School of Mining Engineering

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

GEOMETALLURGICAL INFLUENCE OF CLAYS ON THE JWANENG KIMBERLITE VALUE CHAIN

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2023

DECLARATION

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ABSTRACT

Geometallurgy is a cross- disciplinary function that provides a better understanding of the ore characteristics impacting the treatability of the material. Optimal treatment of the material is enabled by understanding variability in the ore body. Having this understanding leads to flexibility when planning mining mixes.

The present investigation of the Jwaneng DK2 deposit's geometallurgical responses demonstrate that various rock lithologies impact the treatability of the Jwaneng kimberlites. The plan t is therefore hindered from achieving design capacity as a result of its treatability constraints. The volcaniclastic kimberlite, which is a majority- treated lithology at Jwaneng Mine, contains the highest volumes of smectite clays. These clays cause settling challenges resulting in higher consumption of processing materials.

To allow for informed strategic planning, all vital treatability information on the clay-rich kimberlites needs to be collected. The clay occurrence can then be incorporated into the creation of the geometallurgy model. Then the completed geometallurgical model can be utilised as a predictive tool for planning.

DEDICATION

I dedicate this research to my spouse Mr Mmoloki Nkgakile for providing the support throughout the research.

ACKNOWLEDGMENTS

I wish to thank the Jwaneng mine Minerals Resource Manager Mr Emmanuel Boiteto for giving me the opportunity to purse my research.

It is with immense gratitude I acknowledge the support and help received from Debswana Geometallurgy section under the supervision of Mr Oupa Gilika.

I am gratefully to my colleagues Ms Botlhe Mokgethi and Ponalo Tshosa from Ore processing Department and Mr Masedi Otisitswe from the Geology department for assisting with providing data.

I gratefully acknowledge Professor Richard Minnitt for his assistance and supervision.

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ABBREVIATIONS, ACRONYMS AND DEFINATION

Ash VK	Ashy Volcaniclastic Kimberlite
Ca	Calcium
CARP	Completely Automated Recovery Plant.
cm^3/g	Cubic Centimeter Per Gram – magnetic susceptibility unit
CRB_DM	Country Rock Breccia Dolomite Rich
CRB_QS	Country Rock Breccia Quarzitic Shale Rich
CUT	Mining Shell
CV	Coefficient of Variation
DBW	Diamond By Weight
Dk2	Jwaneng Kimberlite Location
DMS	Dense Medium Separation
DMS Yield	The mass of the concentrate calculated as a percentage of the head feed
ESP	Exchangeable Sodium Percentage
Fesi	Ferro silicon
Flocculent	A water soluble substance that aids settling of solids in a water clarification process
g	Gram (mass)
g/cm^3	Gram per cubic centimeter
HLS	Heavy liquid separation

JREP	Jwaneng Resource Extension Project
K	Potassium
KBW_DM	Kimberlite breccia dolomite rich
KBX	Kimberlite shale breccia
kWh/t	Kilowatt hour per ton
LI	Luminescence Intensity
Max	Maximum
Mg	Magnesium
mgbl	Meters below ground level
Mg-OH	Magnesium hydroxyl bearing minerals.
Min	Minimum
Mining mix	The blend of ore fed to the plant
MK	Magmatic kimberlite
MPa	Mega-pascals (Pa x 106), measurement of pressure
MRV	Metallurgical response variable
MTP	Main treatment plant
N	Total number of observations
Na	Sodium
NE	North East
NPV	Net present Value
ODS	Ore dressing study

OH	Hydroxyl-bearing minerals
OK	Oxidized kimberlite
PEN	Pennsylvania Abrasion Index
pH	Scale used to specify the acidity or basicity of an aqueous solution
PIMA	Portable Infrared Mineral Analyzer
PK	Pyroclastic kimberlite
QVK	Quartz rich Volcaniclastic kimberlite
REDS	Rare earth drum separators
RVK	Resedimented Volcaniclastic kimberlite
SAR	Sodium absorption ratio
SEM	Scanning electron microscopy
SG	Specific gravity
SSTBR	Sandstone breccia
Std Dev	Standard deviation
SW	South West
SWIR	Short-wave infrared
t/m^3	Tons per cubic meter, a measurement of density
t_{10}	Cumulative percent passing one tenth of the original particle size used to indicate breakage of a specified particle
T_a	Abrasion Index, indicates amenability to abrasive forces
TBE	Tetrabromoethane is an ore flotation agent used for the separation of dense ore from lighter supporting rock.

