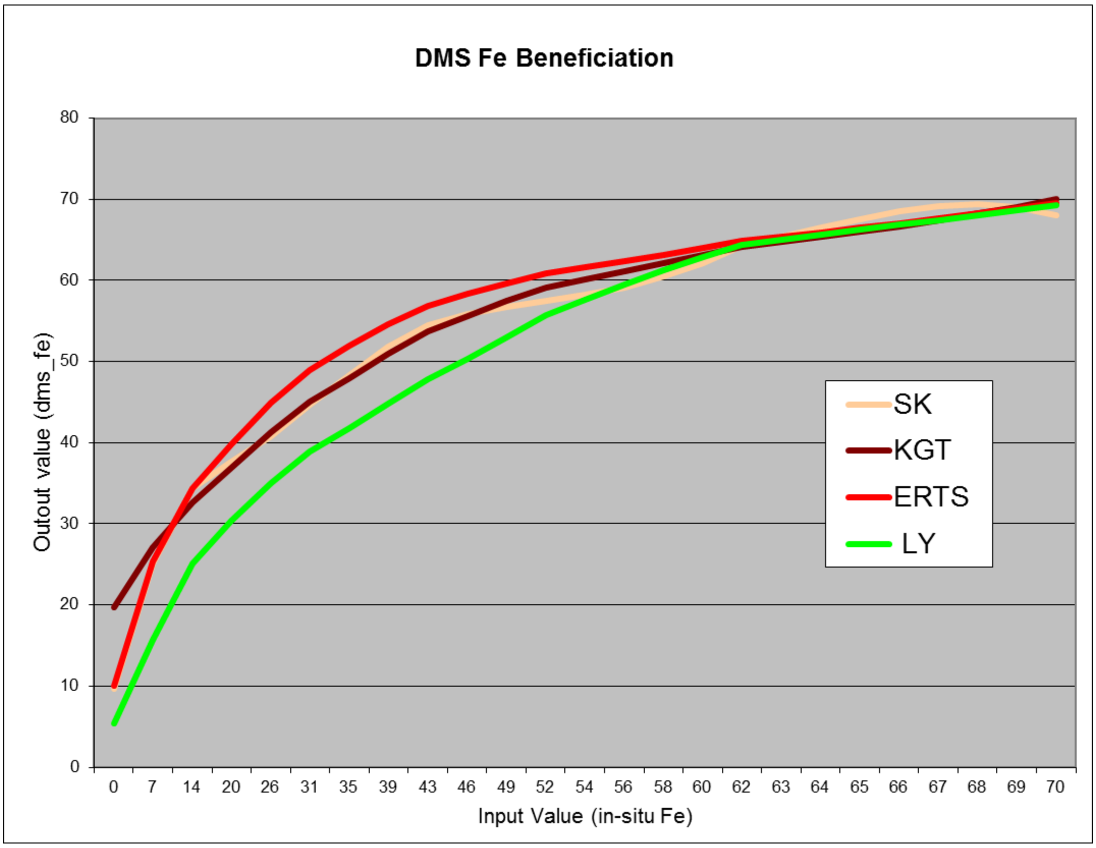


Figure 39 – DMS example of the Sishen beneficiation algorithms - Fe beneficiation, per material type (Pretorius and Van Graan, 2015).

Ore / Waste Material Classes

The values discussed above are then used to classify the individual blocks in defined resource material classes, by applying a framework of criteria (Pretorius and Hoffmann, 2005):

- An in-situ Fe cut-off of 60% is used to distinguish between high-grade ore and low-grade secondary ore material. The ore/waste cut-off grade is defined as 40% in-situ Fe.
- The percentage occurrence of a specific geological material type in the block, representing a mining bench. The criteria for classification is whether material occurs as a full bench occurrence or less or more than half bench occurrences.
- If waste occurs in conjunction with high grade (60% Fe) on a bench, classification will be dependent on whether the waste material has a high relative density (>3.6 g/cm^3) or low relative density (<3.6 g/cm^3).
- Low grade (50-60% Fe) resources are classified as a direct function of material type.

- Beneficiated values of the complete suite of chemical elements will dictate final classification.
- A tonnage weighted average value for all grade value (in-situ and beneficiated) and beneficiation yields are also determined for the block representing the mining bench.

The Material Classification Matrix (Figure 40) graphically indicates the associated class *category* as a function of material occurrence in the mining bench; this being the first condition of classification. The second condition of classification criteria classifies the material in different series of classification *numbers* according to grade cut-offs to dictate final classification assignment. The material classification numbering convention resemble a 3 digit number; XXx; where XX is the class *category* and x is the classification *number* (Figure 40).

Full bench high-grade ore occurrences are assigned to the 10x class category. Class 101 is full bench ore that will beneficiate to a Fe grade value of 64.5% or more and the material must have an effective yield of 80% or more in the DMS plant. Class 102 is full bench ore of a lower grade. Beneficiated Fe grade should be greater than 61%. The 10x class series are primarily DMS ore feed, but may also be utilised to sweeten the grade of the JIG ore feed.

Less than full bench high-grade ore occurrences are assigned to 20x, 30x and 40x class categories. The 20x class series is used if the ore occurs in combination with high-density (>3.6g/cm^3) BIF material on a mining bench. Class 201 is assigned if the ore material occurrence represents more than half a bench, and the material can be beneficiated to at least 61% Fe, K_2O of less than 0.3% and at a yield of 60% or more in the DMS plant. Class 202 represents material in which ore material and waste material are more or less equal on a bench, and the material would achieve at least 58.5% Fe, K_2O less than 0.3%, at a yield of 40% or more in the JIG plant.

The 30x class series represents material where the high-grade ore material occurs with other high-density (>3.6g/cm^3) waste material (shale, conglomerate etc.). The classification structure mirrors that of the 20x classes. Class 301 is allocated if more than half a bench is ore material, with projected beneficiated Fe grades of 61% Fe or more at a yield of 60% in the DMS process. Class 302 represents equal ore/waste on a bench, with Fe grade of at least 58.5%, and a yield of at least 40% in the JIG process.

Material Class		Description	Grade Cut-offs							Mining Class
			Bench In Situ			Bench DMS		Bench JIG		
			Material Proportion	Fe	K2O	Fe	Yield	Fe	Yield	
101	DMS grade ore	High grade				>= 64.5%	>= 80%			A
102		Low to Medium grade	No waste			>= 61%				A
201		Ore + high density waste (high density BIF + CGB >= 50% of total waste)			< 0.3%					A
301		Ore + high density waste (high density BIF + CGB < 50% of total waste)								A / K (K if Bench JIG K2O >= 0.6%)
401		Ore + low density waste (weighted ave. rd of waste < 3.6)					>= 60%			A
202	Jig grade ore	Ore + high density waste (high density BIF + CGB >= 50% of total waste)	Ore >= 25%		< 0.3%			>= 58.5%	>= 40%	L
302		Ore + high density waste (high density BIF + CGB < 50% of total waste)								B / K (K if Bench JIG K2O >= 0.6%)
402		Ore + low density waste (weighted ave. rd of waste < 3.6) (DMS grade on Fe but DMS yield <60%)				>= 61%	< 60%			B
501		Ore + high density waste (high density BIF + CGB >= 50% of total waste)	Ore < 25%		< 0.3%			>= 58.5%		L
601		Ore + high density waste (high density BIF + CGB < 50% of total waste)								B / K (K if Bench JIG K2O >= 0.6%)
502	Waste	Medium in situ Fe material (JIG grade on Fe but JIG yield < 40%)		Fe >= 40%				>= 58.5%	< 40%	C
602		Medium in situ Fe material (not DMS/JIG grade)								C
701		Low in situ Fe material (not DMS/JIG grade)		Fe < 40%						D
801		Clay	Clay >= 30%							E

Figure 40 - The Sishen Material Classification Matrix (Pretorius and Van Graan, 2015).

The 40x class series is assigned where the high-grade ore material occurs with low-density (<3.6g/cm^3) waste on a bench. Class 401 is allocated if the ore fraction is more than half bench and a Fe grade of 61% at a yield of 60% or more is achievable utilising DMS beneficiation. Class 402 denote ore occurrences of less than half bench fraction, with an achievable DMS Fe grade of 61% at a yield of between 40% and 60%. 40x classes are also regarded as DMS ore, as the light waste is easily separable from the heavier ore material. If there is good geological continuity of the ore/waste contact on the bench these classes will be marked "S" for selective mining, where the ore and waste are separated, during mining, using secondary equipment.

If a bench contains less than a quarter bench of high-grade ore material (Fe greater than 60%), the beneficiated bench grades will be too low to be captured in the above ore classes. Low-grade material class categories 50x and 60x are subsequently assigned. Class 501 is high density BIF material containing a small high-grade, hematite ore component, which should beneficiate to grades of at least 58.5% Fe, K_2O less than 0.3%, at a yield of at least 40% in the JIG plant. 501 is exclusively JIG feed, due to its high-density waste component. Class 502 is the remaining high-density waste with a beneficiation yield of at least 40%. Class 601 is similar to class 501, but represents other (aluminous) waste types associated with a small component of high-grade ore on the bench. It should also beneficiate to at least 58.5% Fe by the Jigging process at a yield of at least 40%. Class 601 is also exclusively JIG feed, due to its high-density waste component. Class 602 represents the remaining full bench high density waste that does not conform to the above criteria, but has at least a 40% in-situ Fe grade.

Finally, for the remaining waste, class 701 is assigned to full bench waste material, with an in-situ bench grade of less than 40% Fe. 701 is regarded as sterile waste. This material is destined for the waste dump. If clay makes up more than 30% the mining bench, the material is assigned as class 801. Due to its high clay component, this material must be separated from other sterile waste and disposed of with care, ensuring that waste dumps do not have a clay component that is too high, which could cause geotechnical issues.

For mining, the 15 individual numerical classes are grouped in 5 material types (Figure 40). The A-material type (classes 101, 102, 201, 301 and 401) is DMS plant-feed material. B-material (classes 302, 402 and 601) and L-material (classes 202 and 501) are JIG ore-feed material, suitable to be fed in conjunction with good-quality A-material to create a blended product within specification. C-material (classes 502, 602) is regarded as potential low-grade ore material and should be stockpiled separately from the other sterile waste. D-material (class 701) is sterile waste, destined for the waste dump. Finally E-material (class 801) is clay-rich sterile waste material.

A series of cross-sections through the Sishen resource block model visually explains the elaborate material classification system at Sishen. Firstly Figure 41 shows the geological model in sectional view. Figure 42 illustrates how the geological model is translated to the ore component attribute, expressed at the mining bench scale. This attribute is essential for the Sishen material classification system. Next Figure 43 shows the in-situ Fe grade on the section. Notice the sharp Fe grade contact between the ore main ore horizons and the host rock. Figure 44 and Figure 45 shows how the in-situ grades are converted to their respective DMS and JIG projected beneficiation grades. There is a large discrepancy in beneficiation grade potential as a function of the material type and the beneficiation method utilised. Lithologies behave distinctively differently during beneficiation, as a direct function of their physical properties. Figure 46 and Figure 47 shows the respective bench DMS and bench JIG projected plant yields of the material. These attributes are expressed for the full mining bench. Notice how yields are affected in areas where both ore and waste material are present on the same bench. Figure 48 shows the RD of the waste material, which is also essential in determining in which class suite the material will be classified.

Figure 49 show the final Sishen material classification. Notice that the resolution for the material class allocation is the entire bench height, regarded the smallest mining unit (SMU), defined as 12.5m at Sishen. Two material classes will never occur on top of each other on the same mining bench. Compare Figure 49 and Figure 41; notice the strong correlation between the two cross-sections showing the distribution of the respective material class and geological model, especially between the ore horizon and the 101 material class distribution. The cross-section also shows how the different suites of classes are distributed. Observe how the 30x and 40x classes are located at the hanging wall of the main orebody while 20x classes are located at the footwall of the main orebody.

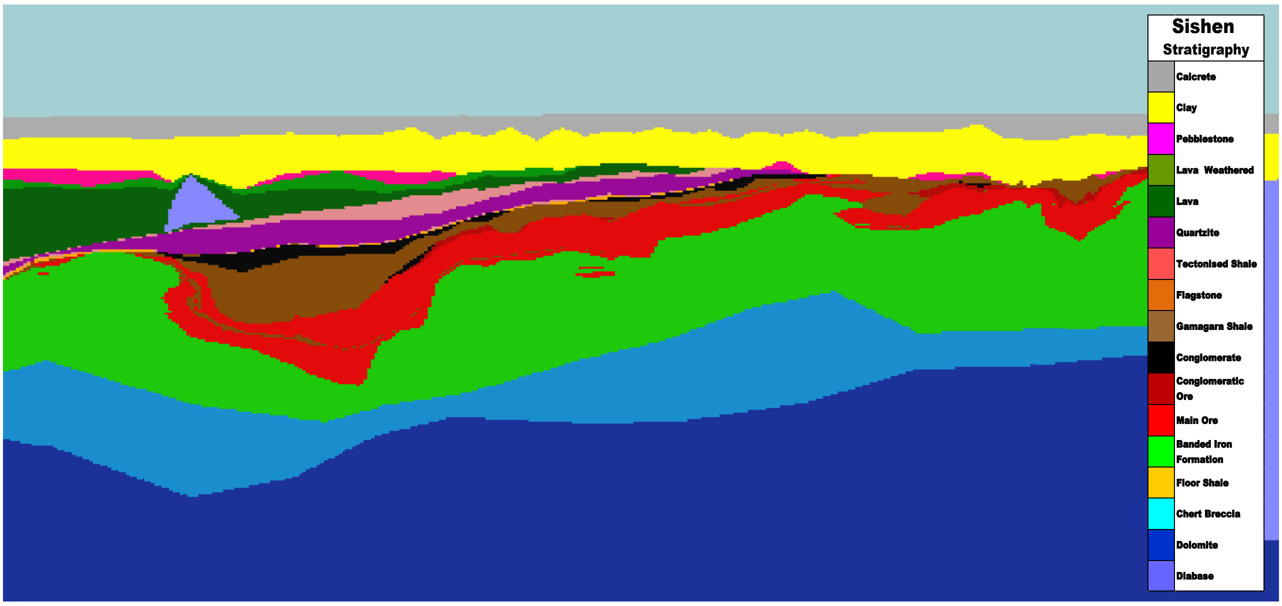


Figure 41 – W-E block model cross-section showing the geological material type allocation in the Sishen Resource Model (Y direction = 67777.5m).

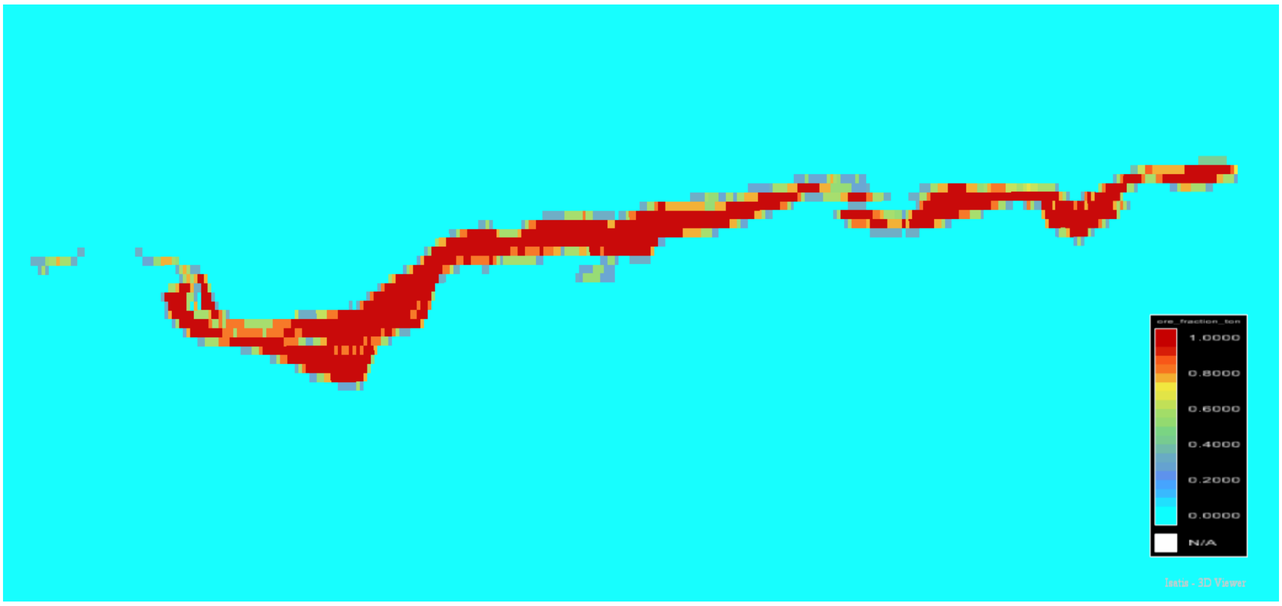


Figure 42 - W-E block model cross-section showing the ore component attribute defined per mining bench in the Sishen Resource Model (Y direction = 67777.5m).

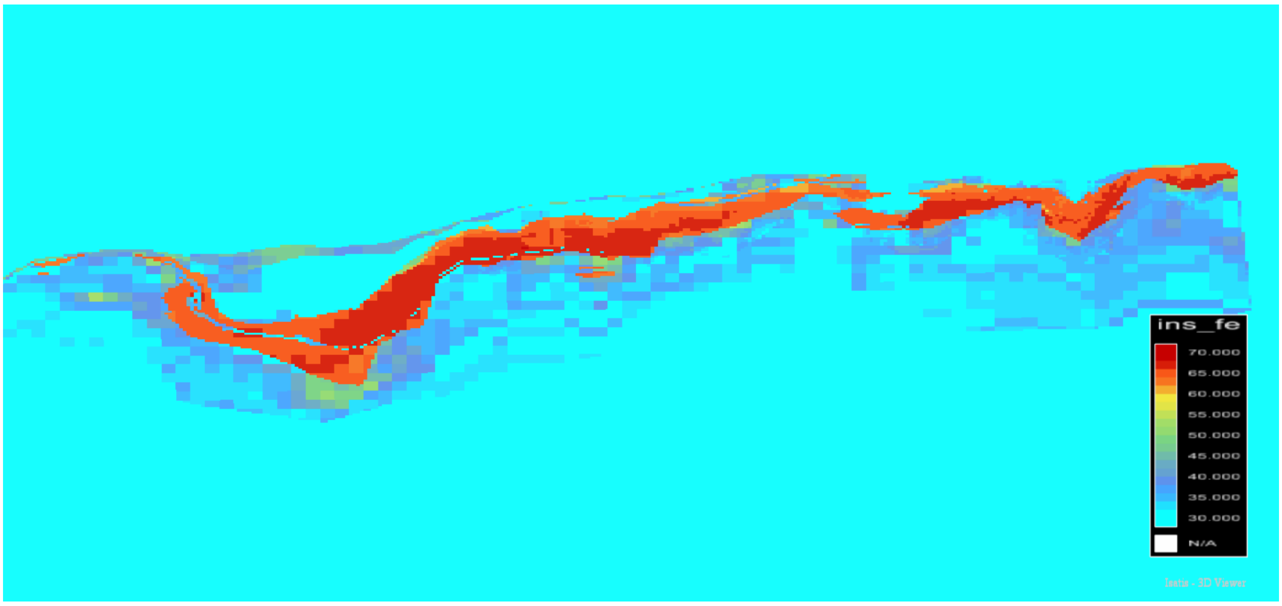


Figure 43 - W-E block model cross-section showing the in-situ Fe grade in the Sishen Resource Model (Y direction = 67777.5m).

