Case study: From benches to zones: unlocking the potential of a complex coal resource with Python and LIMN modelling

Jonathan Fairbairn-Stewart[1,*], and *Premeeth* Ramsaywok[2]

[1]Exxaro Resources Ltd, 0163 Centurion, South Africa
[2]Exxaro Coal, 0163 Centurion, South Africa

Abstract. Coal processing plants are typically designed to treat specific run-of-mine (ROM) feed to meet market specifications. This design is closely linked to mining and sales strategies to optimise the exploitation of the orebody. At Exxaro's Grootegeluk Coal Complex (GGC), a significant shift from bench-based to zone-based geological modelling introduced additional granularity in coal characteristics. This new, more detailed information provided an opportunity to re-evaluate and confirm whether the current exploitation strategy remains the most optimal approach. This paper provides a detailed description of the orebody characteristics and highlights innovative means to determine optimal exploitation of an orebody. Given the limitations of Excel in handling large geospatial datasets, Python Programming language and LIMN simulation software were employed. This method does not supersede current geological and mining processes or modelling but serves as a supplementary tool to work jointly while executing the exploitation strategy, complementing the process with geological, mining, and metallurgical knowledge and guidance. Python was utilised to process vast amounts of data efficiently and to perform robust data validation of the geological model. Limn was used to model different plant configurations. This study focuses on the processing of coal to achieve a desired mass percent ash in the products. Other deleterious contaminants, however, such as moisture content, volatile matter, free swelling index, sulphur content, and phosphorus are also considered. The orebody, with 11 distinct zones, highlights its complex nature and the multitude of viable mining and processing options that can be applied across these zones. These zones were modelled through various plant configurations. Normalised and site-specific processing costs were applied to evaluate the best product options per zone, assuming the entire ore is mined. Product revenue was normalised based on quality. The outcomes validate certain processing routes and identify potential alternative mining and processing strategies which require further evaluation.

Keywords: Coal, LIMN, processing, modelling

1 Introduction

The Grootegeluk Coal Complex (GGC), located in the Waterberg region of South Africa, is the world's largest integrated coal beneficiation facility operating from a single open pit mine with extraction on multiple benches simultaneously (Macnamara, 2022). Coal mining, particularly in surface operations, is characterised by its high productivity and relative lower costs compared to underground methods. Material extraction is typically conducted in stages, with each stage carefully designed to balance operational efficiency and long-term resource management (Arteaga et al., 2014).

GGC operates eight beneficiation plants with a processing capacity exceeding sixty million tonnes annually. It supplies coal for domestic power generation (Power Station Coal: PSC) at Matimba and Medupi power stations, accounting for ~18% of South Africa's installed coal fired power generation capacity, as well as to other domestic (Metallurgical Coal: MET Coal) and export markets (Semi-Soft Coking Coal: SSCC). The distribution of coal deposits and coal-fired power plants across South Africa is depicted in Figure 1. It highlights the strategic significance of GGC within the national energy supply chain, emphasising its role in supporting domestic and international energy demands.

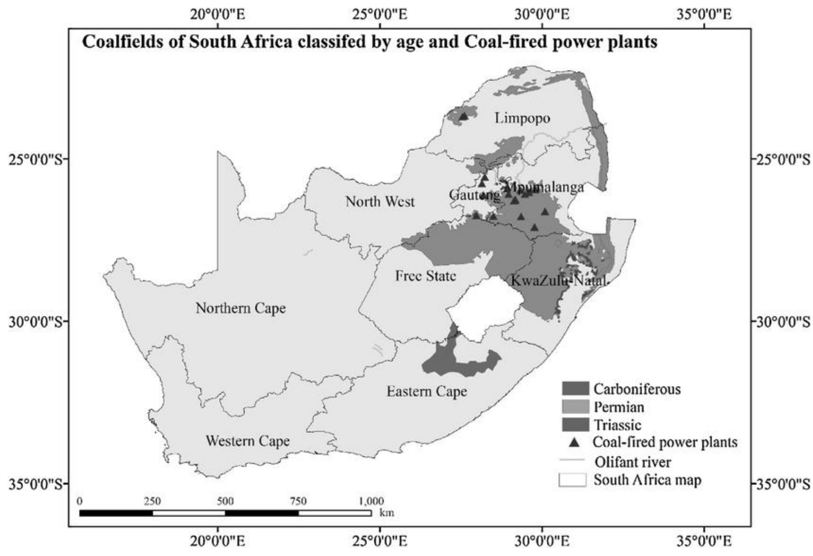

Figure 1. Distribution of coal deposits and coal-fired power plants in South Africa (Scholtz, 2022).