UCS	Uniaxial Compressive Strength
μm	Micrometer unit of measurement for wavelengths of infrared radiation
VK	Volcaniclastic kimberlite

SYSTEM OF UNITS

The international metric system of units (SI) are used throughout the design in all documentation, specifications, drawings, reports and all other documents associated.

CHAPTER 1: INTRODUCTION

1.1. Chapter overview

The introductory chapter provides the research background, which looks at the overall research area and all processes involved in the mineral value chain. An insight as to the reason and motivation behind the research is explained as well as the significance this work will have on the mineral processing chain. A discussion on the new challenges which mining companies are currently faced with as mining depths have increased and changes in mining methods introduced. Variability of mining a mineral resource with geological complexities results in complicated downstream processing challenges resulting in higher operational costs. A brief discussion on the highly impacted metallurgical processes by clay occurrences is introduced. The chapter looked at the Jwaneng geometallurgical parameter which focusses on the impact, the clay mineral has on the mineral value chain.

1.2. Background Information

The Debswana Diamond Company’s Jwaneng Mine is located 160km west of Gaborone as on Figure 1.1. It is the richest diamond mine by value in the world which is formed through a joint venture between De Beers Company and the Government of Botswana. Jwaneng kimberlite pipes were first discovered in the Naledi River valley in 1972 and officially started full operations in 1982 as discuss in the company website.

Figure 1.1: Location map of Jwaneng

1.2.1. The Geology of D/K2

The Jwaneng kimberlites are emplaced in a thick sequence of shales, sandstones and dolomites with thin occurrences of mudstones and siltstones in areas as described by Rachere, Mmualefe & Otisitswe (2015). The Jwaneng Mine exploits a diamond-bearing Kimberlite complex of three main pipes known as the D/K2 Kimberlite. The three main pipes have been named South (S), Centre (C) and North (N) pipes as illustrated on Figure 1.2. At the current levels of mining the three main D/K2 pipes have separated and appear as three separate pipes.

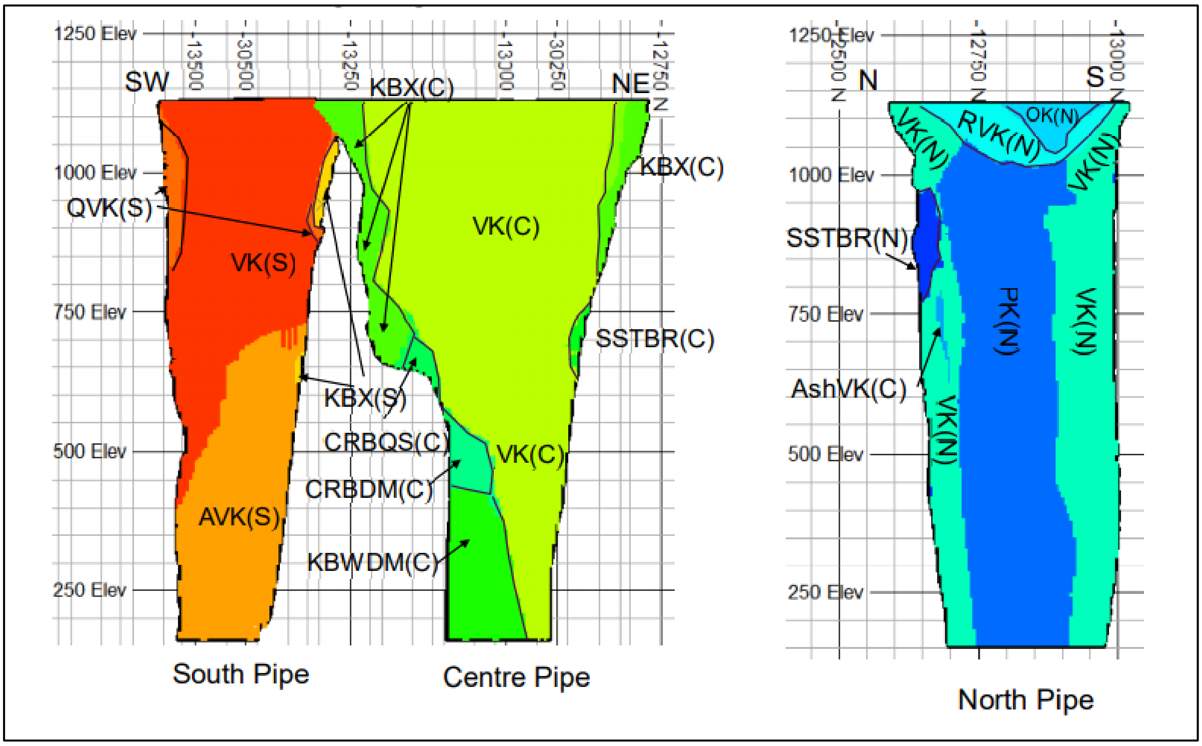

Figure 1.2 Cross section of the 3 main pipes. (Rachere, et al., 2015)