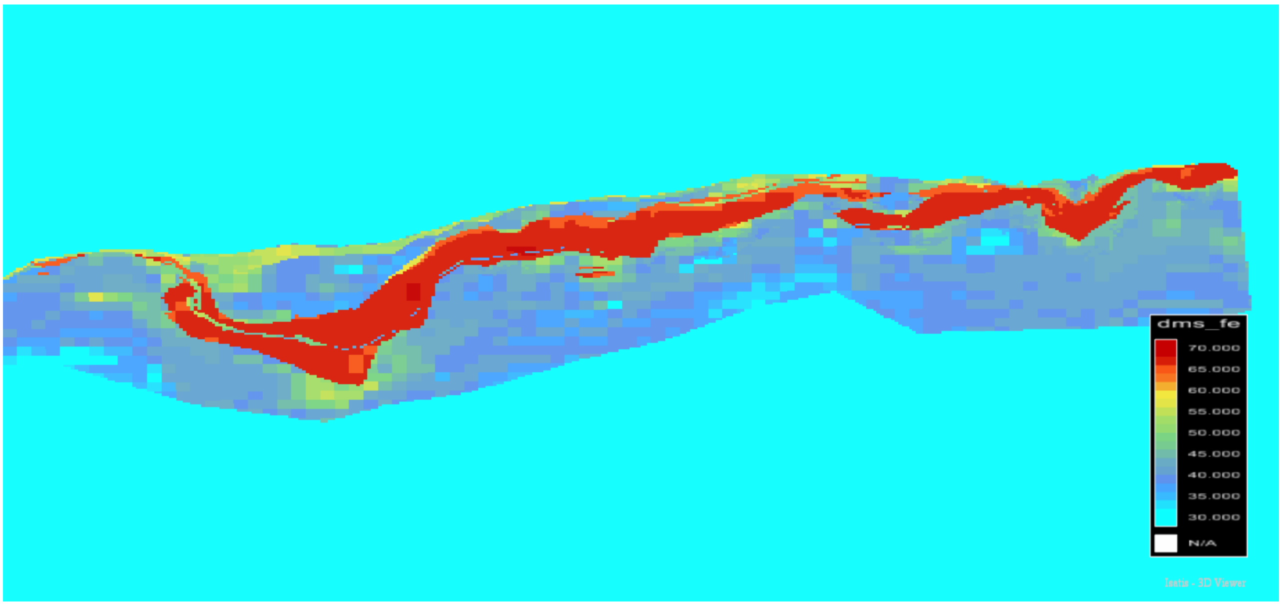


Figure 44 - W-E block model cross-section showing the DMS beneficiated Fe grade in the Sishen Resource Model (Y direction = 67777.5m).

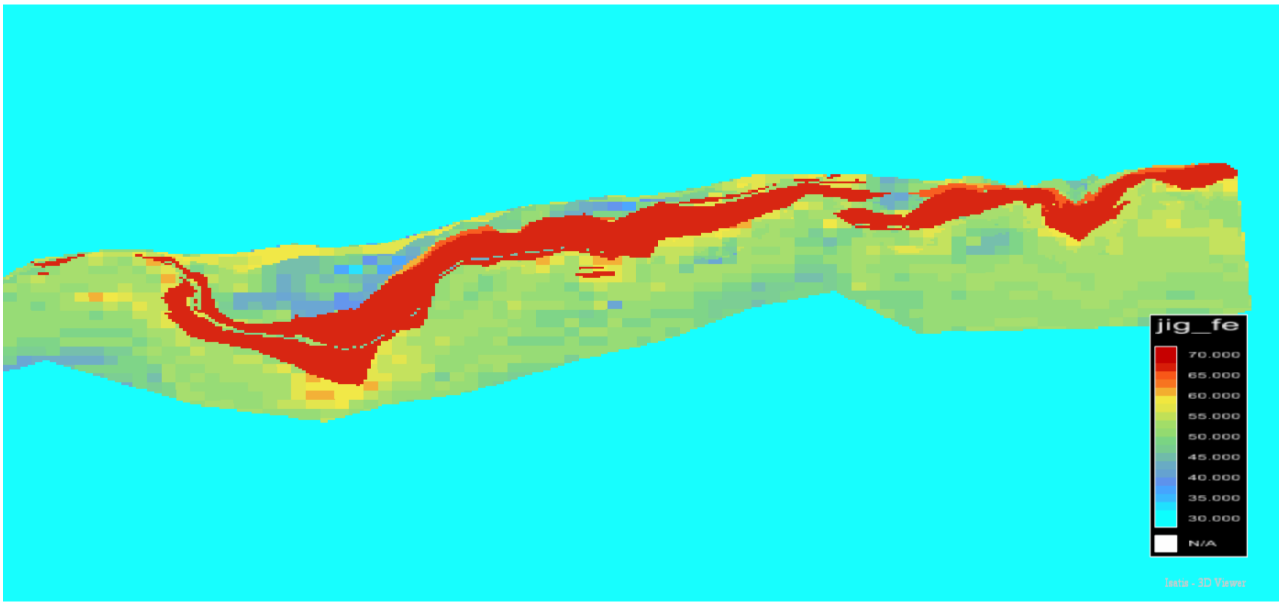


Figure 45 - W-E block model cross-section showing the JIG beneficiated Fe grade in the Sishen Resource Model (Y direction = 67777.5m).

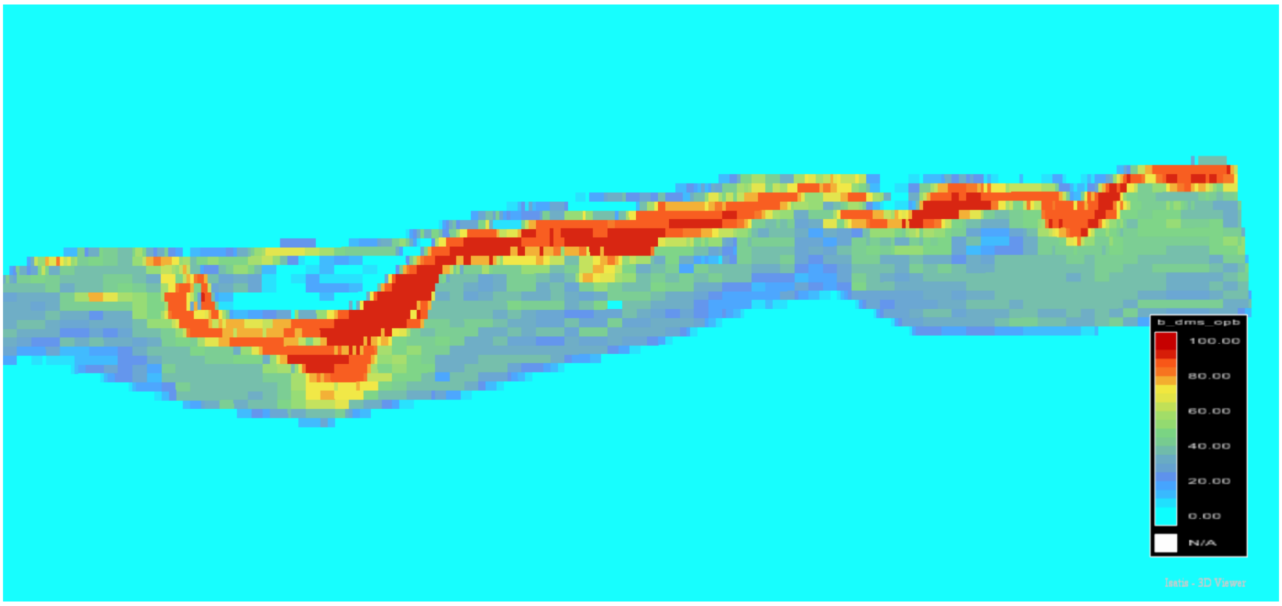


Figure 46 - W-E block model cross-section showing the Bench DMS Yield values in the Sishen Resource Model (Y direction = 67777.5m).

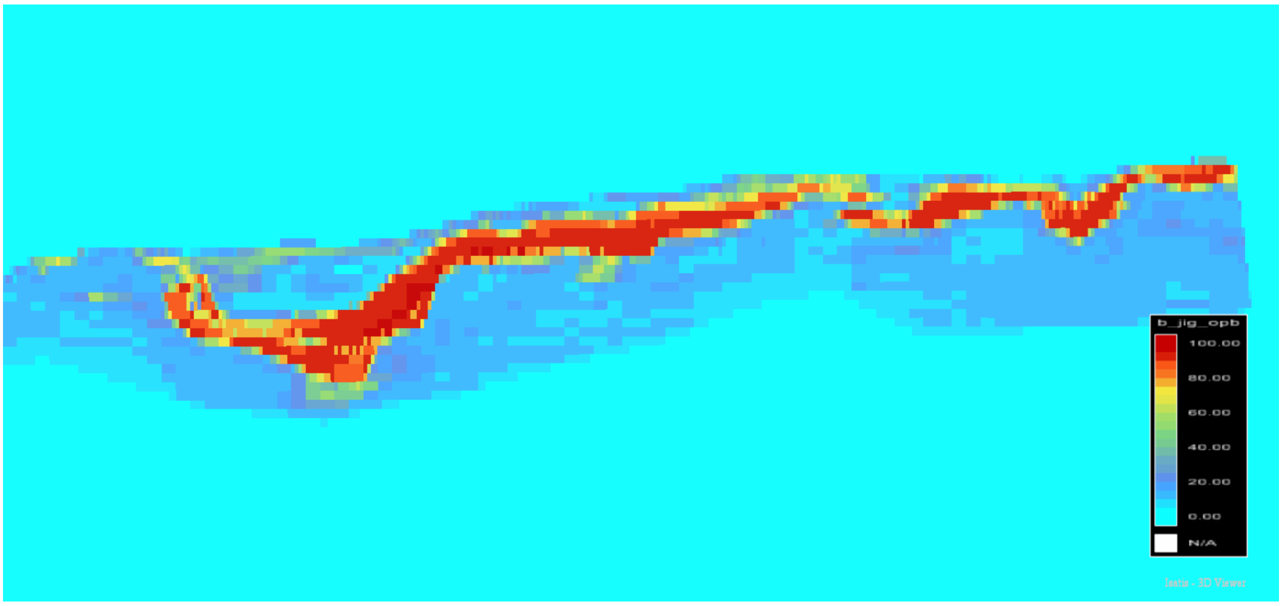


Figure 47 - W-E block model cross-section showing the Bench JIG Yield values in the Sishen Resource Model (Y direction = 67777.5m).

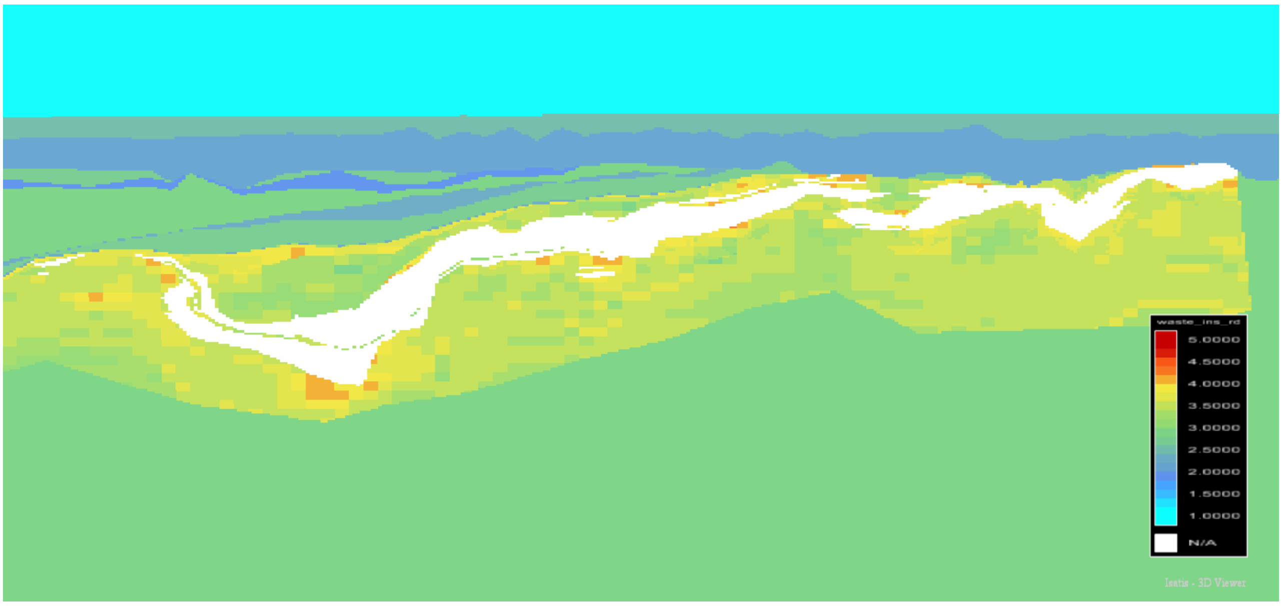


Figure 48 - W-E block model cross-section showing the Waste In-situ RD in the Sishen Resource Model (Y direction = 67777.5m).

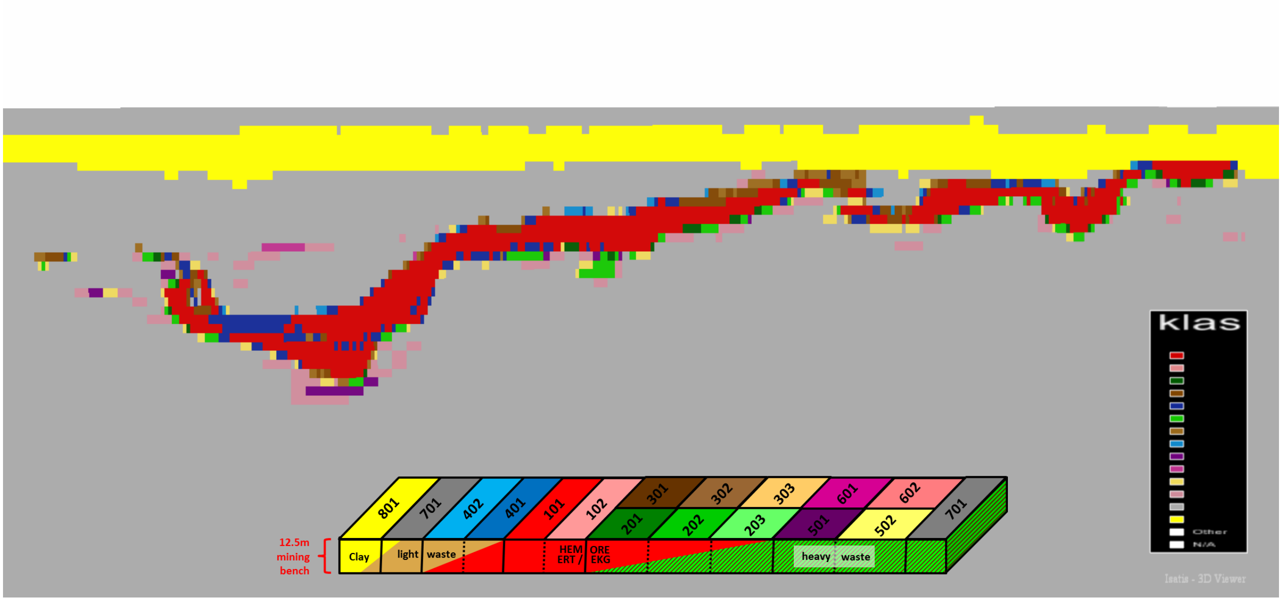


Figure 49 - W-E block model cross-section showing the Material Classification in the Sishen Resource Model (Y direction = 67777.5m).

The Sishen material classification may seem complex, but the main driver for classification is essentially the geological material type on the mining bench. Recall the strong correlation observed between Figure 41 and Figure 49 in the previous section. This concept is further elaborated by Figure 50. This diagram represents a conceptual mining bench with various geological material types occurring at different fractions on the mining bench, shown in front on the mining "face" of the diagram. The top of the diagram shows how the typical material type or a combination of material types on the mining bench will be classified utilising the Sishen material classification matrix.

Starting from the centre of the main orebody, a full bench high-grade ore occurrence will be classified as 10x. Moving left into the hangingwall of the ore body the 40x class will appear where there is a combination of ore and light waste on the bench. Moving right into the footwall of the orebody, the class suites of 20x and 30x appear, depending on which material type occurs in combination with the high-grade ore on the bench. The high-grade ore fraction on the bench controls the XX1 and XX2 number allocation of the final classification. Where more than half bench high-grade ore occurs on the bench, the XX1 class is used, while a fraction of less than half bench ore receives the XX2 class. Where no high-grade ore occurs on the mining bench, class suites 50x, 60x, 70x and 80x are employed. Review the block model sections Figure 41 and Figure 49 to observe the realisation of these concepts.

This concept of geological interpretation and resource classification symbiosis can also be linked to the pit mapping section 2.3.2. (Figure 16) of this report, where the importance of geological contacts and how these influence the grade control process and ultimate utilisation of the orebody were discussed.