1.1 Orebody characteristics

The Waterberg (Ellisras) coalfield extends between 15 and 400m deep. The coal resource at GGC is endowed and divided into 11 distinct zones, each presenting unique metallurgical and processing considerations. Figure 2 provides a schematic representation of the Grootegeluk Mine lithology with two distinct formations.

The Volksrust Formation primarily consists of bright coal interbedded with carbonaceous shale, mudstone, and carbonate lenses. It is characterised by a higher proportion of interbedded non-coal material, influencing its beneficiation approach (Tavener-Smith, 1988). Due to its composition, this formation requires selective mining to maximise yield and minimise dilution, complemented by tailored processing techniques. The relatively high

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percentage of carbonaceous shale in certain zones affects its washability, necessitating more detailed classification to optimise processing strategies.

By comparison, the Vryheid Formation features dull to bright coal interbedded with carbonaceous mudstones and thin shale bands (Steyn et al, 1979). This formation is particularly notable for its high-quality coking coal, with Zones 2 and 4 exhibiting superior coking properties.

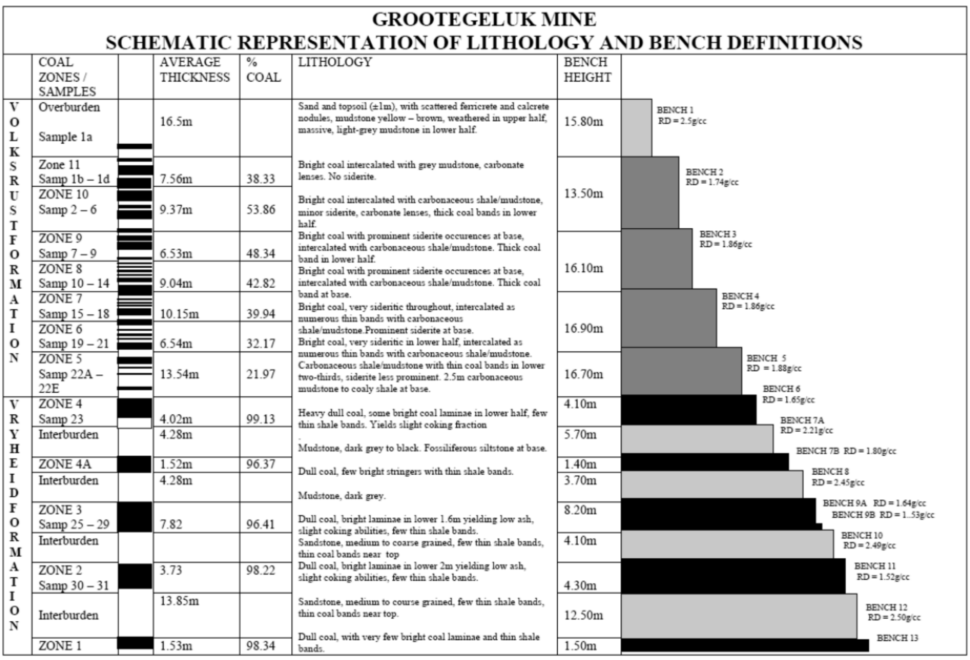

Figure 2. Grootegeluk lithology and zone (bench) classification.

A zone is defined as a geologically distinct stratigraphic unit within the Grootegeluk Coal Complex. These zones are characterised by specific coal quality attributes, washability properties, and metallurgical responses. Unlike benches, which are defined based on vertical mining intervals for operational purposes, zones are delineated based on the composition of coal seams, lithological variations, and washability behaviour (Tavener-Smith, 1988). Each zone is classified according to its depositional characteristics rather than arbitrary height intervals, facilitating more precise beneficiation planning. The study identifies 11 distinct zones within the orebody, each with unique processing and quality parameters.

1.2 Resource exploitation at GGC

Strategic planning for resource exploitation requires careful integration of geological, mining, metallurgical and market considerations to maximise value creation. Effective exploitation strategies must account for the inherent uncertainties in orebody characteristics and market dynamics, including fluctuating coal qualities across zones, varying economic conditions, and the interplay of extraction methodologies and processing capabilities. Consequently, the mine planning process must iteratively refine preliminary assumptions to ensure robust and adaptable strategies (De Kock, 2007).