The three kimberlite pipes display geological inhomogeneity in terms of their modal composition and texture as a result of different genetic characteristics. The Jwaneng pipes are dominated by two contrasting textural types of kimberlite, which are the volcaniclastic kimberlite (VK) and the dark pyroclastic kimberlite (PK). The pyroclastic kimberlites occurs only in the North pipe, with minor magmatic kimberlite (Rachere, et al., 2015). Volcanoclastic kimberlite is common in all three pipes, whose margins all contain kimberlite breccias, which increase thickness with depth. The South and the Centre pipes show similarities as they predominantly contain volcaniclastic kimberlite at the core of the pipes. The north pipe's core, on the other hand, is predominantly dominated by pyroclastic kimberlite, with occurrences of volcaniclastic kimberlite on the pipe's edges. In all three pipes, breccias are common on the edges of the pipes; but with depth the Centre pipe becomes significantly dominated by breccias. There is a distinctive variance in the grades of the three pipes. The Centre pipe contains the highest grade while South pipe contains a lower grade. Physical rock properties such as hardness, density and geo-metallurgical characteristics vary across the three pipes. Mineral resource extension projects

From 2004 to 2007, a resource extension project was carried out to extend the resource from 400 to 1000mbgl, the extension project was known as the D/K2 Jwaneng Resource Extension Project (JREP) Phase 1. JREP Phase 1 project was a delineation program aimed at establishing the geology, volume and density of the resource to an indicated level of confidence up to a depth of 1000mbgl. After drilling into the kimberlite to a depth 650mbgl, the project team encountered difficulties that resulted in the objectives of the project not being met.

A Phase 2 resource extension project was carried out from 2009 to 2014. The objective of the second phase was to extend the kimberlite pipes' mineral resource grade and size distribution to below 400mbgl to achieve an indicated resource classification. The respective depth objectives for the pipes were: Centre pipe: 850mbgl, north pipe: 800mbgl and south pipe: 700mbgl

The JREP Phase 1 and Phase 2 projects produced a lot of data including data from ore dressing studies and a majority of the density data. The Jwaneng D/K2 geological model was updated with the new geological information obtained from the two phases of the extension projects. (Rachere, et al., 2015)Described and defined the various modelled rock types as can be seen in Appendix 7.1.

1.2.2. Jwaneng strategic stockpiles

To meet the feed demand requirements, there is a need to build capacity that will cater for production volumes in the event of unplanned mining interruptions. These interruptions may be as a result of equipment failure, harsh weather conditions or any destruction which may result in not being able to access the ore fed. Jwaneng mine has developed these strategic stockpiles to create flexibility and provide business continuity by accumulating ex-pit material on the surface for future use in the event of a disruption. Due to the variance in the grades from the D/K2 pipes, the material from the south, north and centre pipes are stockpiled separately. Where the ex-pit material has not been mixed from the source pipe, the material in these stockpiles is determined using the geoscientific classification of the source pipe. Table 1.1 from Boiteto (2018) gives a summary of the available stockpiles as well as the source of the material.

Table 1.1: Summary of Jwaneng mine Stockpiles (Boiteto, 2018)

Stockpile code	Describe	Grade category
SPO1S	Undiluted ore material from the South pipe	High grade
SPO3N	Undiluted ore material from the North pipe	High grade
SP02C	Undiluted ore material from the Centre pipe	High grade
SP05M	Diluted material from all the three pipes this includes calcrete, shale, mudstone and dolerite	Low grade
SPO5U	Upper bench material from all the three pipes which includes highly diluted(90-95%) material with calcrete	Low grade
SP13	Historic cut 5 Sump weathered and diluted material which contains significant volumes of North and south pipe.	N/A
SP04F	Undiluted ore material from the fourth pipe	Low
SP14	Undiluted Vk rich Centre pipe material rich in clay	High grade
SP200	Undiluted upper bench South pipe material	

1.2.3. Mining extraction Methods

The D/K2 is an open pit, which is mined in split shell, with the split axis running on the North-East – South-West line. The current mining cuts, as designed by Kasitiko (2021), include Cut 8 and Cut 9, as illustrated in Figure 1.3. The cuts comply with the mining parameters in Table 1.2.

Table 1.2: Jwaneng mining DK2 pit parameters.