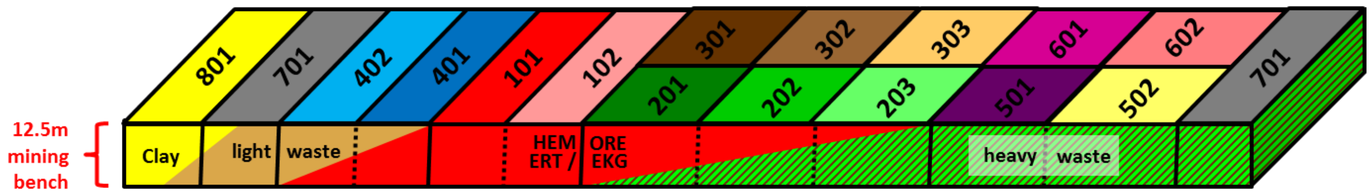


Figure 50 – The Sishen material classification expressed as its first order of classification; geological material type.

In the context of this report, which deals with the performance of geological models, this concept is of utmost importance. It is clear that the geological interpretation, and thus the geological model, have a paramount influence on a resource definition processes such as the material classification systems employed at Sishen. Any changes to the geological model, which will alter geological contact positions and geometry, will have an extensive impact on the defined mineral resources and reserves at mining scale.

3. COMPARING EXPLICIT VERSUS IMPLICIT GEOLOGICAL MODELLING – SISHEN MINE CASE STUDY

The current *Explicit* GeoVia Surpac® geological wireframe model versus the new *Implicit* Aranz Leapfrog Geo® geological wireframes model constructed for the Sishen orebody as discussed in section 2.3.3. will be evaluated in this section.

3.1. Visual Comparison

Figure 51 and Figure 52 show a visual comparison of the Main - and Conglomeratic ore volume modelled respectively as explicit wireframe models and implicit wireframe models. Not appearing totally dissimilar, substantial differences in geometry and connectivity are however observed. The explicit model connects ore intersections more extensively as a function of the manual interpretation. The implicit model is more discontinuous, as it follows simple rules (search radii) to determine whether intersections are associated and therefore connected.

These connectivity differences are also apparent in cross-section view (Figure 53). Extensive differences in how the orebody is constructed by the two modelling conventions are clearly observed. Notice how the manually created explicit model show a succession of tabular modelled orebodies, while the implicit model associates all intersections collectively to model one singular orebody. Also, take note of the relative difference in orebody geometry when the models are compared.

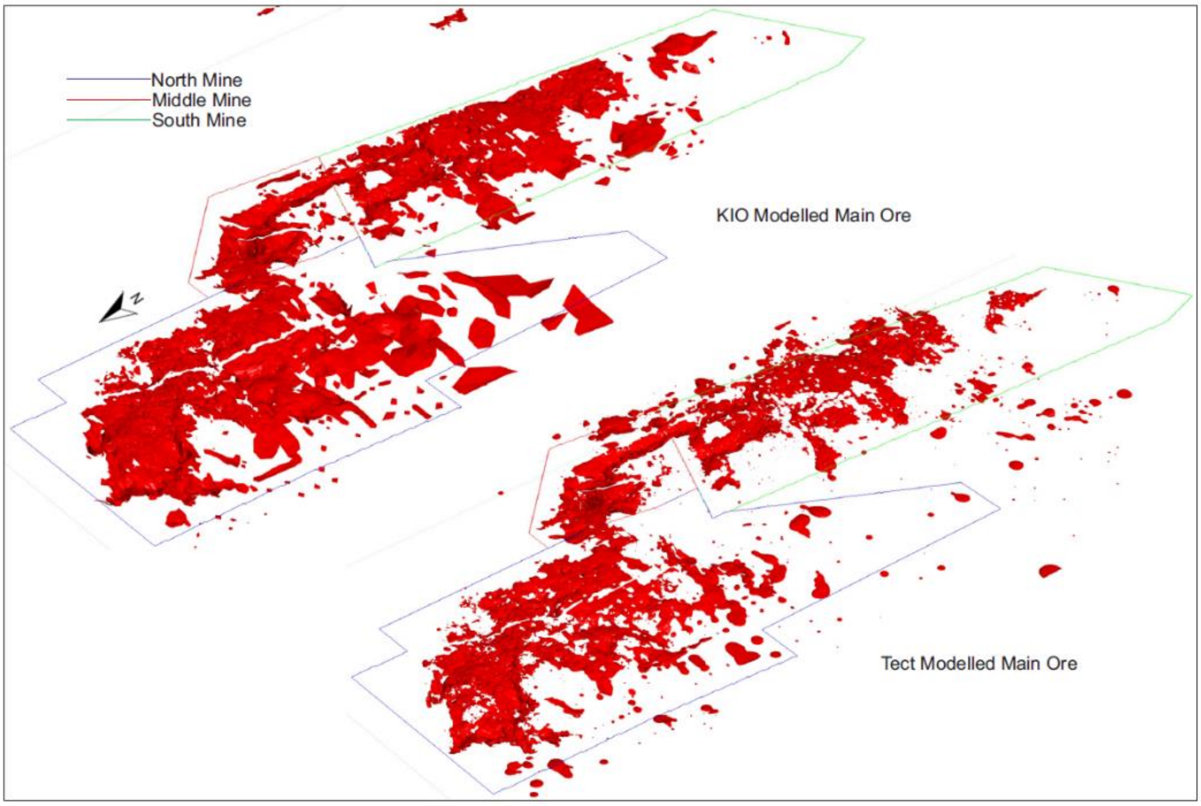


Figure 51 - Comparison of the traditional wireframe Main Ore model (Explicit - top) with the implicit model of the Main Ore (Implicit - bottom) (Anthonissen *et al,* 2016).

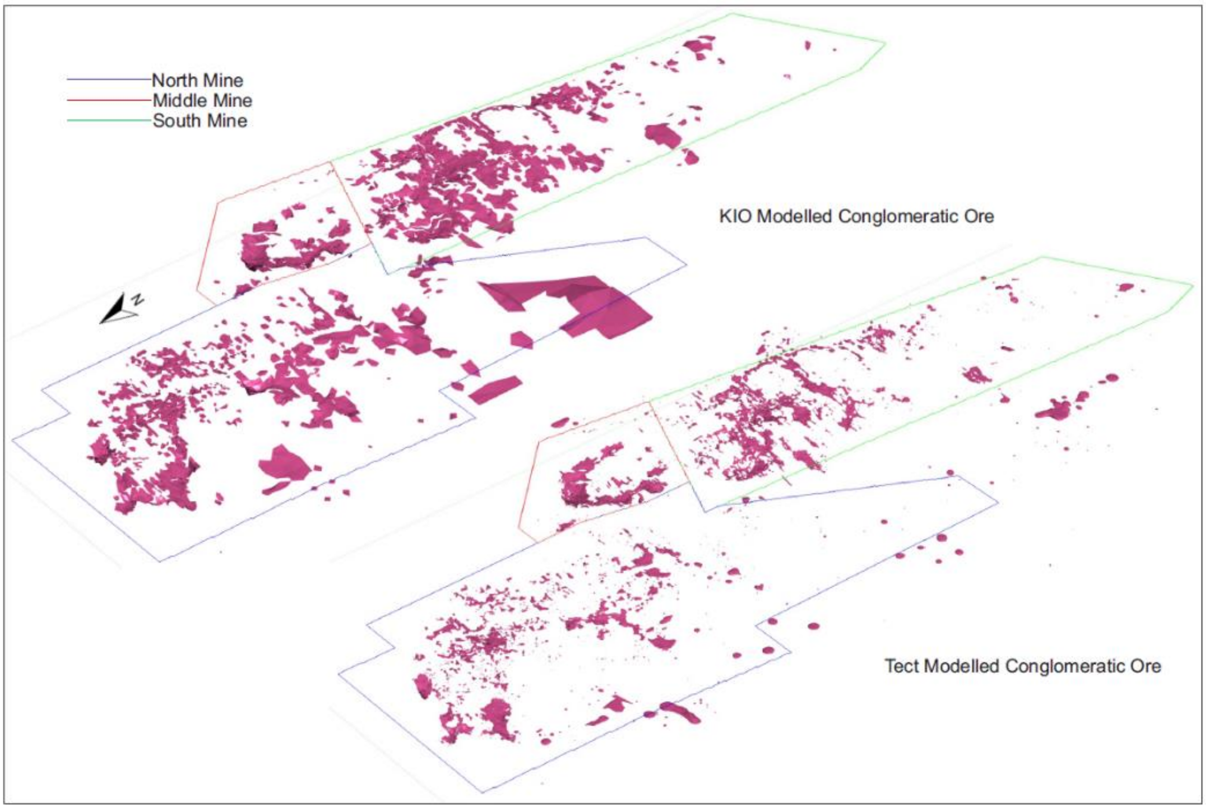


Figure 52 - Comparison of the traditional wireframe Conglomeratic Ore model (Explicit - top) with the implicit model of the Conglomeratic Ore (Implicit - bottom) (Anthonissen *et al,* 2016)

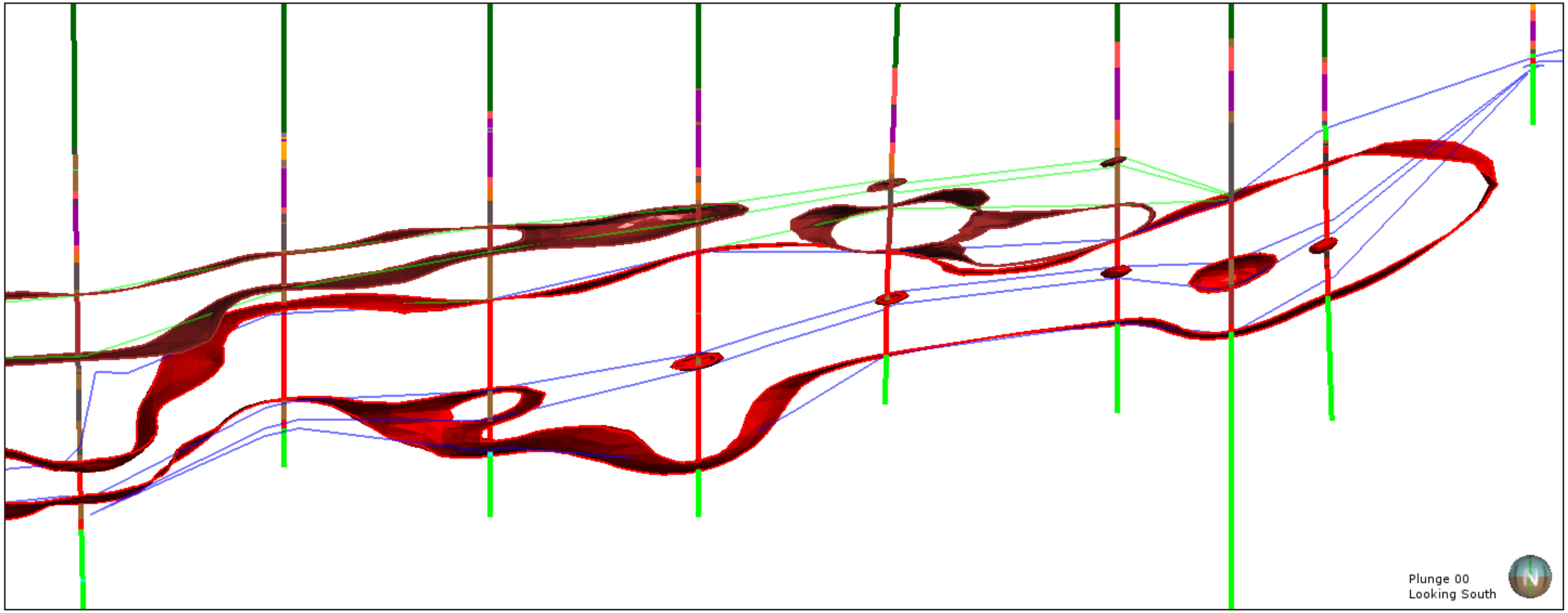


Figure 53 – W-E Cross-section through the explicit ore wireframe (blue and green lines) and implicit ore wireframe models (red and dark red surfaces), showing the connectivity differences (E-W section; Y=67325m).

As discussed in the previous sections, the Sishen resource definition is driven primarily by the geological material content at mining scale (mining bench). It is envisioned that different geological modelling conventions will impact the classification system substantially, as the positions of geological contacts and their orientations are altered on a large scale.

Figure 54 aims to illustrate this concept visually. Figure 54a shows how the geological material type of a single mining bench is populated in the resource block model from the current explicit wireframe model. Figure 54b subsequently shows how the mining bench is classified in the different material classes in the resource block model. Notice the material class distribution and sequencing as a function of geological contacts on the mining bench. Figure 54c shows the new implicit ore wireframes with the current material classification (from the explicit model). Observe the shift in the position of the geological contacts on the bench, and the disparity it show with the current material classification.

Modelling methods have a significant impact on the spatial location and orientation of geological contacts. These modelling induced discrepancies can be amplified in a confined scenario like a singular mining bench. Due to these observations, substantial differences in resource definition are expected as a function of modelling convention for the Sishen orebody case study.

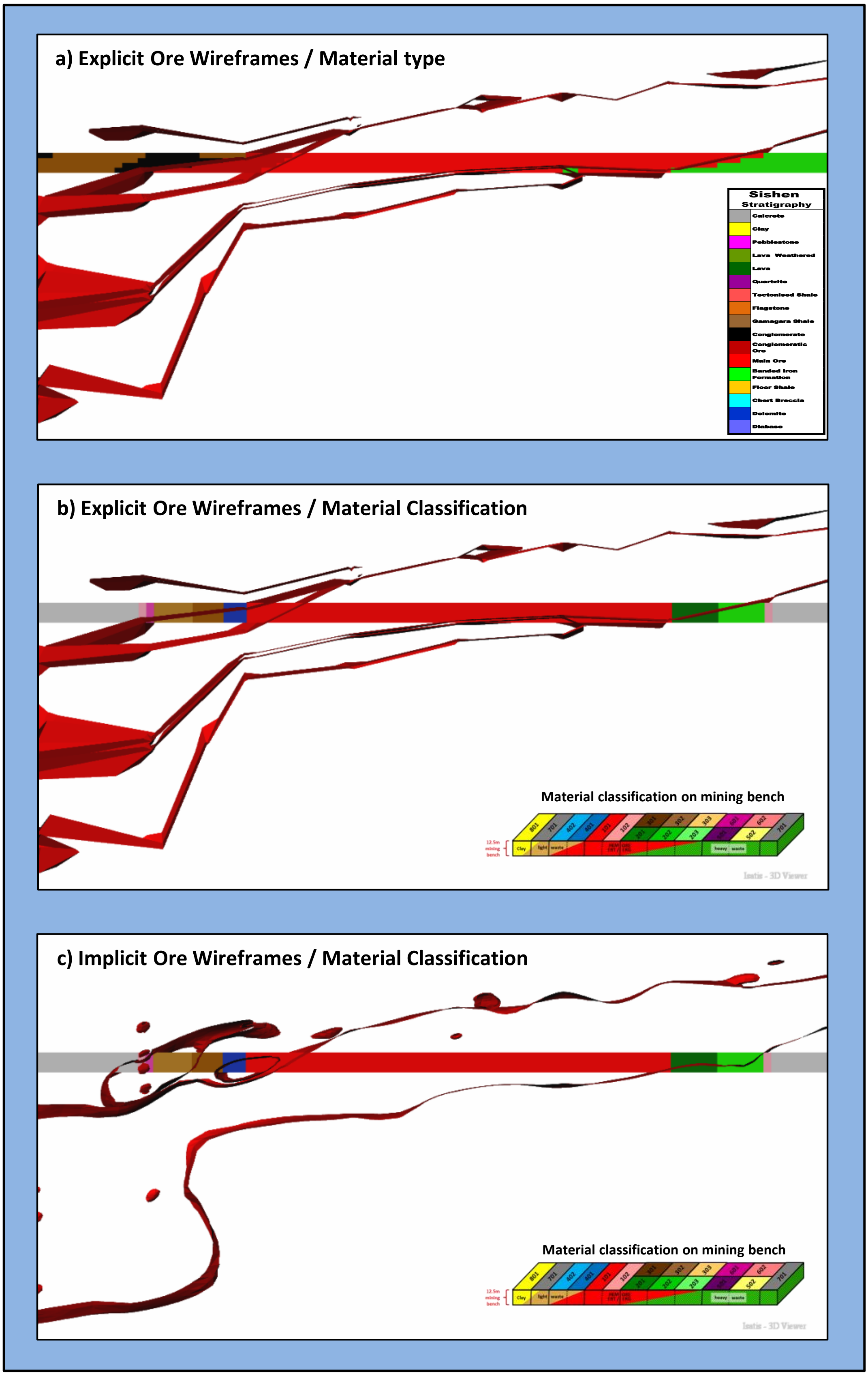


Figure 54 – W-E cross-section of Sishen North Mine, Y = 67075m. Ore wireframes and bench 19 of resource block model shown. a) Explicit ore wireframe models and geological material type assignment in resource model. b) Explicit ore wireframe models and material classification in resource model. c) Implicit ore wireframe models with current material classification in resource model (as in b).

3.2. Volumetric Comparison

First, quantitative comparison of the ore volumes between the current Sishen explicit wireframe model and the new implicit model was undertaken. To facilitate this analysis, the volume was calculated in cubic meters (m^3) for the respective ore wireframe models. The implicit ore model volume was determined in Leapfrog Geo® software. The software reports a calculated volume of the model unit of interest as part of the model validation process. To determine the volume of the explicit ore models, the Surpac® DTM models were migrated to Leapfrog Geo® as DXF files. The software calculates the volume of all the enclosed wireframe elements, producing a total inclusive wireframe volume in cubic meter (m^3). These volumetric reports for the respective explicit and implicit geological ore model wireframes were tabulated for comparison as shown in Table 3 and Table 4.

A total volumetric difference between the implicit and explicit ore model versions of +5.8% and +2.9% for the respective Main Ore - and Conglomeratic Ore volumes are observed (Anthonissen *et al,* 2016). Individual sub-models, however, exhibit ore volumetric movements ranging from -86.84% to +41.06% (Anthonissen *et al,* 2016), which questions the local accuracy of the comparative model performance (Table 3 and Table 4). These aspects warrant further investigation and validation. The impact these discrepancies might introduce in the Sishen resource evaluation process should also be determined.

Table 3 - Normalised volume discrepancy – Main Ore (After Anthonissen *et al,* 2016).