Strategic mine planning defines the overarching decisions governing the exploitation of resources, including the mining method, sequence, scale, and processing routes. These strategic decisions are complemented by tactical planning, which focuses on the operational aspects of implementing the strategy, such as equipment deployment and production scheduling (Pasch & Uludag, 2018). The integration of these activities ensures alignment between value-driven goals and on-the-ground execution.

Grootegeluk Coal Mine operates as a market-optimised large-scale operation, supported by extensive mining fleets and infrastructure designed to sustain its production capacity. The current bench-based geological modelling approach is integral to resource planning, aligning with the scale and operational requirements of the mine. While effective, this method does not fully capture the inherent variability of coal seams. Transitioning to zone-based modelling enhances geological granularity, providing a more detailed understanding of seam characteristics. This approach enables validation of the existing methodology while identifying potential areas for further optimisation, ensuring that mining and processing strategies remain aligned with plant configurations and product specifications.

The transition from bench-based to zone-based modelling demonstrates the iterative refinement necessary for strategic mine planning. This shift offers enhanced granularity in resource understanding, enabling tailored exploitation schemes that consider both economic and operational constraints. By leveraging advanced analytical tools such as Python for data validation and LIMN for process modelling, this study explores and optimises the potential of a complex coal resource.

2. Methodology

This study employed a structured, value-driven approach to optimise coal resource exploitation by integrating geological modelling, economic analysis, and process simulation. Data preparation, visualisation, and validation were conducted using Python to clean and structure large geological datasets, ensuring consistency in zone characterisation. Python was selected for its capability to efficiently process and visualise over 730,000 blocks of washability data across the zones in a structured and systematic manner. This enabled the team to work through the entire dataset efficiently, narrowing down processing options for further analysis. Traditional tools such as Excel are not equipped to handle datasets of this scale with the same speed and flexibility, making Python an essential tool for this study.

2.1 Data Sorting and visualisation

Data was sourced from the 2024 zone-based geological model, with each block's coordinates and associated washability data, and imported into Python for structured processing. Before detailed analysis, pre-sorting was conducted to ensure data consistency and eliminate potential anomalies.

Heat maps, alongside assay histogram distribution plots of the zones (like those depicted in Figure 3), were used to visually validate the data, identify trends, and detect outliers. This approach provided an initial quality check before scenario modelling and process simulations.

The data was structured using Pandas python library and converted into Data Frames, enabling efficient querying and manipulation. Custom validation checks ensured expected column structures and verified consistency in seam trends, preventing errors such as non-increasing or non-decreasing patterns in key attributes.

For visualisation, the Bokeh python library was used to generate interactive plots, including histograms, box-and-whisker diagrams, and scatter plots, to analyse exploratory data in detail. These graphical outputs helped to systematically refine data selections, narrowing down processing options for further analysis.

This structured approach facilitated a streamlined workflow, ensuring that data integrity was maintained while providing a robust foundation for downstream metallurgical modelling, scenario analysis, and process simulations.