Bench Height	16m
Minimum Mining Width	80m
Ramp Gradient	8%
Ramp width	40m

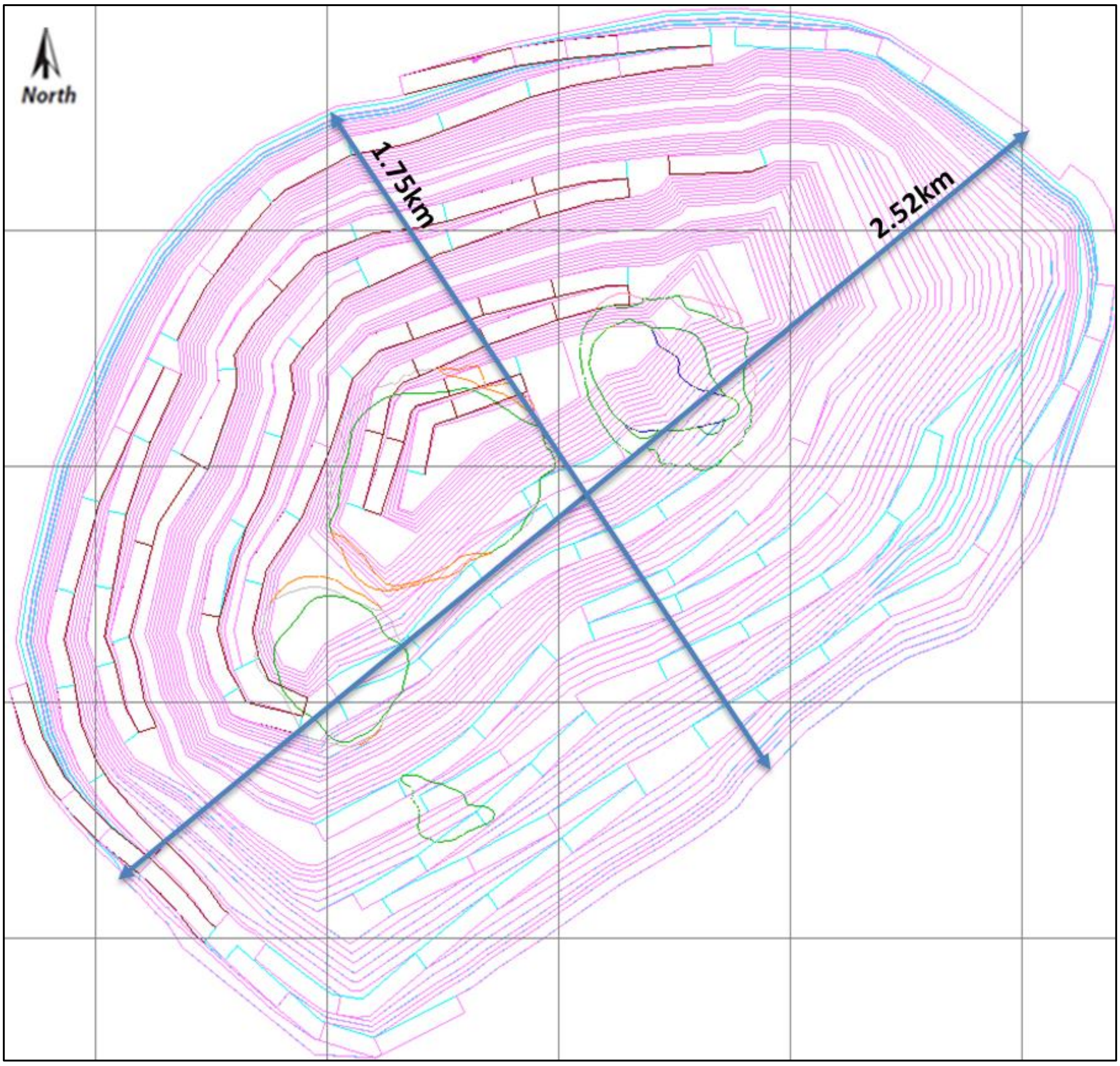

Figure 1.3: Jwaneng mine cut 8&9 pit design (Kasitiko, 2021)

1.2.4. Treatment methods

The kimberlite mined from the D/K2 is then treated through the Main Treatment Plant (MTP) for processing. The diamond processing involves comminution, which entails the breakdown of the kimberlite particles into smaller fractions. This breakdown assists in liberating the diamonds in the kimberlite. After liberation, the diamonds are separated from the gangue material through dense medium separation (DMS) and recovered at the aquarium as illustrated in Figure 1.4.