Main Ore (ERT) Wireframe Volume				
Sishen Block Model	Surpac Explicit Model	Leapfrog Implicit Model	Difference	
	Percentage of Total Ore Body - Normalized to Surpac Model	Percentage of Total Ore Body - Normalized to Surpac Model		
NN1	17.19%	18.29%	6.36%	
NN2	14.37%	15.90%	10.60%	
NN3	12.85%	13.70%	6.61%	
NN4	8.26%	7.06%	-14.59%	
North Mine Subtotal	52.68%	54.94%	4.29%	
MM1	14.80%	15.93%	7.64%	
Middle Mine Subtotal	14.80%	15.93%	7.64%	
SS1	13.45%	14.05%	4.51%	
SS2	17.94%	19.59%	9.20%	
SS3	1.13%	1.29%	13.65%	
South Mine Subtotal	32.52%	34.93%	7.41%	
	100.00%	105.80%	5.80%	Total Difference

Table 4 - Normalized Volume discrepancy – Conglomeratic Ore (After Anthonissen *et al,* 2016).

Conglomeratic Ore (EKG) Wireframe Volume				
Sishen Block Model	Surpac Explicit Model Percentage of Total Ore Body - Normalized to Surpac Model	Leapfrog Implicit Model Percentage of Total Ore Body - Normalized to Surpac Model	Difference	
NN1	12.12%	11.08%	-8.66%	
NN2	10.41%	13.43%	29.00%	
NN3	6.59%	6.20%	-5.94%	
NN4	*23.12%*	*3.04%*	*-86.84%*	
North Mine Subtotal	52.24%	33.74%	-35.41%	
MM1	13.43%	15.34%	14.23%	
Middle Mine Subtotal	13.43%	15.34%	14.23%	
SS1	20.38%	19.66%	-3.52%	
SS2	12.89%	11.90%	-7.64%	
SS3	1.07%	1.51%	41.06%	
South Mine Subtotal	34.33%	33.07%	-3.68%	
	100.00%	82.15%	-17.85%	Total Difference
		102.90%	*2.90%*	*Total excluding model NN4*

3.3. Resource Model Comparison

To facilitate the comparative analysis of the potential resource the respective implicit (Leapfrog Geo®) versus explicit (Surpac®) geological models produce, two sets of resource block models with each modelling conventions' wireframe models as the geological model base were created. The block models was constructed to the following shared characteristics:

- Models extend the entire Sishen prospect.
- Models created at the resolution with best proven material classification support (5mx5mx3.125m sub-block size).
- Mineral grades were "frozen" in both models. Grades for the respective modelled geological zones were extracted from the grade estimation "envelopes" created for the resource model. As these grade envelopes are dilated around the zone of interest, it facilitated this process well. Where the modelled geological zone however extended over the grade envelope, a default block grade as defined for each geological zone was allocated.
- The same beneficiation algorithm version was applied to both models to ensure the response of the geological models are comparable.
- Pit progression was defined as the June 2016 pit position in both models ensuring comparable volume of interest (VOI) studies.

A third set of resource block models were then compiled. This model included the geological model (mat) and resource material class (klas) of both models collectively, enabling spatial (block-to-block) analysis and reconciliation.

The following main analyses were performed:

A) Spatial Ore Reconciliation
B) Spatial Full Bench Ore (material class 101) Reconciliation
C) Resource Balance Reconciliation
D) Value Chain Reconciliation Model Performance (monthly production scale) – 3 month period **-** Apr 2016 to Jun 2016

Where applicable the analysis was executed for the complete model and the remaining portion within the reserve shell (final pit design), representing the area within the current life-of-mine (LOM) schedule.

The analyses will use the explicit geological model as baseline, as it is the current, implemented geological interpretation of the deposit. The quantitative measure of difference between the proposed implicit model and baseline explicit model will be determined for all analyses.

3.3.1. Spatial Ore Reconciliation

A spatial reconciliation (location based ore-to-waste; waste-to-ore changes) can be a very informative tool to quantify the exact orebody emplacement difference between the 2 geological model versions. Figure 55 and Figure 56 show this concept visually. The particular geological section shows just how different the orebody geometry can be interpreted with different modelling techniques. The explicit model shows more continuous modelling of stratiform orebodies, indicative of a unique interpretation by a geologist. The implicit model can simply not reproduce this interpretation as a direct function of the choice of "geometry" style (Leapfrog Geo® – Intrusion, Figure 24), and following a rule-based approach, resulting in the implicit model's connectivity characteristics being very different from that of the explicit model.

On this particular section (Figure 55) the total ore modelled (area) with the respective modelling techniques are probably not that dissimilar. Spatially, however, the amount of ore-to-waste and waste-to-ore conversions induced by modelling technique is substantial (Figure 56). These conversions should be quantified and recognised to determine the true potential impact on the resource incurred by modelling technique.

To facilitate this study, the resource block model which included the geological model (mat) and resource material class (klas) of both models collectively were used. A series of block model reports were generated catering for scenarios of block-to-block ore-to-waste and waste-to-ore discrepancies. These results were tabulated and graphs were created to show the spatial reconciliation between the models.

Ore Material in the Full Prospect

Figure 57 show the quantified spatial movements of the total Sishen orebody modelled respectively implicitly and explicitly as a waterfall chart. The chart shows a spatial ore volume loss (ore-to-waste) of 26.47% from the current explicit model and a spatial ore volume gain (waste-to-ore) of 24.46% over the current explicit model when the orebody is implicitly modelled. The difference between the loss and gain expresses the net ore volume difference of only -2% between the explicit and implicit models. 73.57% of the orebody is defined as unchanged (ore-to-ore), where ore was defined at the same spatial position in both models.

Although the total volumetric ore volume change is small (only 2%) the spatial difference between the two models is substantial. From the graph, we can interpret that 26.47% of the current defined explicit modelling based orebody is not defined as ore anymore based on the implicit model (ore-to-waste loss). 24.46% of "new" ore were created by the implicit model in locations previously defined as waste by the explicit model. 50.93% (gain plus loss) of the current defined Sishen orebody is thus spatially altered by modelling the orebody with respective explicit - and implicit modelling techniques.

The spatial ore volume movements can also be expressed in geological material exchange terms as a doughnut chart. Figure 58 and Figure 59 show the respective material type exchanges of the Main Ore and Conglomeratic Ore when the two ore models are spatially reconciled. Firstly the chart shows the ore component that stayed unchanged (ore-to-ore movement) in both version of the ore models. Inter-ore zone cannibalism (fraction of conglomeratic ore converted to main ore and vice versa) are also shown, where there was a spatial ore type change in the respective models. The inner doughnut shows the ore loss fraction (ore-to-waste) where ore defined explicitly was converted to waste in the implicit model. These conversion losses are colour coded to show to which geological material types current explicitly defined ore was lost by definition in the implicit model. The outer doughnut shows the ore gain fraction (waste-to-ore) where ore outside the current explicit model (previously waste) was defined by the implicit model.

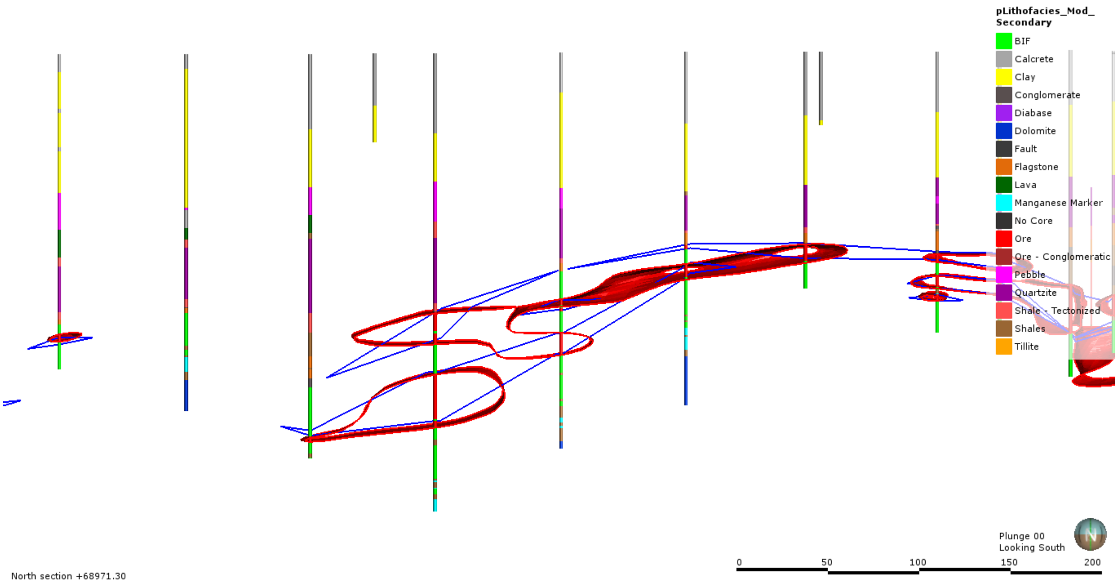


Figure 55 - Explicit - versus implicit geological ore model. Explicit model - blue outline; implicit model - red surface elements.

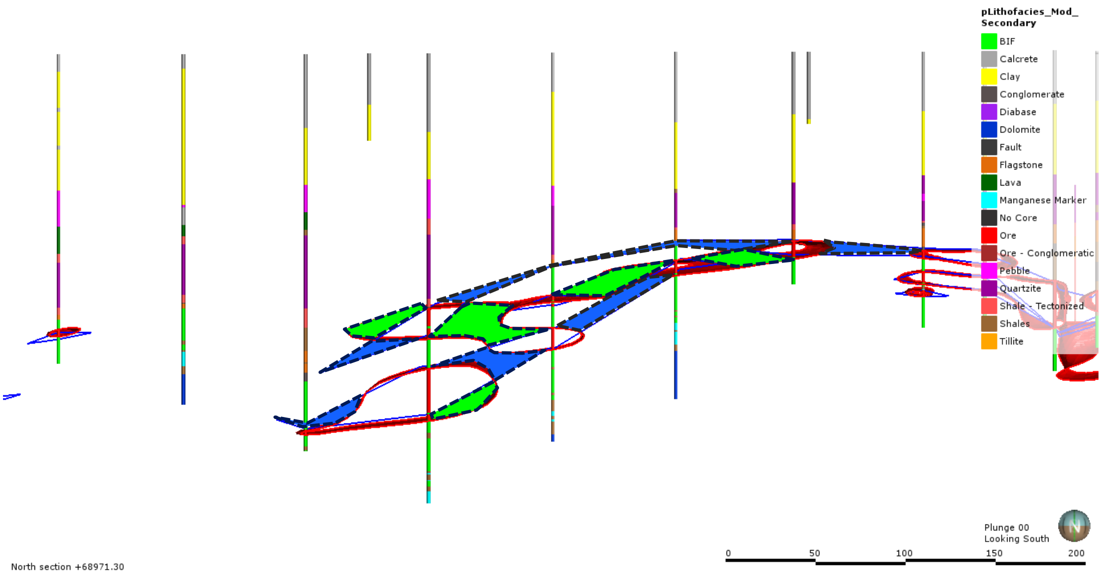


Figure 56 - Spatial volume discrepancies between explicit and implicit ore models. Green area – implicit model spatial gain in ore volume by modelling ore outside the explicit model definition (ore gain); blue area –previously defined ore in explicit model lost by implicit modelling definition (ore loss).

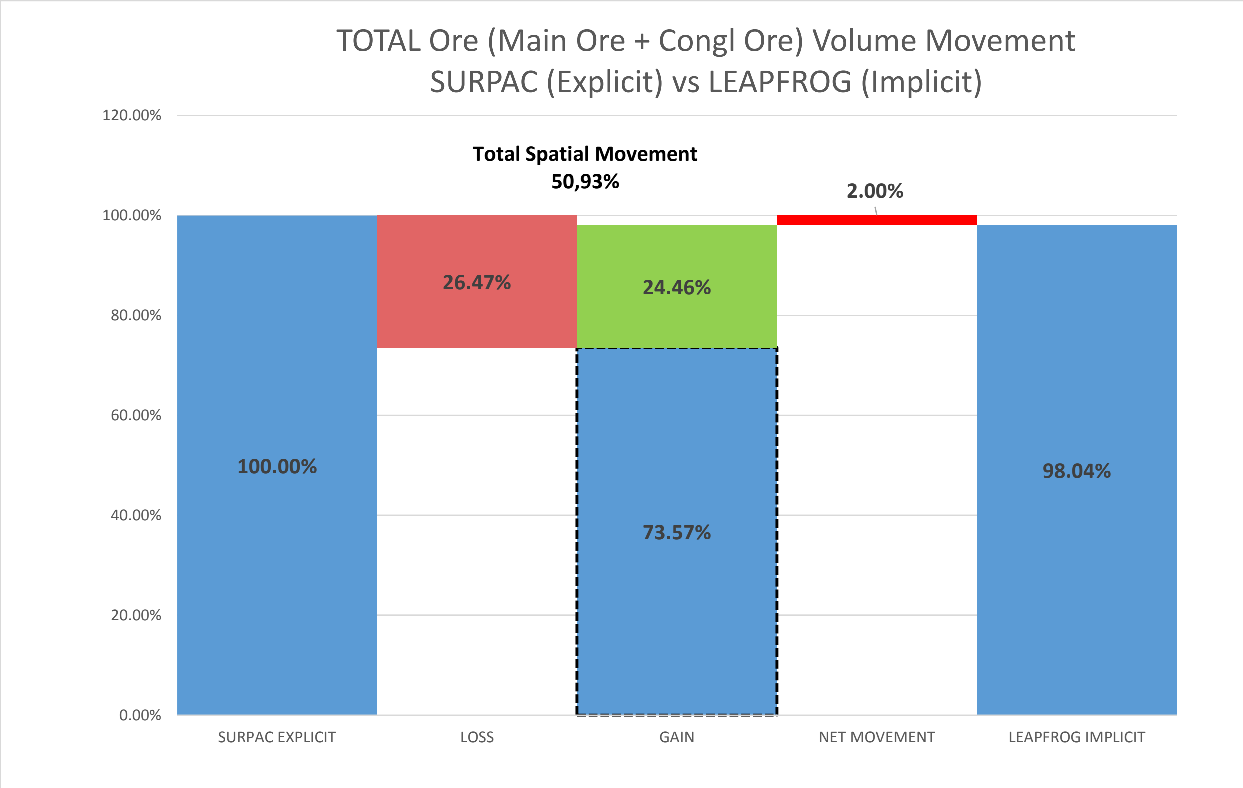


Figure 57 - Spatial volume reconciliation between the current explicit model and the proposed Implicit model for the total ore volume in the full Sishen prospect. Notice how the large fractions of spatial losses and gains collectively produce a small net difference in model volume.

These comparative gains of implicitly-defined ore are also colour coded to show from which explicitly-defined waste geological material types ore volume were additionally created. The ore/gain spatial volume reconciliation is balanced by including the net ore type volume gain or loss in the hatched component on the graph (Figure 58 and Figure 59).

It is expected that the conglomeratic ore will show more conversions to hangingwall geological units (Figure 59), while the main ore shows more conversions to footwall geological units (Figure 58) due to their stratigraphic positions. If there is ore loss/gain imbalance to a certain geological unit it warrants further investigation to determine the cause.

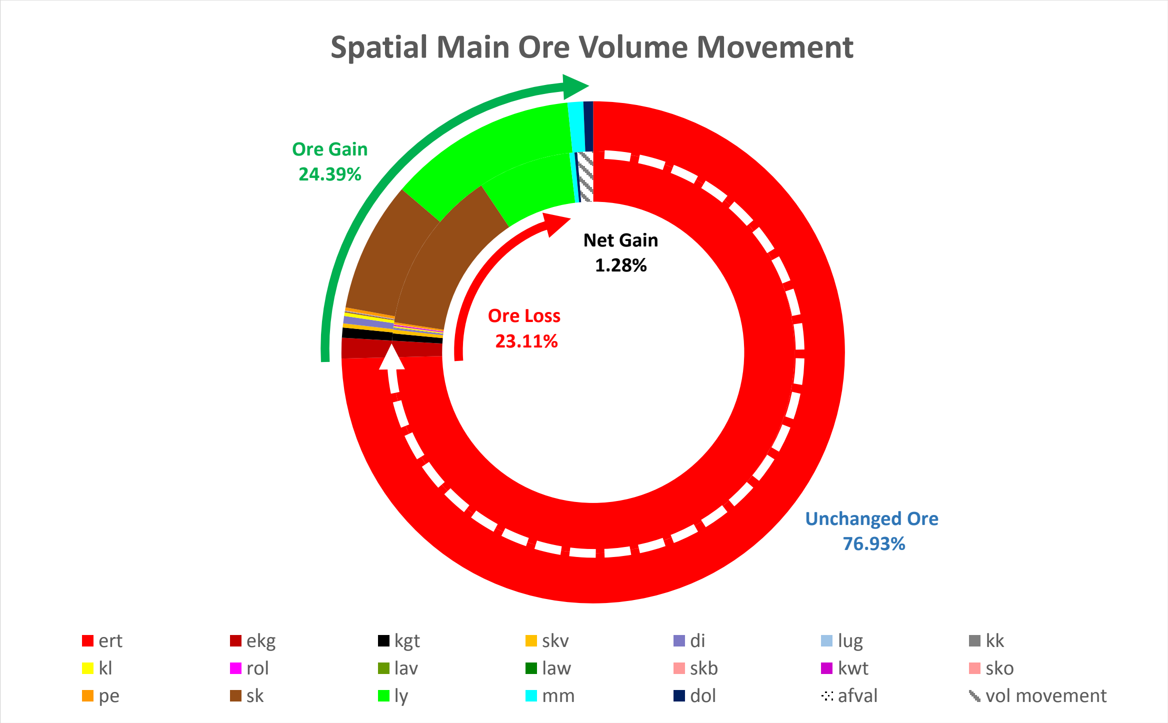


Figure 58 - Main Ore spatial volume reconciliation, expressed as geological material type exchanges. Complete Sishen orebody. Unchanged Ore = Ore that spatially occurs as ore in both models. Ore Loss = Explicit modelled ore that converted spatially to waste material in Implicit model (coloured by waste type). Ore Gain = Ore that was created by Implicit model, defined spatially as waste in explicit model (coloured by waste type). Reconciliation balanced with Net volume Gain/Loss (dashed fraction).