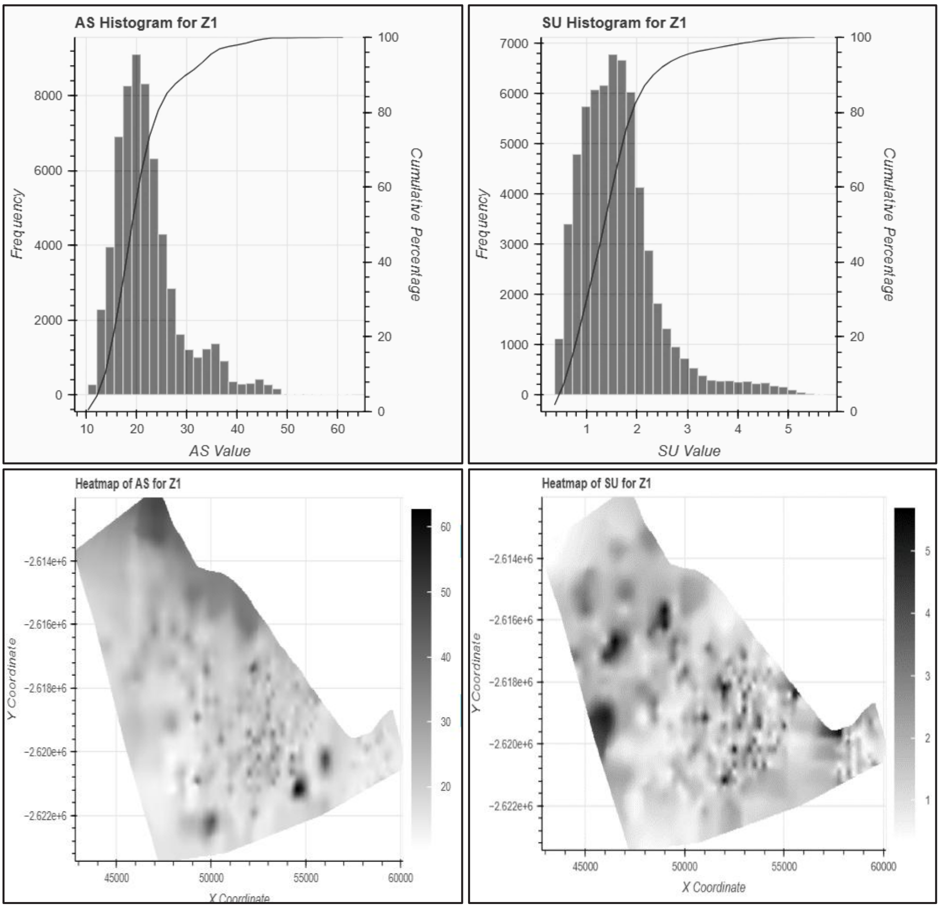

Figure 3. Gradient maps developed: S (wt.%) and ash (wt.%) with corresponding histogram plots

2.2 Data transformation

To determine representative washability characteristics for each zone, raw geological model outputs were aggregated and statistically processed. The washability data, consisting of various assays at different density fractions, was averaged for each zone using a percentile-based approach. Specifically, P25 (25th percentile), P50 (50th percentile or median), and P75 (75th percentile) values across different washability fractions (RD values from 1.35 to 2.50) values were computed to capture variability within each zone. For each assay component (ash, calorific value, sulphur, yield, fixed carbon, volatile matter, phosphorous, inherent moisture), numerical data was analysed, and percentiles were computed to represent variability in quality. This transformation simplified the dataset for efficient processing and modelling, enabling a robust understanding of coal processing behaviour, including yield predictions, product quality trends, and sensitivity to feed variability.

2.3 Attribute selection for analysis

Key attributes like yield, ash, sulphur, fixed carbon, and volatile matter were selected to optimise beneficiation potential, product quality, and economic viability, ensuring efficient resource utilisation and market alignment.

Yield indicates product potential and volumes, enabling effective supply planning and maximising recoverable coal. Ash value is crucial for quality control, affecting combustion efficiency and compliance with customer and regulatory standards. Fixed Carbon (FC) and Volatile Matter (VM) determine metallurgical coal suitability, influencing reactivity and energy content. Sulphur content is monitored due to its downstream impact on emissions, slagging behaviour, and strict environmental and processing constraints.

Using analytics on key attributes supports a detailed and optimised mine plan, ensuring that each zone is processed for the right product and client, enhancing efficiency, market competitiveness, and sustainability.

2.4 Process plant modelling to determine product qualities and volumes

Beneficiation will be dependent on the unique characteristics of each orebody and considerations of its size, quality, and distance to markets (Cawood, 2011). Scenario modelling and process simulation were performed using LIMN. Various processing routes include single-stage processing, double-stage processing and crush-and-stack (C&S). The simulations were regulated using process controllers to maintain ash levels within target ash specification for all high-value products. While the PSC product also employed process controllers, its control was constrained by RD. As a result, the target ash specification for PSC could not always be met in the lower zones, sometimes yielding a better-quality product (lower ash). This is attributed to the geological characteristics of the coal and the inherent cut-RD limitations applied in the process simulation. All other product quality parameters (assays) are reported relative to the ash produced, ensuring a comprehensive assessment of product quality in relation to process constraints. The lower-ash PSC produced in these zones presents strategic blending and yield optimisation opportunities, allowing for improved overall product balance and enhanced economic recovery.

GGC plant efficiencies were incorporated to validate model accuracy and simulation outputs were benchmarked against actual plant performance data. These scenarios were assessed based on all quality assay parameters, such as ash, sulphur, and yield performance, allowing for an informed selection of optimal product strategies.

2.5 Economic assessment

Economic and feasibility assessments evaluated processing routes based on normalised and site-specific costs. Zone-level processing alternatives were assessed to compare against the base case. Margin analysis was conducted to compare financial deviations from the base case scenario.

Gross profit margin was calculated by subtracting direct expenses (cost of goods sold) from net sales (gross revenues minus returns, allowances, and discounts). The resulting value is then divided by net revenues and expressed as a percentage to determine the gross profit margin ratio.