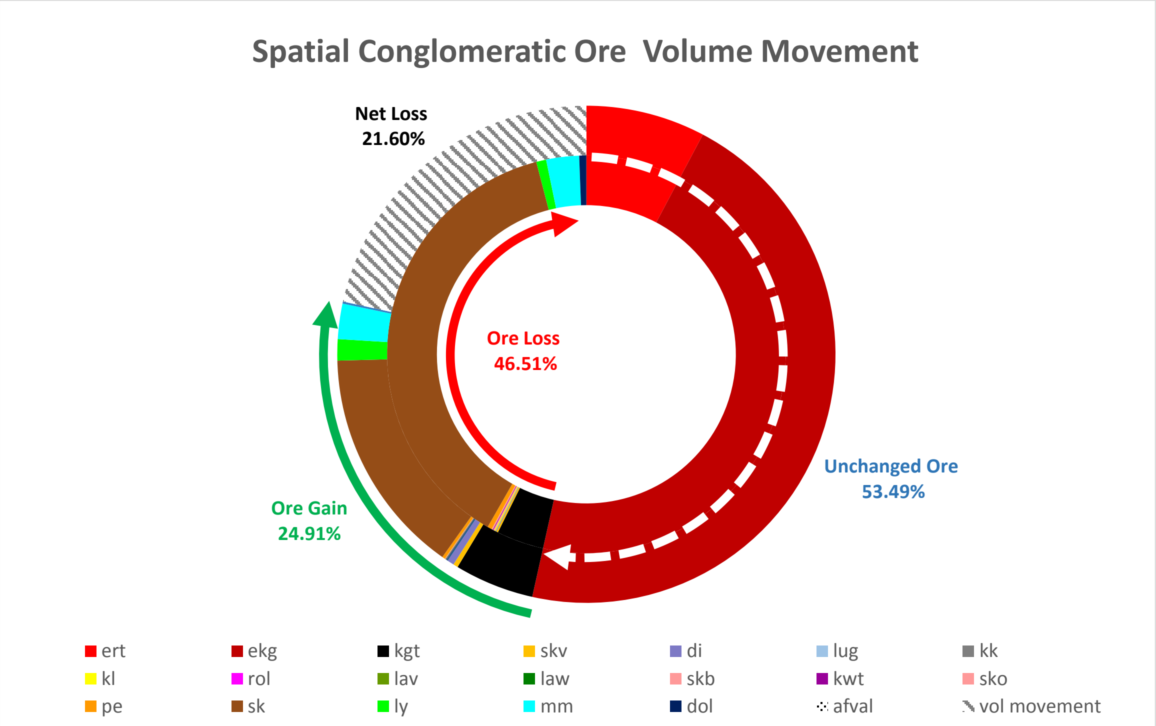


Figure 59 - Conglomeratic Ore volume spatial volume reconciliation, expressed as geological material type exchanges. Complete Sishen orebody. Unchanged Ore = Ore that spatially occurs as ore in both models. Ore Loss = Explicit modelled ore that converted spatially to waste material in Implicit model (coloured by waste type). Ore Gain = Ore that was created by Implicit model, defined spatially as waste in explicit model (coloured by waste type). Reconciliation balanced with Net volume Gain/Loss (dashed fraction).

Ore Material in the Final Pit Layout

For the remaining Sishen resource (portion within the final pit design) the same trends of spatial movements are observed (Figure 60) as in the full extent of the orebody (Figure 57). The spatial loss and gain fractions from the explicit geological model are slightly smaller compared to the movements of the total orebody at respectively 22.53% and 19.35% when the geological model is implicitly defined. The net ore volume loss from the explicit model increased slightly to 3.18% for the orebody portion in the remaining life-of-mine (LOM) schedule when defining the ore volume implicitly.

The spatial geological movement graphs show reduced spatial losses and gains of ore (Figure 61 and Figure 62) in the final pit design compared to the total orebody (Figure 58 and Figure 59). The doughnut charts for the remaining minable ore also show more balanced spatial losses and gains to other geological material types when the 2 geological model versions are compared. This can be attributed to the higher drill data density within the LOM area compared to a mixture of drill densities used to define the orebody in its entirety. This analysis confirms just how critical data quality and density is for the geological modelling and resource definition. It is clear that data density has a direct impact on the interpretation of the orebody. Areas with more data-support will have more similar interpretation characteristics, while many interpretation possibilities exist in areas where only limited data is available.

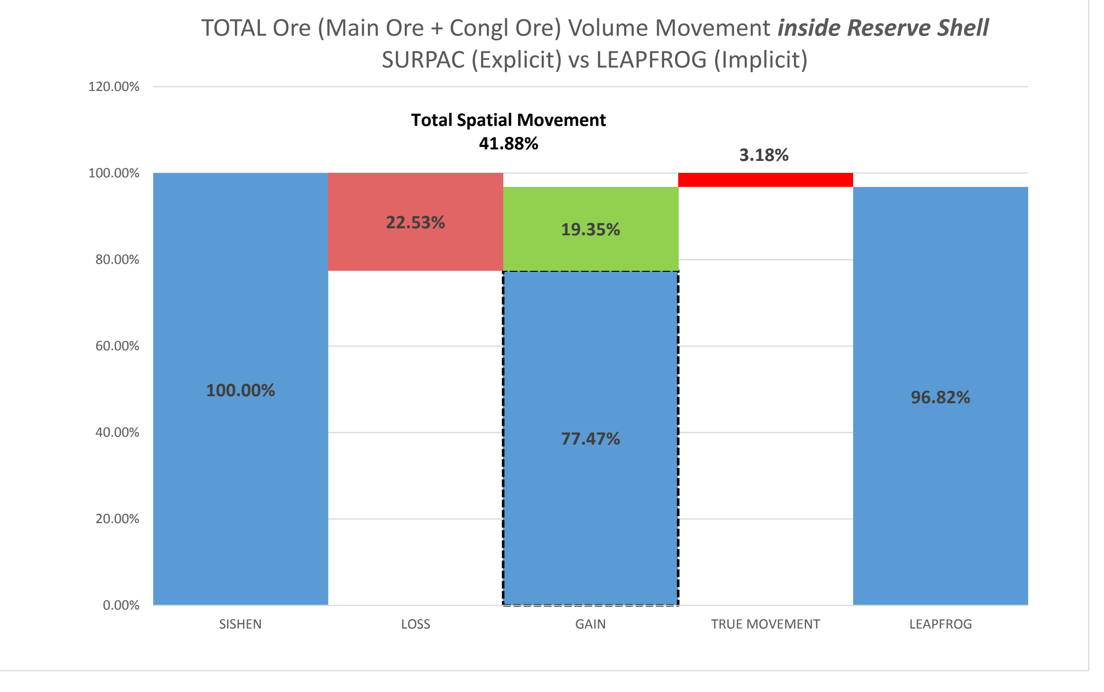


Figure 60 - Spatial volume reconciliation between the current explicit model and the proposed implicit model for the ore volume in the Sishen final pit design. Observe slightly smaller fractions of spatial losses and gains compared to unconstrained full orebody (Figure 57).

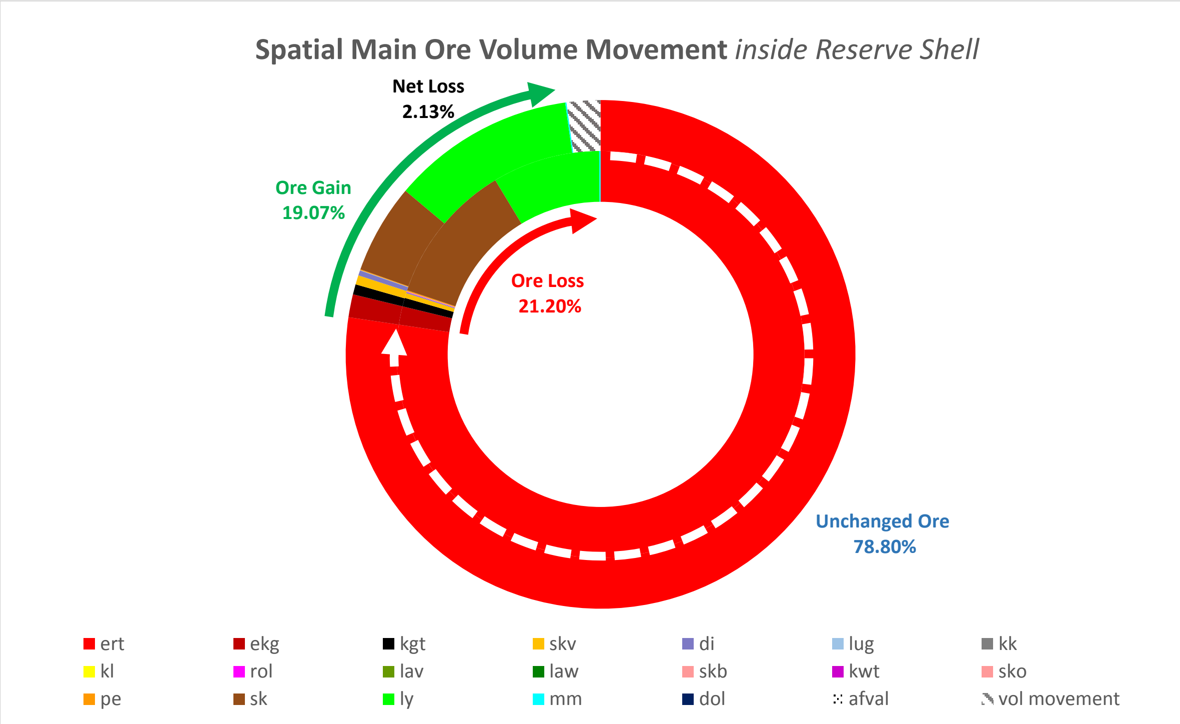


Figure 61 - Main Ore spatial volume reconciliation, expressed as geological material type exchanges. Remaining ore in the Final Pit design. Unchanged Ore = Ore that spatially occurs as ore in both models. Ore Loss = Explicit modelled ore that converted spatially to waste material in Implicit model (coloured by waste type). Ore Gain = Ore that was created by Implicit model, defined spatially as waste in explicit model (coloured by waste type). Reconciliation balanced with Net volume Gain/Loss (dashed fraction).

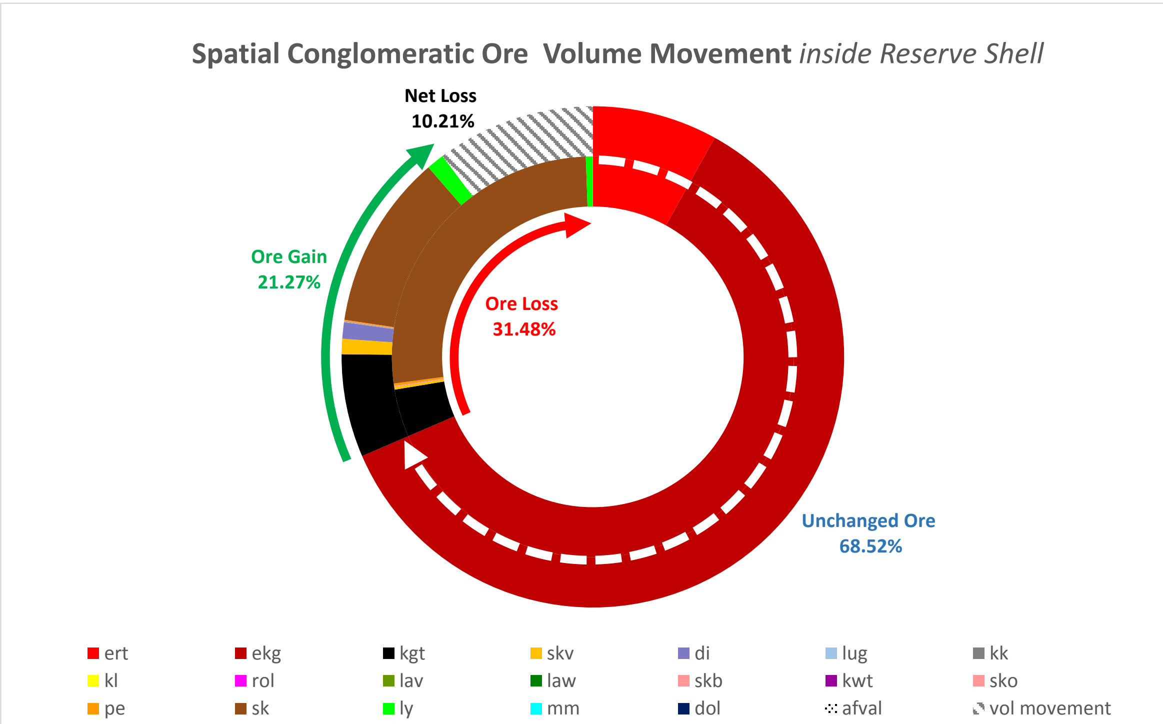


Figure 62 - Conglomeratic Ore volume spatial volume reconciliation, expressed as geological material type exchanges. Remaining ore in the Final Pit design. Unchanged Ore = Ore that spatially occurs as Ore in both models. Ore Loss = Explicit modelled ore that converted spatially to waste material in Implicit model (coloured by waste type). Ore Gain = Ore that was created by Implicit model, defined spatially as waste in explicit model (coloured by waste type). Reconciliation balanced with Net volume Gain/Loss (dashed fraction)

3.3.2. Spatial Full Bench Ore Reconciliation

Sishen produces a niche high-grade lump ore product, very desirable in the market due to its physical properties. Most of this product is produced from the full bench high-grade ore material class 101 as produced by the Sishen Material Classification based resource definition. It is therefore important to test how different geological models affect the occurrence of these full bench ore realisations at mining scale.

The same methodology as for the spatial ore volumetric study was followed. Block-to-block reconciliation of the 101 material class resource was undertaken to quantify how much of this critical full bench ore material class was spatially lost or gained as a direct function of the geological model used as the base of the resource definition.

Full Bench Ore Material in the Full Prospect

The waterfall chart Figure 63 shows the spatial reconciliation in the resource as defined using the respective explicit and implicit geological models as a base for the Sishen resource definition (material classification) process. Within the total Sishen prospect, 22.77% of the current defined 101 material class material as defined by the explicit model is spatially lost by using the implicit model as base for the resource definition process. Concurrently, 32.19% new full bench ore realisations are spatially created when the implicit model is applied in areas not defined as full bench 101 material class resource by the explicit model. The net increase in full bench ore 101 material class when the implicit model is used is 9.42%, compared to the current explicit geological model based resource. 77.23% of the 101 material class stay spatially unchanged in both versions of the geological models as full bench defined resource definitions.

The doughnut chart Figure 64 indicate the spatial movements observed in the 101 material class when the resource is based on the implicit model and shows to which material classes full bench ore material is lost and gained from the current explicit model based resource definition. As expected the bulk of spatial (block-to-block) full bench ore conversions were to and from the contact material classes 201 to 402. It is concerning that a large fraction of the full bench ore spatial gains over the explicit model were conversions from the material classes 501 to 701 when the implicit model was used as a base for the resource definition process. No ore component was previously defined in these spatial locations with the explicit model as a base, while the implicit model creates full bench ore realisations in these locations.

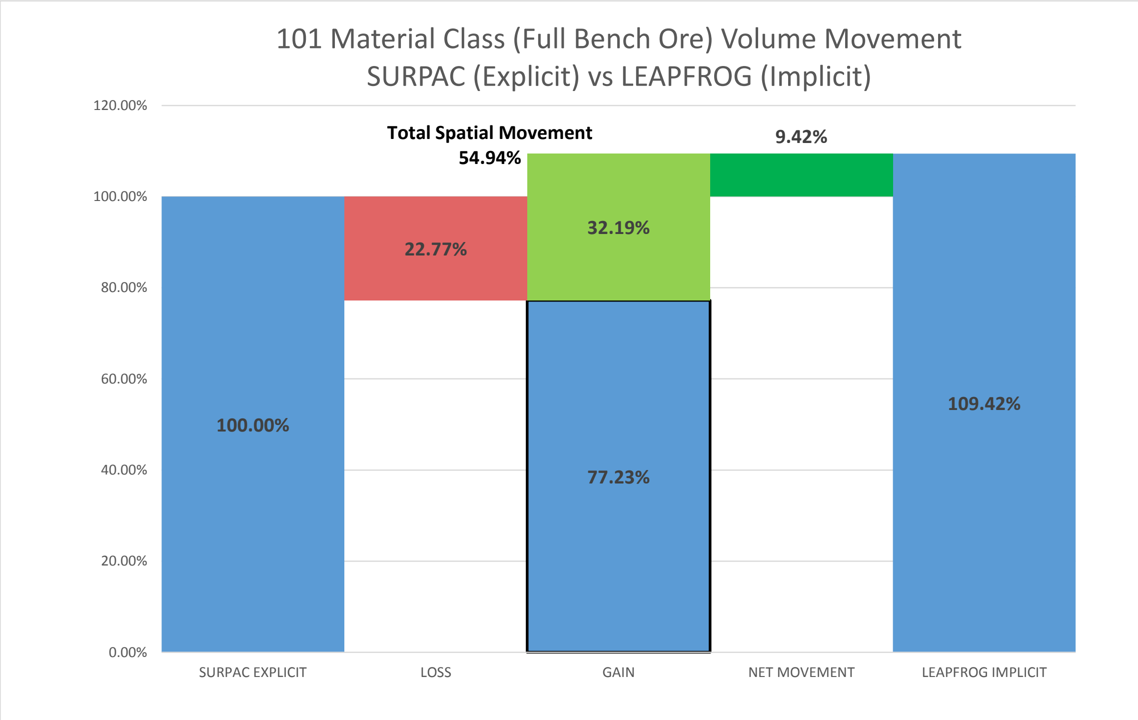


Figure 63 – Spatial volume reconciliation between the current explicit model and the proposed implicit model for the full bench ore material class 101, for the full Sishen prospect. Notice how the net increase in volume is created by relatively large spatial gains and losses from the explicit model.

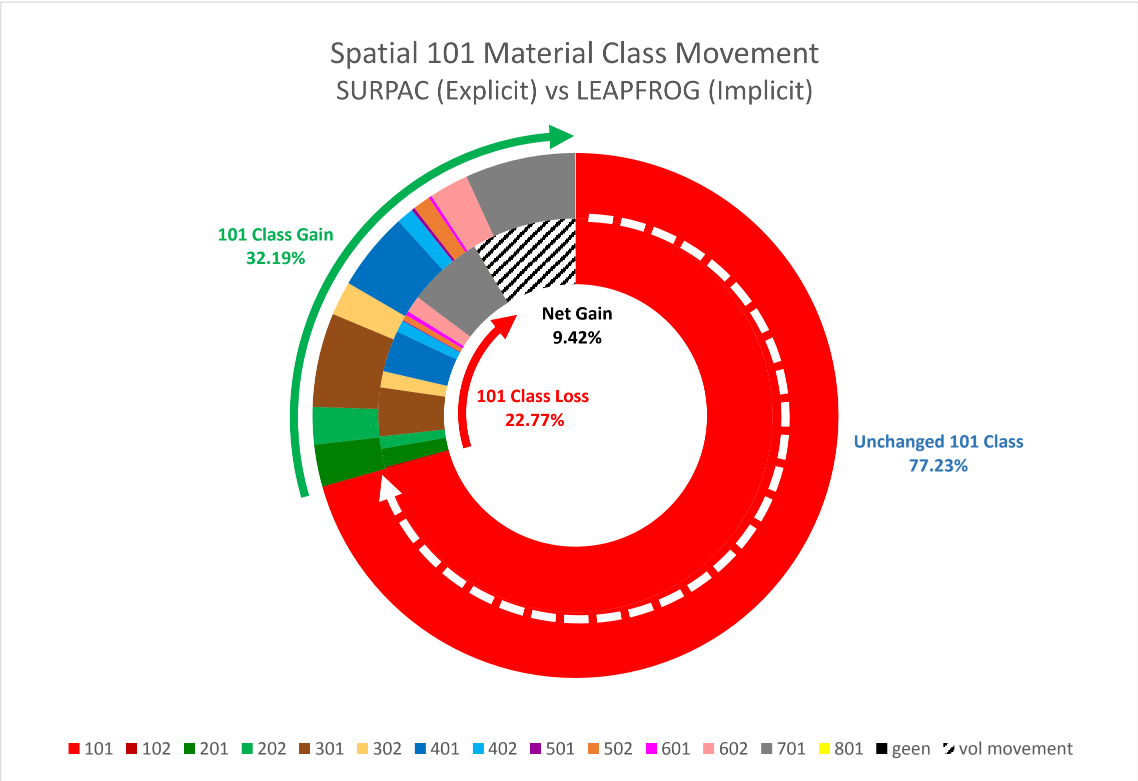


Figure 64 - Material Class 101 spatial volume reconciliation, expressed as resource definition type exchanges. Complete Sishen orebody. Unchanged 101 Class = Full bench ore class that spatially does not convert to another class in both models. 101 Class Loss = 101 Class material produced from explicit model that converted spatially to another class based on the Implicit model (coloured by class). 101 Class Gain = 101 Class material that was created based on the Implicit model, defined spatially as another class by means of the explicit model (coloured by class). Reconciliation balanced with Net volume Gain/Loss (dashed fraction).

Full Bench Ore Material in the Final Pit

The portion of the Sishen deposit inside the current life-of-mine (LOM) schedule show the same trends of spatial movements in the 101 full bench high-grade ore material class as for the full prospect. The total volumetric gain induced by implementing the implicit geological model increased to 11.04% (Figure 65 versus Figure 63). The doughnut chart shows good balance in the relative gains and losses of resource class exchange by basing the resource definition on the respective explicit and implicit geological models.

The full bench high-grade ore conversion from the non-ore component classes 501 to 801 is also less than observed for the full prospect (Figure 66 versus Figure 64). This is again indicative of the greater data support in the life-of-mine (LOM) area, which leads to more comparable interpretations in the respective explicit and implicit geological models.

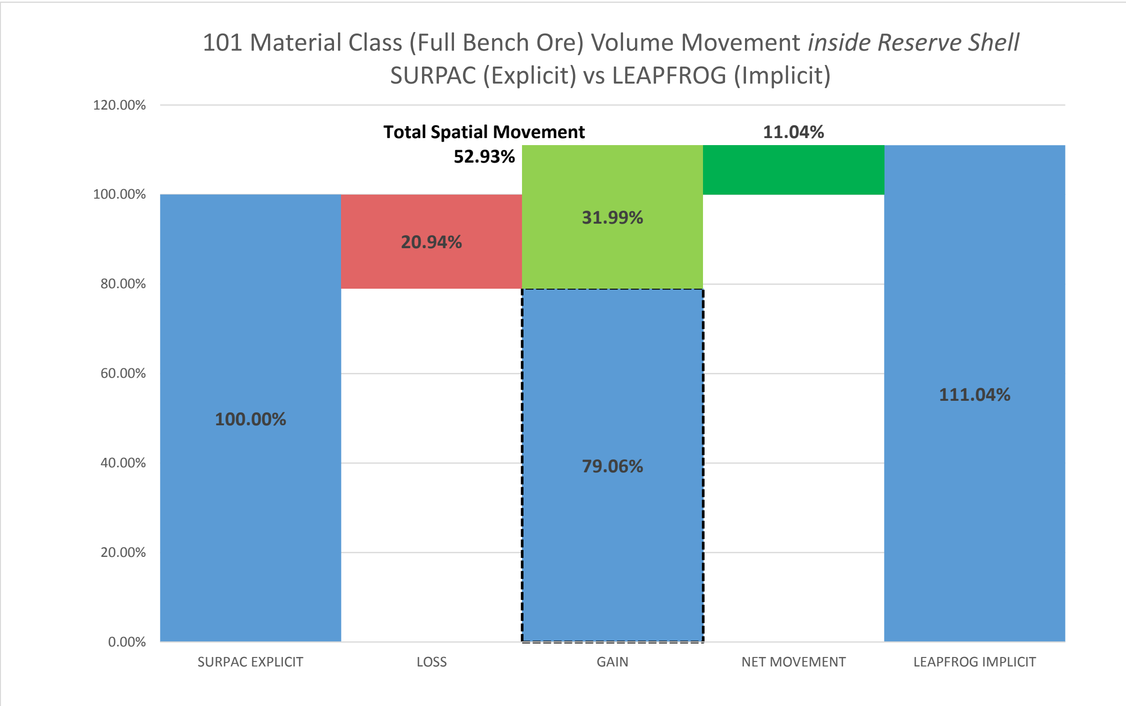


Figure 65 - Spatial volume reconciliation between the current explicit model and the proposed implicit model for the full bench ore material class 101, in the remaining minable portion of the orebody. Notice how the large net increase in volume created by the implicit model created by large spatial gains and losses from the explicit model definition.

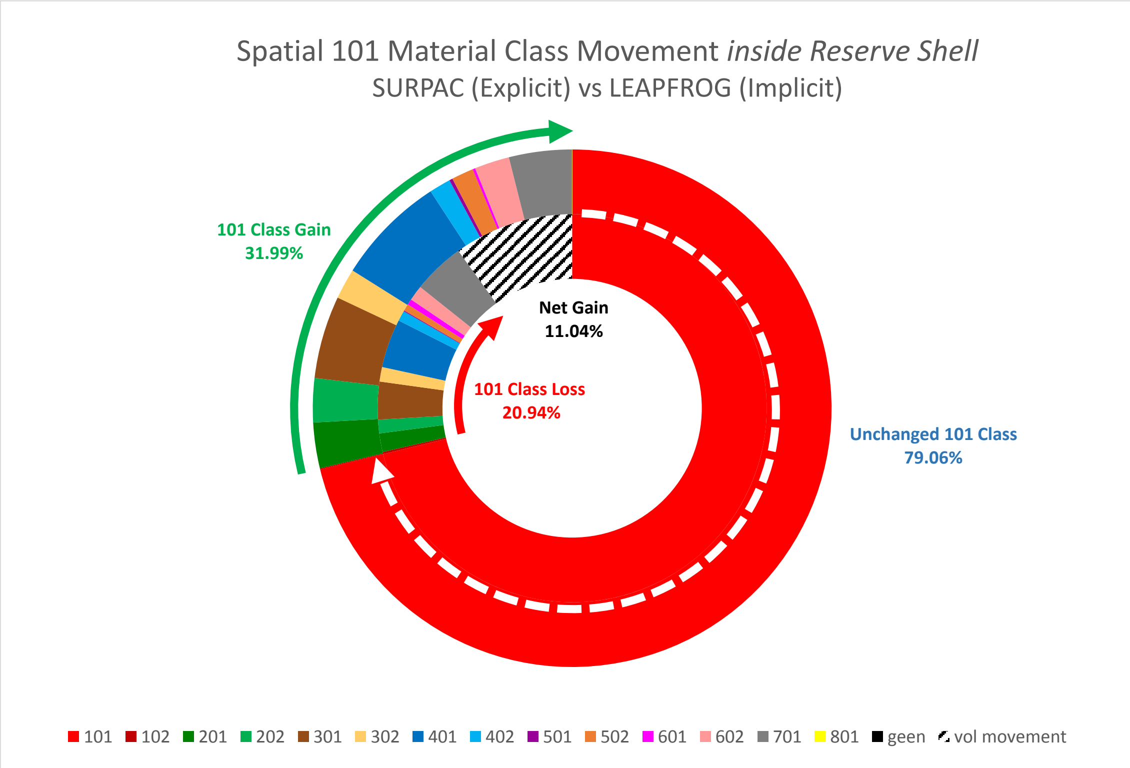


Figure 66 - Material Class 101 spatial volume reconciliation, expressed as resource definition type exchanges. Remaining minable portion of the orebody. Unchanged 101 Class = Full bench ore class that spatially does not convert to another class in both models. 101 Class Loss = 101 Class material produced from explicit model that converted spatially to another class based on the Implicit model (coloured by class). 101 Class Gain = 101 Class material that was created based on the Implicit model, defined spatially as another class by means of the explicit model (coloured by class). Reconciliation balanced with Net volume Gain/Loss (dashed fraction).

It is clear from this analysis that the different modelling conventions change the geological contact distribution and geometries substantially. This has an immense effect on the Sishen resource definition process, with large portions of the currently defined resource translating spatially due to changes in the geological model.

Figure 67 to Figure 74 show how the comparative geological models shepherd the Sishen material classification and resource definition process. Different modelling conventions lead to substantially different distributions of geological material types, fundamentally influencing the defined resource distribution (Sishen resource material classes).

Figure 67 and Figure 68 represent the current explicit geological model and the associated material class distribution it produces. Figure 69 and Figure 70 are the implicit geological model and associated material class distribution the implicit model produces. This set of figures represents the typical geological setting of Sishen North Mine. Comparing the geological models in Figure 67 and Figure 69, good correlation between the distributions of material types are observed. Notice however the clear differences in model connectivity, with the implicit geological model exhibiting “smoother” and “globular” orebody geometries compared to the explicit model. The ramification of these geometric changes in the orebody are apparent in the material classification distribution the respective explicit model (Figure 68) and implicit model (Figure 70) produce. Notice the distinct discrepancies between the 2 material classification products. Significant changes in resource definition are observed at the hangingwall and footwall of the main high-grade orebody, where the relative position of the geological contact changes.

The series of Figure 71 to Figure 74 show another example (Sishen South Mine) of this concept. Because the orebody is generally thinner and more erratic in Sishen South Mine, compared to Sishen North Mine, the perceptible discrepancies in geological connectivity and defined resource class distribution are amplified. This may be attributed to the greater impact of convoluted geological contacts, associated with a thinner orebody, at the mining scale (bench).

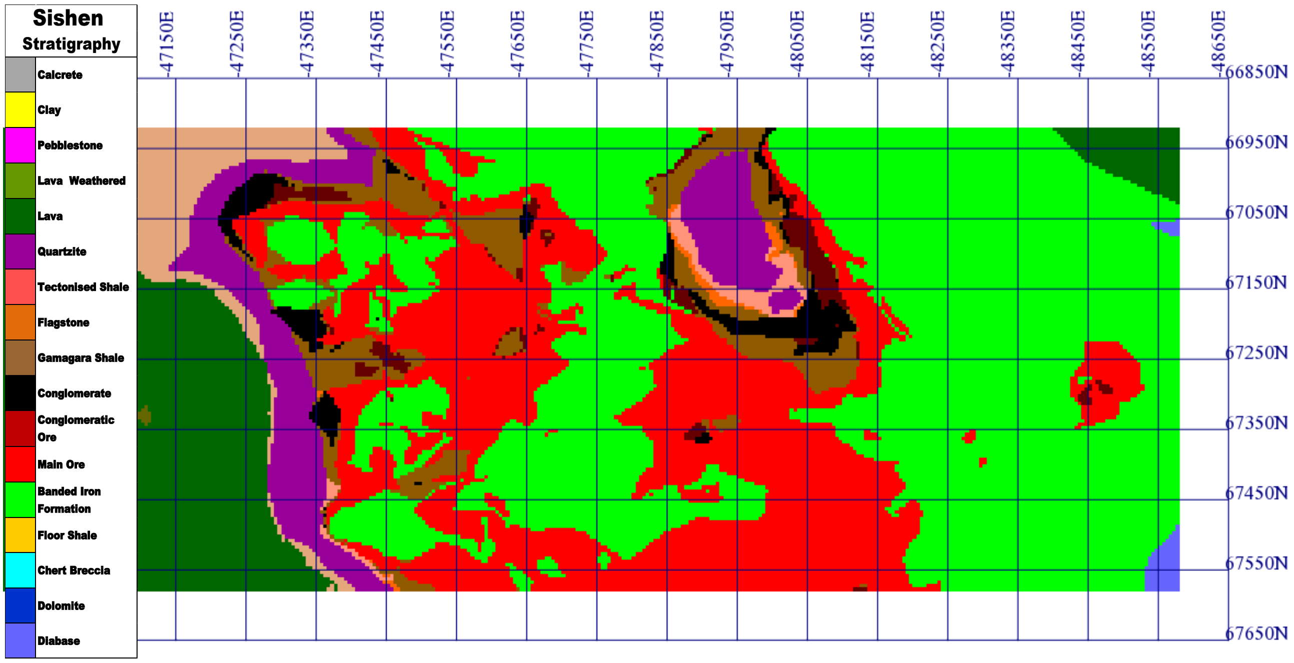


Figure 67 - Bench plan from Resource Model based on the explicit geological model showing the defined geological material type. Sishen model nn1_b; bench 15.

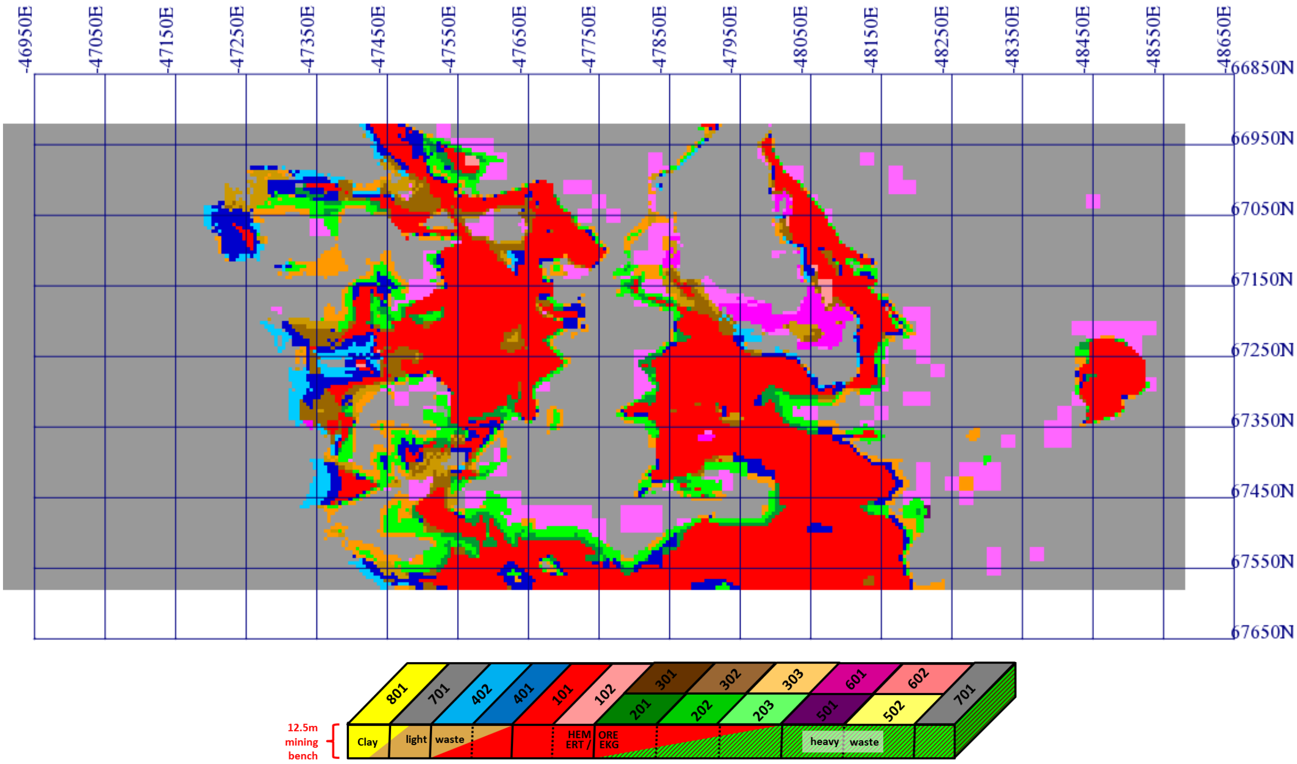


Figure 68 - Bench plan from Resource Model showing the defined resource material classification as a function of the explicit geological model (Figure 67). Sishen model nn1_b; bench 15.

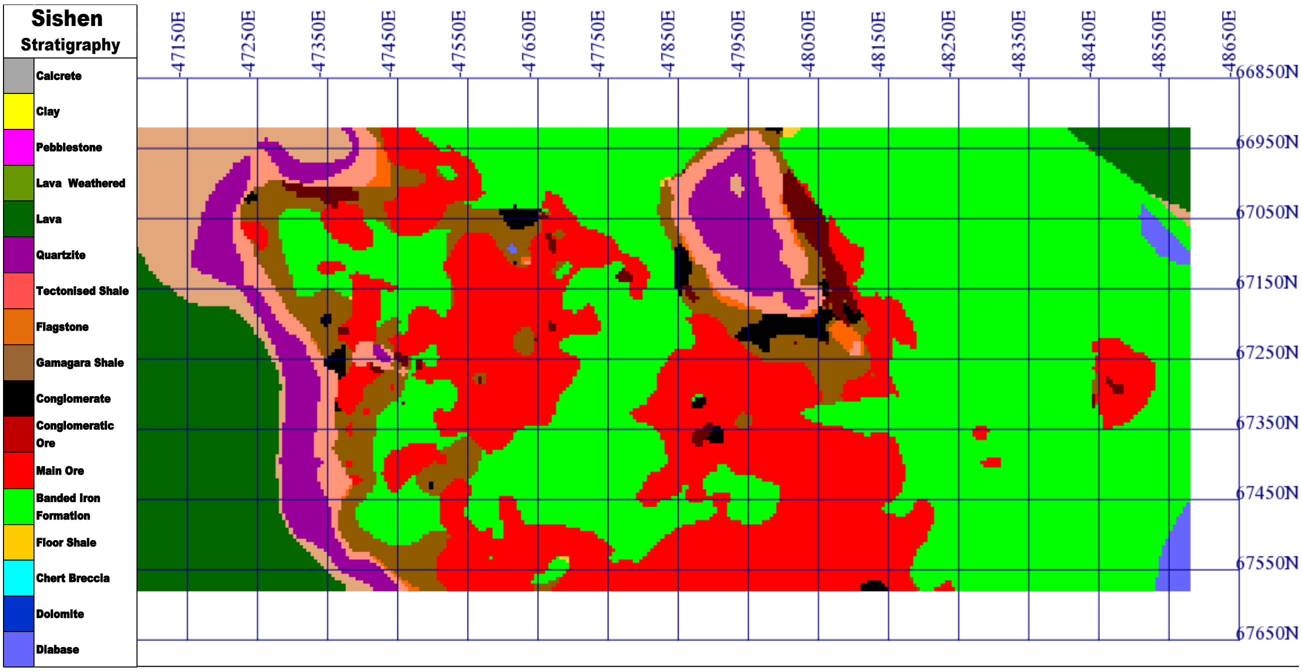


Figure 69 - Bench plan from Resource Model based on the implicit geological model showing the defined geological material yype. Sishen model nn1_b; bench 15.