The base case margin was defined using zone allocation, product optionality, and prevailing cost and revenue structures to establish a baseline. Each scenario in the study was analysed at a zone level, with margins calculated accordingly. The results are presented as deltas from the base case, where the base case margin is set at zero.

This structured approach allowed for a clear comparison of processing strategies and options and provided a systematic framework to identify potential opportunities for further study to enhance overall profitability.

3. Results

This paper presents some of the key attributes, influencing the margins, such as yield, ash, fixed carbon, volatile matter, and sulphur. The outputs from single-stage processing (Met only), double-stage processing, and crush-and-stack (PSC only) provide the basis for assessing economic gains and losses in the following section.

3.1 Comparative yield versus product scenarios

The yield distributions across zones highlight significant geological influences on recovery potential. Ash value of product was the primary constraint in the product yield. Figures 4 and 5 highlight the expected yield when single stage processing for either high value products or PSC only as well as double stage processing where both high value and PSC are produced. Across all zones, higher processing density cut points targeting a 35.0% ash (ad) product deliver the highest yields. However, this approach results in PSC as the sole product. Yield is not the only criteria that determines best utilisation of this orebody.

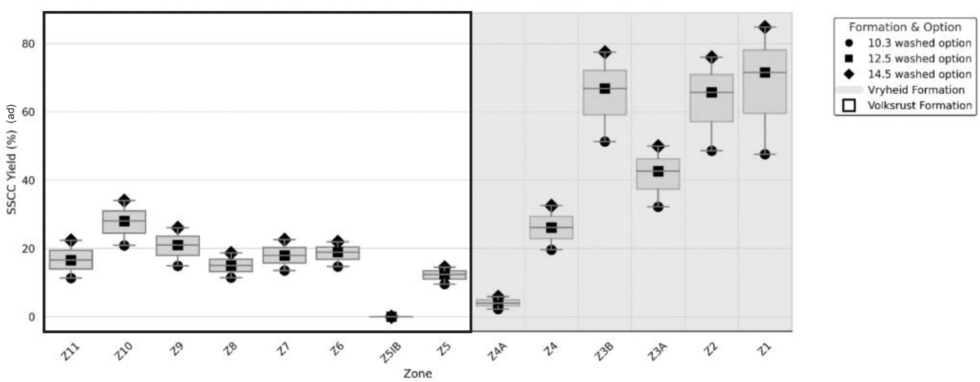

Figure 4. High value product (SSCC) yield % (ad) distribution per zone

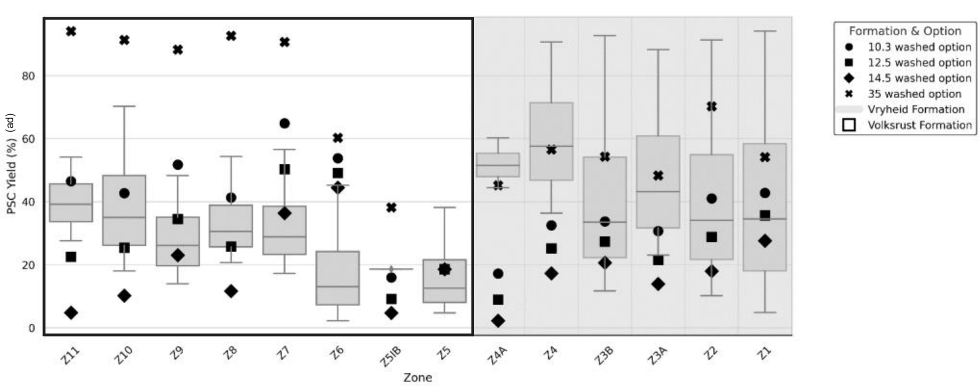

Figure 5. PSC yield % (ad) distribution per zone

Vryheid Formation zones (Z1–Z4A) consistently deliver higher and more stable yields, making them prime candidates for optimised processing strategies. In contrast, Volksrust Formation zones (Z5–Z11) exhibit greater variability, with Z5IB showing particularly low yields, especially for SSCC products, suggesting limited viability outside of PSC-only production.