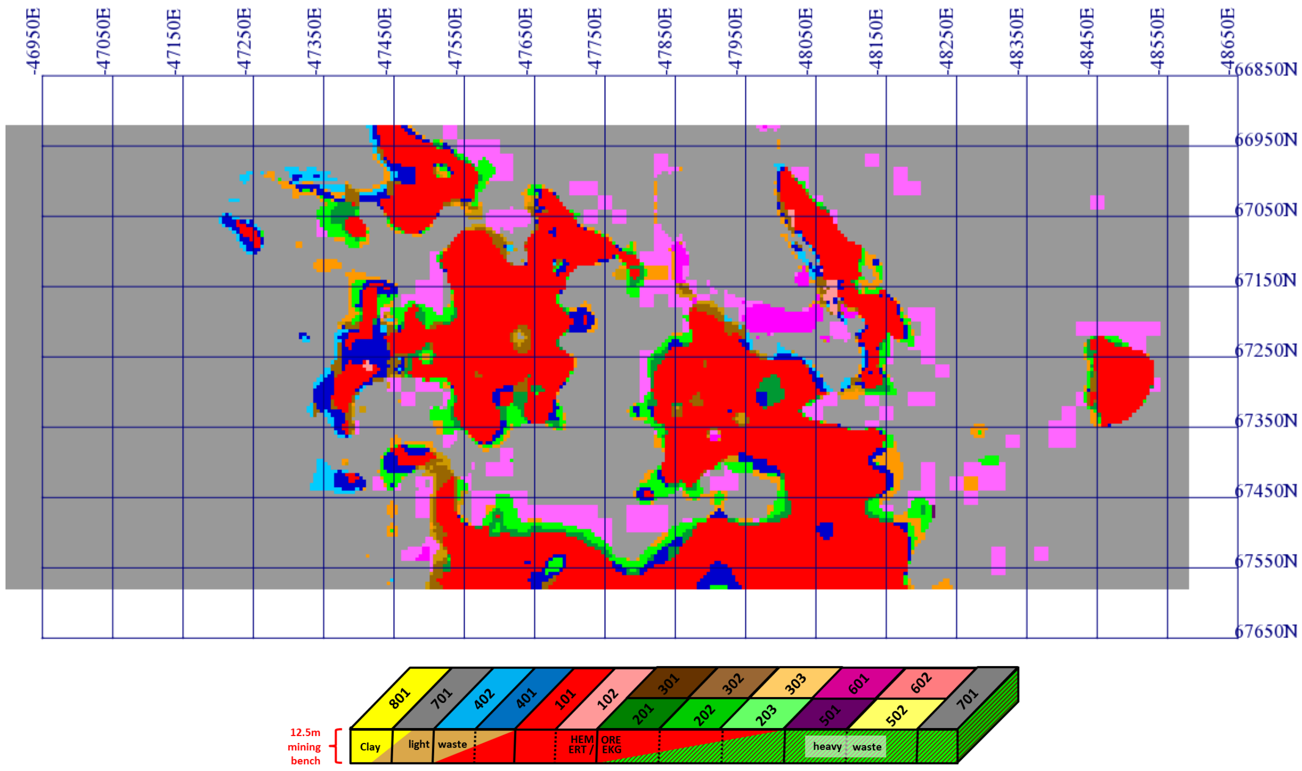


Figure 70 - Bench plan from Resource Model showing the defined resource material classification as a function of the implicit geological model (Figure 69). Sishen model nn1_b; bench 15.

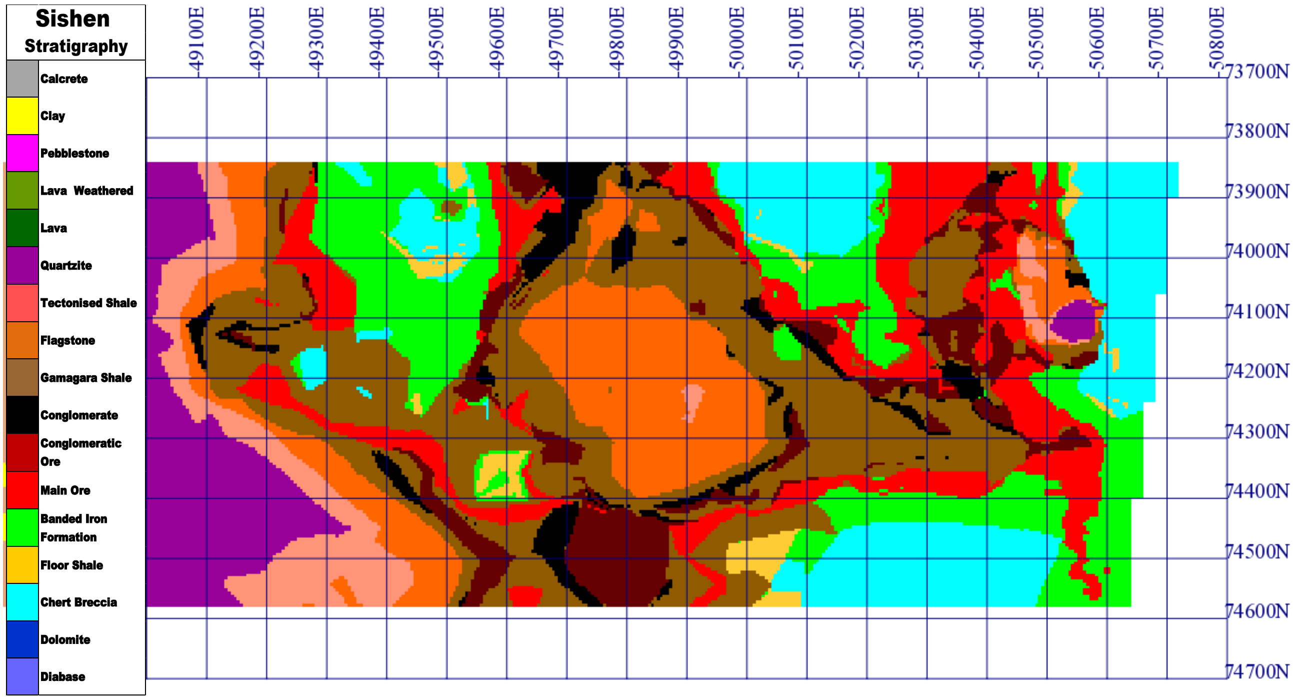


Figure 71 - Bench plan from Resource Model based on the explicit geological model showing the defined geological material type. Sishen model ss1_c; bench 8.

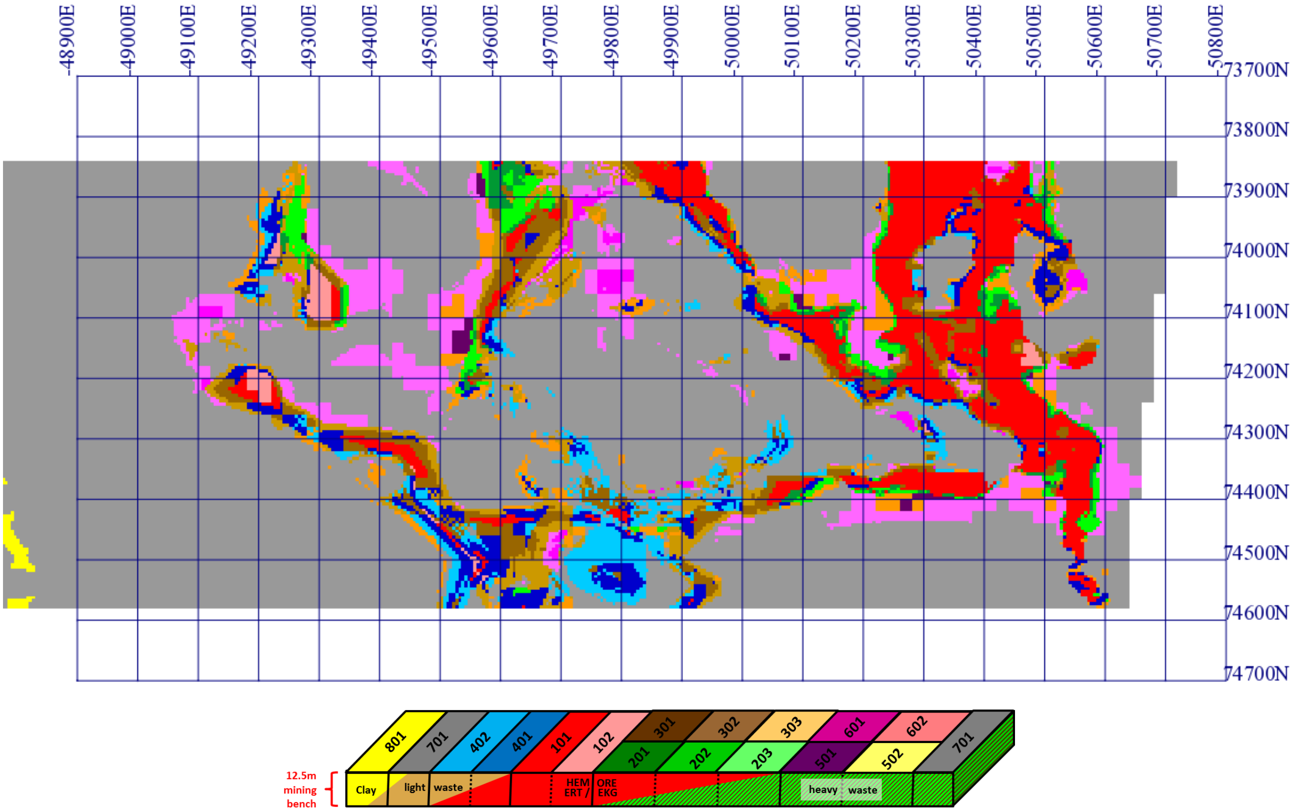


Figure 72 - Bench plan from Resource Model showing the defined resource material classification as a function of the explicit geological model (Figure 71). Sishen model ss1_c; bench 8.

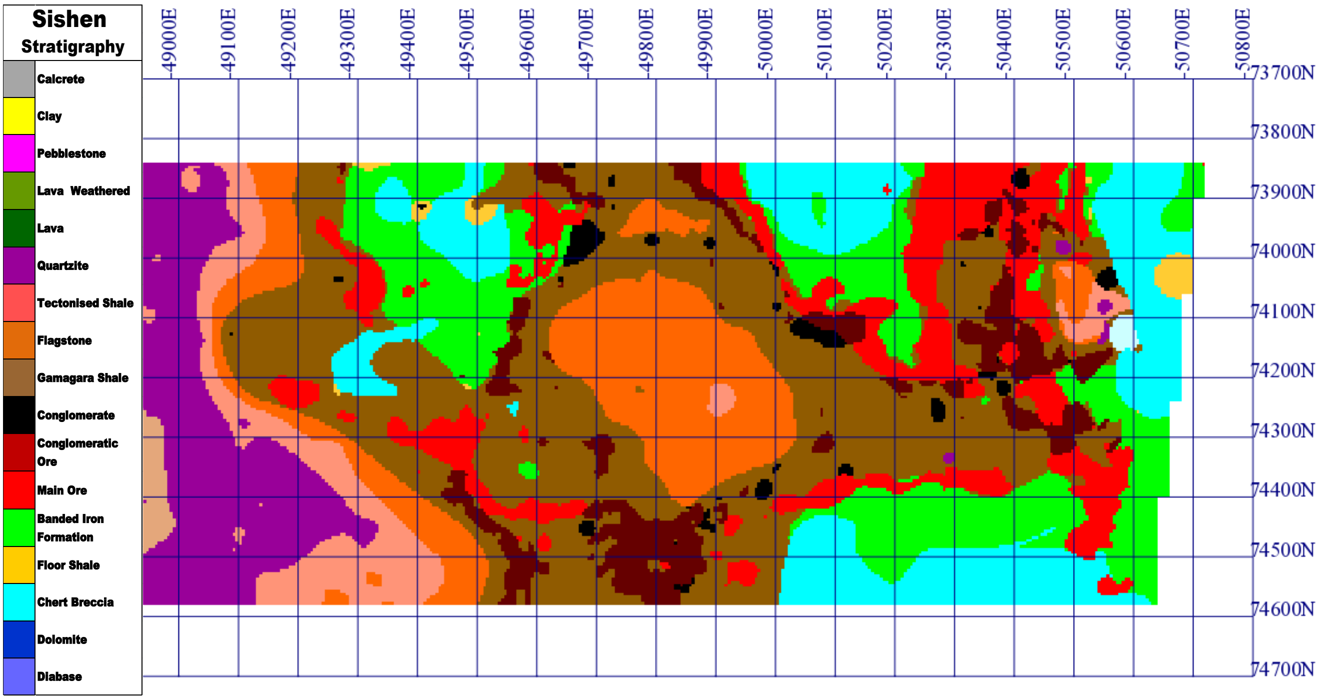


Figure 73 Bench plan from Resource Model based on the implicit geological model showing the defined geological material type. Sishen model ss1_c; bench 8.

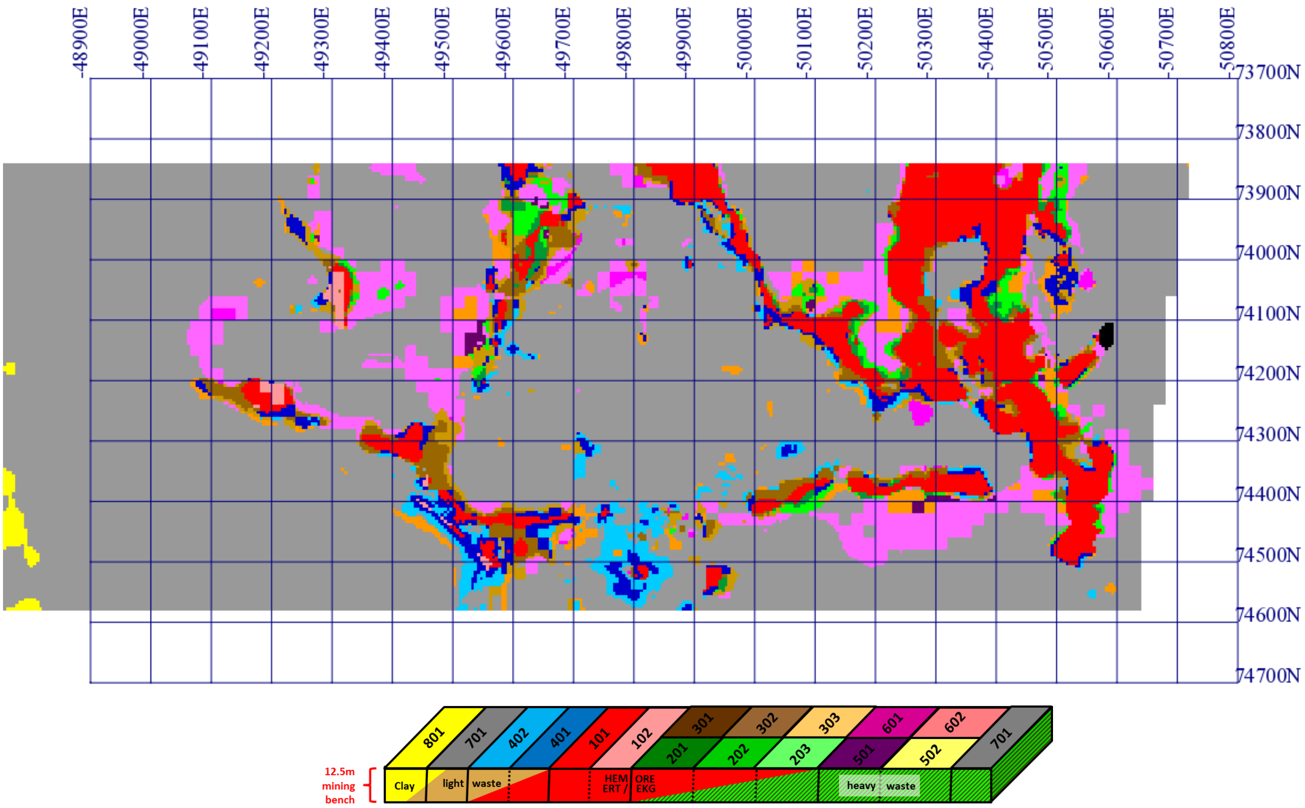
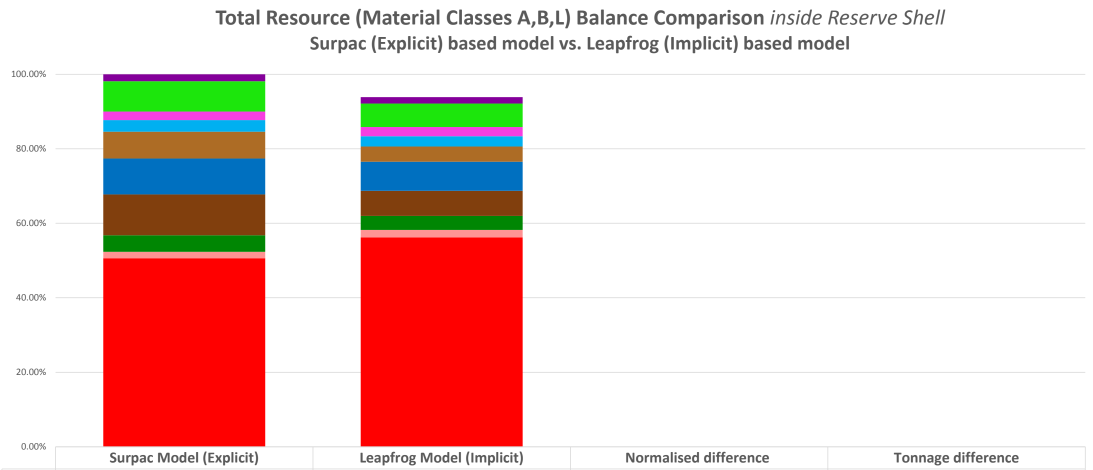


Figure 74 - Bench plan from Resource Model showing the defined resource material classification as a function of the explicit geological model (Figure 73). Sishen model ss1_c; bench 8.