3.2 Comparative ash and sulphur product quality realised versus product scenarios

Figure 6 and Figure 7 present the processed ash and sulphur quality distributions for the entire orebody across all formations. In the Volksrust formation, when processing for PSC only, zones 9 to 11 will normally deliver a product that is below 35% ash (ad). This is because the plant often reaches its maximum cut densities when processing these high-grade zones. Remaining zones in this formation will wash to a 35% ash (ad) product. When double stage processing for two products, strict processing control is required to ensure that PSC is limited to 35% ash (ad). Zone 6 is an anomaly showing sulphur in high value products above 1.4% (ad) with the remaining zone products between 0.8% (ad) to just over 1% (ad). Sulphur content is a critical determinant in processing decisions. The findings indicate that sulphur levels in primary products are generally manageable, with the exception of Zone 6, which presents significant challenges. High sulphur content in this zone poses risks for meeting market specifications and necessitates targeted management strategies. Sulphur in PSC is generally below 1.6% (ad) if all the coal is processed

In the Vryheid formation when processing for a PSC only, apart from Zone 4A, all other zones in this formation deliver a product that is less than 35% ash (ad). When double stage processing for two products, the resulting PSC is generally less than 35% ash (ad) when the high value washed product is below 12.5% ash (ad). However, for a 14.5% ash (ad) high value washed product, strict processing control is required to ensure the PSC qualities do not exceed the 35% ash (ad) target. All processed products from this formation generally contain less than 1% sulphur (ad).

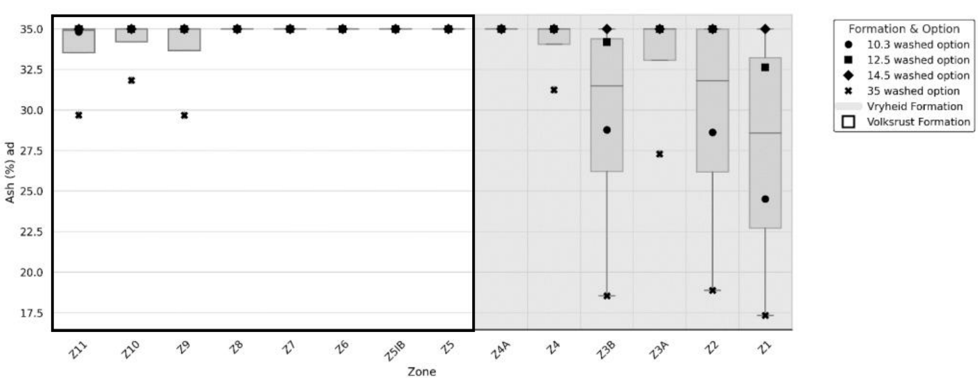

Figure 6. PSC product ash % (ad) quality by zone

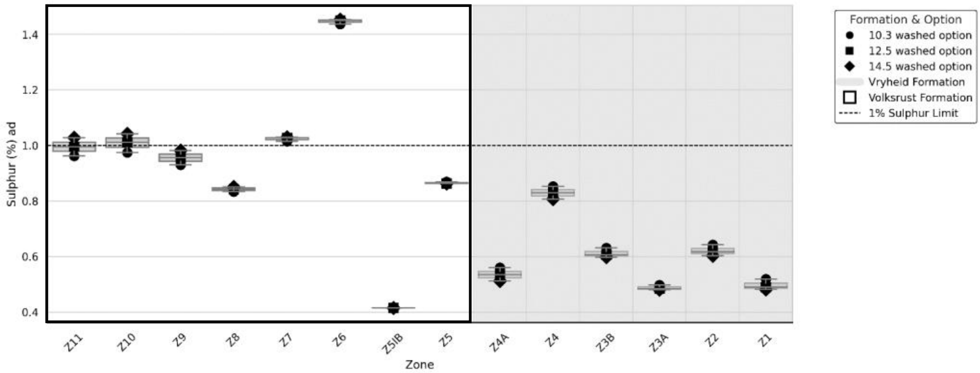

Figure 7. High value (SSCC) product sulphur % (ad) content quality by zone

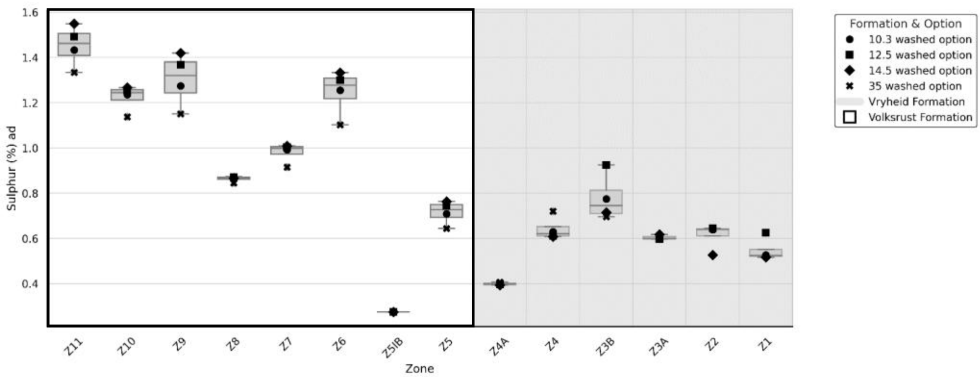

Figure 8. PSC product sulphur % (ad) quality by zone

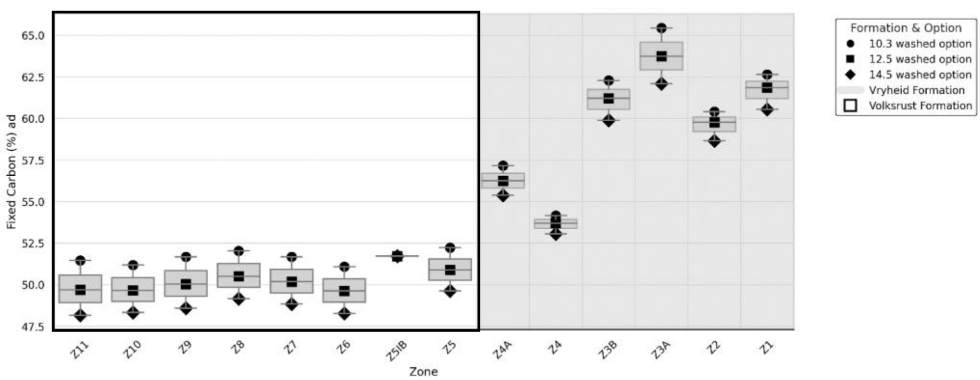

Figure 9. High value (SSCC) product fixed carbon % by per zone

The Vryheid Formation zones demonstrate favorable characteristics for metallurgical coal production, particularly in the lower zones FC (generally above 57%) and VM content (generally below 28%) as shown in Figure 9 and Figure 10. By contrast, the Volksrust zones are less suitable for metallurgical applications but remain viable for export markets. This differentiation underscores the need for tailored processing strategies that align with market demands to maximise revenue.

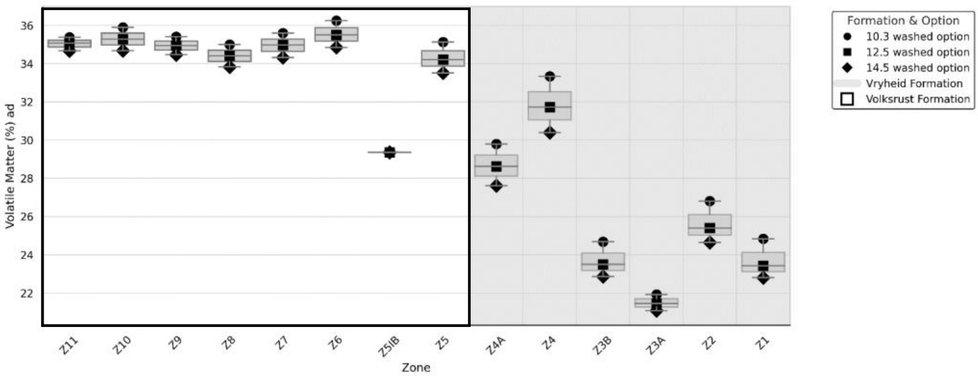

Figure 10. High value (SSCC) volatile matter content distribution per zone for 10.3, 12.5, 14.5 and 35.0 percent ash (ad) scenario options

The analysis provides valuable insights into processing performance trends across different scenarios. The results highlight that double-stage processing enhances yield optimisation, particularly in zones 7 through 9, but the elevated sulphur levels in these zones impact high value product quality (Figure 7 and Figure 8). Additionally, certain zones with highly variable ash (Figure 6) and sulphur levels present a strong case for implementing a crush-and-stack approach to maximise product yield where opportunities allow. Operational constraints, however, including infrastructure and logistical considerations, influence the feasibility of various processing options. As a result, a balanced approach is required, integrating both economic and operational execution considerations.

The primary coal quality risk arises when untreated zones from C&S are incorporated into the product mix. A balanced approach of blending washed and unwashed materials can mitigate sulphur risks while optimising overall yield.

3.3 Comparative financials by margin

A financial comparative marginal analysis of each zone and product scenario is presented in Figure 11. The margins are expressed in percentage buckets with gains of 5% margins from the base case, with the base case representing the current exploitation of the reserve and current beneficiation techniques.