3.3.3. Resource Evaluation Reconciliation

To quantify the impact geological modelling induces on the total Sishen resource the ore material classes 101 to 601 product of the resource models created with the respective explicit (Surpac®) and implicit (Leapfrog®) geological models were compared (figure 75). A total of 6.15% of the current explicit geological model based resource is lost by using the implicit geological model as the base for resource definition. Individual material class discrepancies show strong variability. Respecting the findings of the previous sections, the biggest material class gains observed when the implicit geology model based resource model was compared to the explicit geologic model based resource model was in the full bench high-grade ore material classes 101 and 102. The contact material classes showed the biggest overall movement when the resource is based on the implicit geological model, all of which were negative (losses) from the explicit based resource. It is also evident that there is a big difference between the relative ratio of full bench high-grade ore to other contact ore material classes in the comparative models based on different geological modelling conventions. These discrepancies fundamentally alter the characteristics of the resource. All down-stream processes based on the resource model, including the life-of-mine (LOM) schedule, will be affected. This study confirms that the geological model has a direct impact on the business plan of the operation.



	Surpac Model (Explicit)	Leapfrog Model (Implicit)	Normalised difference	Tonnage difference
Total	100.00%	93.85%	6.15%	
501	1.88%	1.72%	-0.16%	-8.71%
202	8.13%	6.28%	-1.84%	-22.66%
601	2.29%	2.48%	0.19%	8.36%
402	3.13%	2.75%	-0.38%	-12.11%
302	7.21%	4.08%	-3.12%	-43.33%
401	9.63%	7.83%	-1.79%	-18.64%
301	10.95%	6.74%	-4.21%	-38.46%
201	4.47%	3.75%	-0.72%	-16.11%
102	1.73%	2.02%	0.29%	16.97%
101	50.60%	56.20%	5.60%	11.06%

Figure 75 - Resource summation created with respective explicit and implicit based geological models.

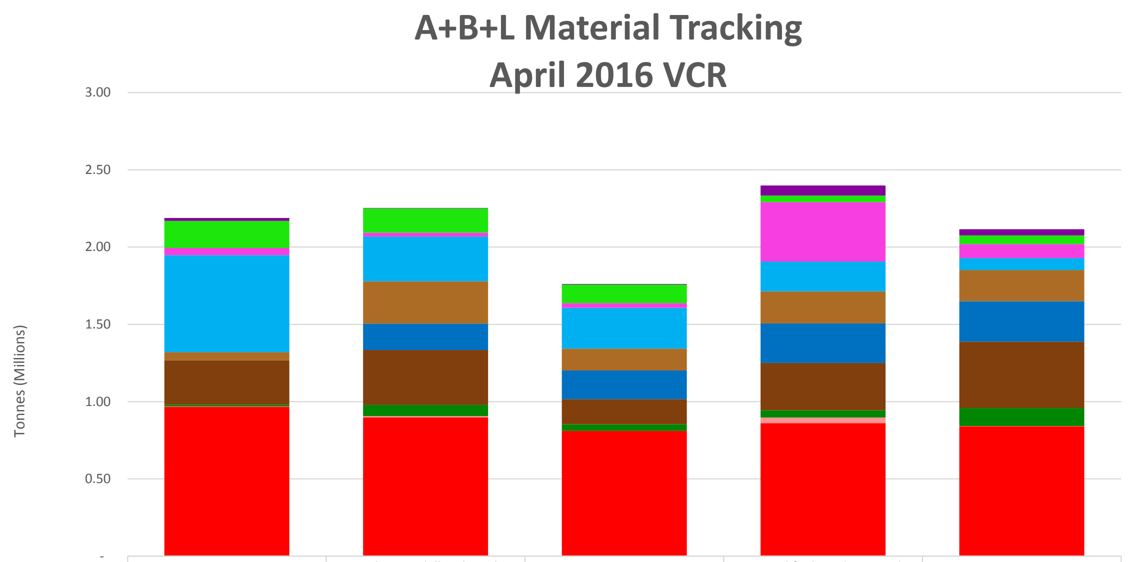
3.3.4. Value Chain Reconciliation

The performance of the respective resource models created for this study was also tested in Sishen's monthly Value Chain Reconciliation (VCR) process over a 3 month period (April 2016 – June 2016). The geological VCR as presented in Figure 76 to Figure 78 shows the reconciliation performance of the geological models for 3 production months. The geological value chain is defined from the resource model to the final grade control blastblock model created afore the material is mined.

The unmodified grade control is regarded as the benchmark in the analysis, as it represents the best in-situ "ground truth" model. The model is built in-time for the mining process, using all available data. The attributes of model is stochastically calculated, with nearest neighbour (NN) and inverse distance (ID2) interpolation used for the respective geology (rock-type) and grade attributes. The modified grade control represents the final minable resource the blast block contains, based on practical mining (SMU) considerations. This model is created by demarcating the material on the blast block in units of minable allocations. Any difference between the unmodified model and modified model can be quantified as dilution and mining loss/gain. Differences between the resource model and the unmodified grade control model are regarded as geological loss/gain.

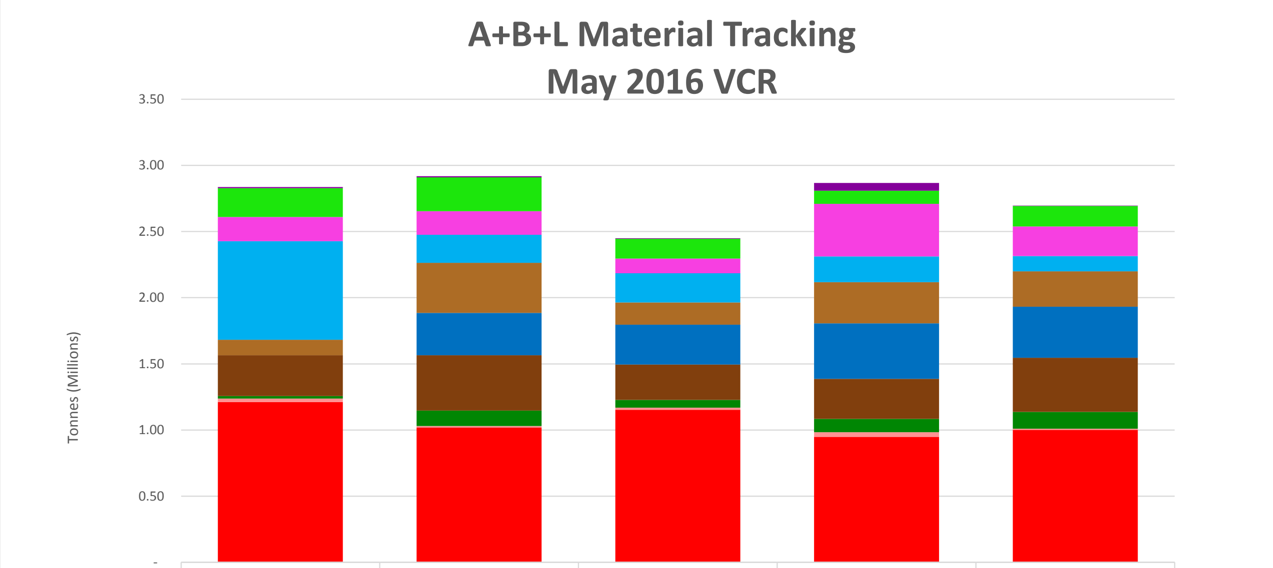
The performance of the control model (explicit modelling based) and Leapfrog® model (implicit modelling based) can thus be gauged in the existing value chain. The control model show good performance in terms of geological gains and losses (Figure 76 to Figure 78). Control model material class performance is good, showing good correlation with the grade control models (Figure 76 to Figure 78). The impact of block model resolution is also evident by comparing the control model with the current resource model. The same explicit geological model is used for both the resource and control models, but a higher sub-blocking resolution (quarter bench; z = 3.125m) is employed for the control model, enabling greater support for more accurate resource definition (Sishen material classification) than the lower sub-blocking resolution (half bench; z = 6.25m) used for the resource model.

The implicit modelling based model shows poor performance in the monthly reconciliation (Figure 76 to Figure 78). It exhibits a substantial geological loss when compared to the resource model. The correlation of material classes of this model to that of the grade control models are also poor, showing unrealistic geological gains. The implicit modelling based model seems to be very conservative, under-predicting especially the contact material classes (201 – 402 classes). It over-predicts the full bench high-grade ore (class 101) tonnages in two of the three test months (May 2016 and June 2016) (Figure 77 and Figure 78). Both the over-prediction of full bench high-grade ore and under-prediction of contact classes is in agreement with the findings of the previous sections.



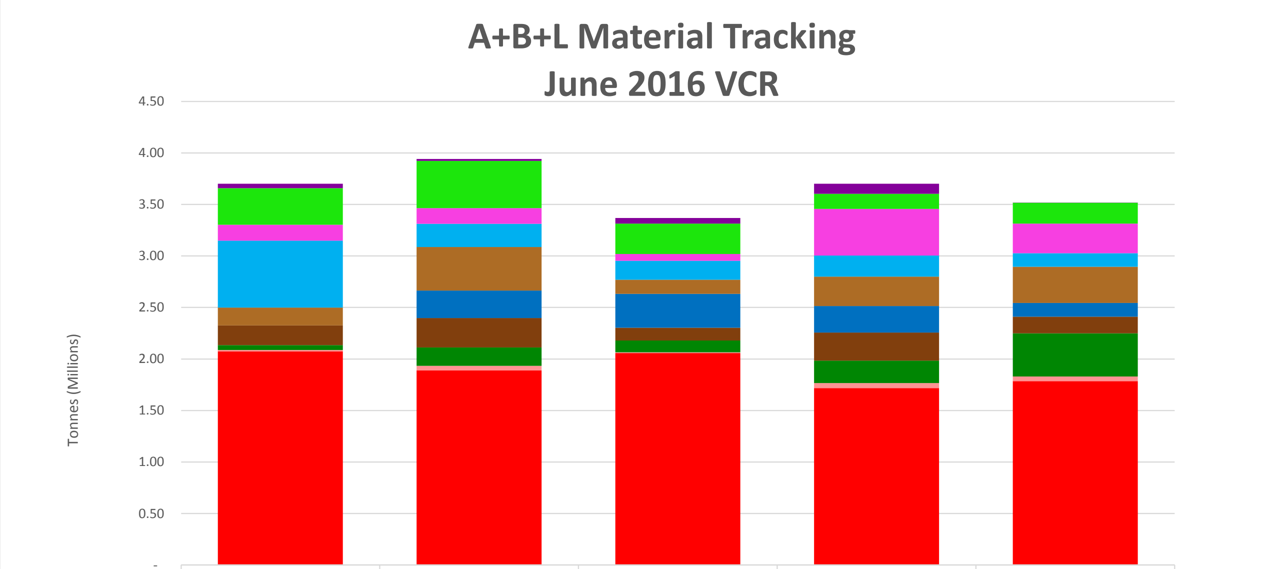
	Current Resource Model	Explicit Modelling based Control Model	Implicit Modelling based Model	Unmodified Grade Control Model	Modified Grade Control Model
501	19 535.64	2 500.94	4 277.30	65 079.69	39 553.86
202	175 368.17	157 789.05	120 174.77	43 393.71	56 407.25
601	46 268.59	25 517.14	29 433.50	384 539.58	89 650.81
402	627 236.91	289 364.97	264 273.02	193 026.30	78 625.97
302	52 653.28	273 473.63	141 600.23	207 668.40	201 137.39
401	-	171 295.75	184 652.97	255 664.10	262 275.92
301	288 190.50	355 292.13	163 453.25	305 278.03	429 334.70
201	11 162.52	72 250.91	41 930.58	47 765.22	116 620.16
102	2 836.19	8 953.80	695.00	36 358.85	766.25
101	965 495.48	897 171.23	810 580.14	860 313.35	840 774.29

Figure 76 - Geological Value Chain Reconciliation for the month of April 2016.



	Current Resource Model	Explicit Modelling based Control Model	Implicit Modelling based Model	Unmodified Grade Control Model	Modified Grade Control Model
501	7 840.48	9 463.17	4 470.02	58 357.76	3 669.52
202	218 371.22	256 139.66	148 854.00	99 823.68	154 702.62
601	182 723.70	178 438.66	112 196.14	397 273.22	224 094.02
402	745 539.38	211 390.30	219 688.69	193 709.04	114 654.70
302	116 340.22	378 392.00	168 082.86	311 627.09	267 748.98
401	-	319 521.77	301 073.16	419 508.03	386 023.99
301	307 682.33	418 287.69	266 906.23	301 690.41	408 248.25
201	19 100.11	116 408.59	59 002.61	101 258.89	127 363.90
102	26 910.23	12 058.80	16 162.50	35 858.52	8 357.74
101	1 211 386.20	1 018 617.86	1 153 209.78	948 123.41	1 001 598.60

Figure 77 - Geological Value Chain Reconciliation for the month of May 2016



	Current Resource Model	Explicit Modelling based Control Model	Implicit Modelling based Model	Unmodified Grade Control Model	Modified Grade Control Model
501	44 578.95	18 764.13	54 436.30	98 268.80	2 159.14
202	354 618.64	458 019.41	294 174.56	145 437.49	202 526.82
601	154 106.09	152 387.08	66 228.70	454 014.86	287 399.47
402	648 973.73	224 667.78	185 072.28	203 429.72	130 805.40
302	173 290.88	422 355.53	136 174.45	285 696.77	351 846.63
401	-	266 982.78	329 731.86	257 201.93	132 183.64
301	190 611.13	286 644.77	124 070.98	272 945.27	162 559.63
201	48 561.19	177 890.20	113 230.05	218 495.36	418 263.21
102	11 788.23	42 992.34	7 400.81	47 105.75	44 969.25
101	2 075 052.08	1 890 424.64	2 058 063.45	1 718 426.00	1 785 625.24

Figure 78 - Geological Value Chain Reconciliation for the month of June 2016

4. CONCLUSIONS

Technological advances make geological modelling easier and more intuitive than ever before. There is a clear shift in the industry concerning the needs of the geological model and what functions it should perform. Modern modelling techniques can be very powerful, but the real challenge lies in ensuring that the geological model performs at a satisfactory accuracy level at its intended point of use in the mining value chain.

This case study on the Sishen iron ore deposit shows that modern implicit modelling techniques can create geological models that are comparable to geological models created using traditional wireframing techniques. In many aspects, these implicit models are superior to their explicit counterparts due to their distinct advantages, foremost the speed of modelling and dynamic update capability where the model is automatically updated upon the addition of new data. Many sources of data can also effectively be included in the implicit modelling process to improve the final model, like the inclusion of extensive structural mapping and modelling data applied to the implicit geological model of the Sishen orebody.

Input data density for the modelling process, however, has a commanding effect on the accuracy and connectivity aspects of the final geological model. Where traditional wireframing allows the user to manipulate the modelling process on a local scale to overcome data density issues, the implicit modelling process is entirely reliant on the input data and the modelling parameters for the geological interpretation.

The Sishen iron ore deposit case study demonstrates that the implicit modelling process can indeed deliver a geological model with equivalent model volumes compared to a proven traditional explicit geological wireframe model. However, for the Sishen case study, the spatial reconciliation between explicit - and implicit versions of the geological models showed substantial differences due to principal geometry and connectivity differences induced by the fundamental contrasting modelling conventions.

Sishen employs an exhaustive material classification system to classify its resources for optimal utilisation. Although the volumes of the orebody created implicitly was comparable to the explicit ore model volume, the large spatial differences between the geological models triggered substantial differences in resource material definition (Sishen Material Classification) characteristics. These discrepancies are the direct consequence of the drastic change in ore-geometry and the local orientation of geological contact displacement at mining (bench) scale when comparing implicit and explicit modelling based resource models.

The Sishen case study conclusively show just how critical geological models are to the entire mining chain; from initial resource definition to the final extraction process. It can thus be concluded that any resource evaluation and planned extraction activity is only as accurate as the geological model used to define the resource initially.

This study also shows how critical it is to test geological model performance throughout the entire mining value chain. Basic volumetric comparisons or tonnage reconciliations can conceal tangible differences affecting the resource definition process. The fundamental parameters of the modelling convention control orebody connectivity and geometry, which have the potential to impact the mining value chain significantly.

It can be concluded that although the newly proposed Sishen implicit model has many advantages over its traditional explicit model rival, it is fundamentally unable to support the current Sishen resource definition process suitably. The study proves that the Sishen material classification system performs better with the traditional explicit geological model as a base. It is conclusively shown that by utilising implicit geological modelling for the base of the Sishen resource definition process a substantial portion of the current explicit geological based defined resource will be abolished and that the induced changes to the resource are not in line with the historic and current mining performance data.

5. RECOMMENDATIONS

The Sishen implicit model needs certain principle aspects of refinement to improve its performance in the current Sishen resource definition process. The following aspects of the modelling convention should be considered:

1. Explore the possibility of creating pseudo-drillholes from the current geological model to populate sparsely drilled areas. This process aims to solve a large component of the connectivity issues observed.
2. Experiment with different modelling "geometries" (Leapfrog® - intrusions, veins etc.) to address geometry concerns.
3. Follow an explicit unit selection process on the data before the model is implicitly modelled. This practice can act as a guide for the implicit geological modelling process, solving connectivity and stratigraphic sequencing problems.

After every major change, the model should be subjected to testing, quantifying how the new version performs in the mining value chain compared to the current baseline explicit geological model based resource. Only when the implicit model's performance is comparable to that of the current explicit model's at mining scale will implicit modelling become a viable option at Sishen Mine.

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