Across all zones, financial modelling highlights double-stage processing—that includes both primary and secondary product yield optimisation—as the most economically favourable approach. This configuration maximises yield as well as margins while maintaining acceptable product specifications, particularly for ash and sulphur content.

Further investigation is necessary to assess additional value-enhancement opportunities. While this study has provided critical metallurgical insights at an exploitation level, unlocking these opportunities will require formal feasibility studies. A comprehensive evaluation of capital (CapEx) and operational (OpEx) expenditures, along with an assessment of infrastructure, contractual constraints, and market dynamics, will be essential to determine the bankable feasibility and long-term viability of these potential opportunities.

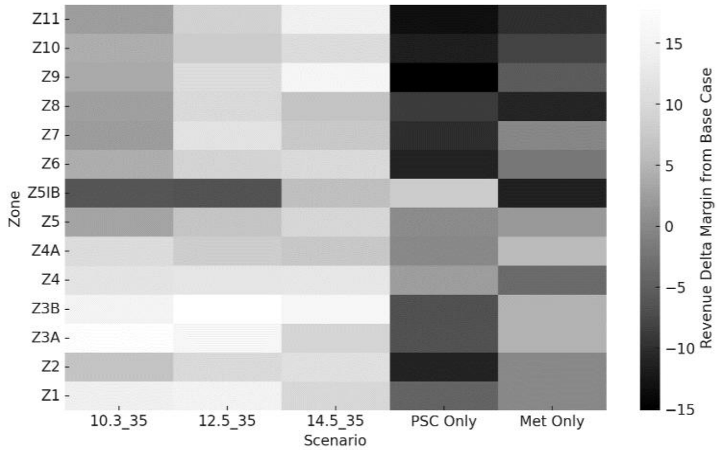

Figure 11. Revenue delta margins from base case across all scenario options

4 Conclusions and recommendations

This project has provided critical metallurgical insights at an exploitation level but advancing these opportunities will necessitate a formal study to fully explore viability.

The transition from bench-based to zone-based modelling improves the granularity of coal resource exploitation at GGC. This enhanced granularity of the orebody has facilitated more precise processing direction for optimal resource utilisation. Single-stage and double-stage processing remain the primary processing routes, with zone-specific adjustments necessary to control sulphur and ash content in products.

A clear distinction is evident between the Volksrust and Vryheid formations in terms of yield and coal quality. The Volksrust Formation generally produces lower yields with higher ash content and unsuitable for metallurgical coal. By contrast, the Vryheid Formation demonstrates higher yields and better-quality consistency across all quality assays. Properties such as FC and VM for Vryheid Formation coal types align well with metallurgical coal market specifications. These findings reinforce the importance of implementing zone-specific processing and optimisation strategies to maximise financial returns while ensuring an efficient allocation of RoM across different processing routes.

The analysis of sulphur content across different zones underscores the impact of sulphur variability on processing decisions. Either blending or complete exclusion strategies from SSCC coal circuits will aid in Sulphur management across the complex. Further investigation is required to explore areas of potential upside

Financial analysis suggests that Z5IB's contribution to revenue is suboptimal under current configurations. Alternative processing routes, blending strategies, or exclusion from specific circuits may be necessary to enhance overall profitability. Further investigation is required to determine the best economic approach for this zone.

Z5-Z11 of the Volksrust Formation shows some room to maximise the mix of export and PSC. A double stage processing strategy is in the base case and remains the preferred alternative. Processing these zones in a single stage will destroy value. As with the Vryheid Formation, the base case scenario is well-defined, but potential revenue improvements can be realised by shifting focus away from metallurgical coal production toward double-stage export/metallurgical and PSC products. Additionally, diverting high-grade zones directly to PSC without processing results in value destruction but remains an option to balance markets.

The integration of Python and LIMN has proven invaluable in validating data accuracy and simulating different processing scenarios. These tools have enhanced the decisionmaking process by providing robust, data-driven insights into predicted plant performance. Moving forward, additional research should focus on optimising blending strategies for high-sulphur zones and refining crush-and-stack configurations to ensure consistent product quality. By continuing to refine processing approaches based on zone-specific characteristics, GGC can maintain its position as a leader in efficient and sustainable coal beneficiation.

By enhancing yield and minimising discard losses, double stage processing emerges as a strategic solution for maximising resource utilisation and financial returns.

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Disclaimer

This paper is not to be used for marketing or sales purposes.

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