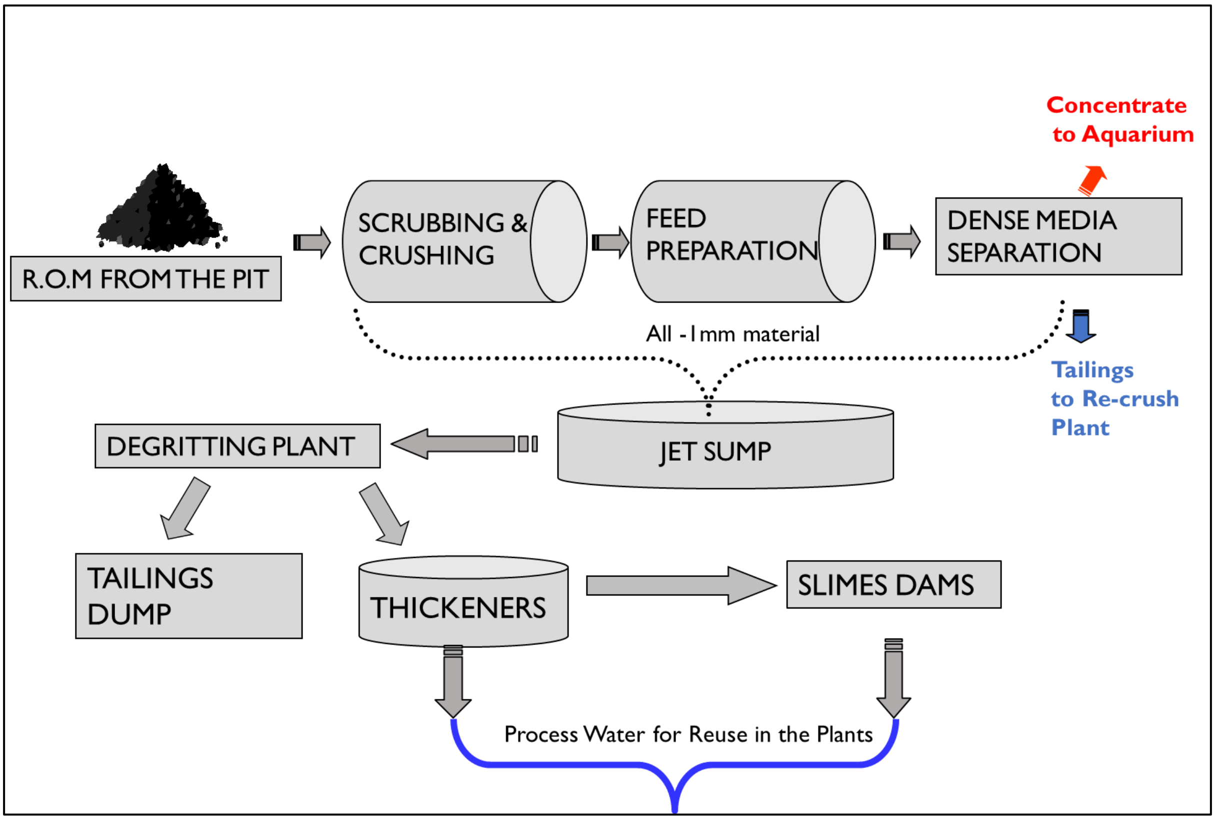

Figure 1.4: Main treatment plant flow sheet

- Comminution process: the MTP receives ore from the mine pit and stockpiles, which is fed to the primary crusher or a standby mineral sizer. Both crushers are set to crush at -150mm; and the ore is conveyed to the primary stockpile. The ore is then withdrawn by two conveyors via a tunnel reclaim system. From the reclaim system the ore is then placed onto the head feed conveyor and then transferred to the storage bins in the scrubbing plant. The ore is fed to the scrubbers and discharged onto double deck, coarse screens to separate +50mm and -50mm ore to +25mm and -25mm. The +50mm and +25mm ore fractions are reconstituted and conveyed to a silo for secondary crushing. The -25mm ore fractions are then discharged onto two fine screens per stream. This is done to separate the -25mm ore into +1.47mm and -1.47mm ore. The latter ore is then transported to the feed prep stockpile and water recovery sections respectively. The +25 mm ore fractions from the silo are fed into the secondary crushers from storage bins to be crushed to 23 mm fractions. Crusher product is fed to a double deck screen that separates the +25 mm and -25mm ore to +1.47mm and -1.47mm ore. The separated products are then also transported, respectively, to the crushing silo, feed prep stockpile and the jet sump for water recovery. The product fraction (-25mm to +1.47mm) is further washed in the feed prep section by banana screens and conveyed to the DMS as illustrated in Figure 1. 5.

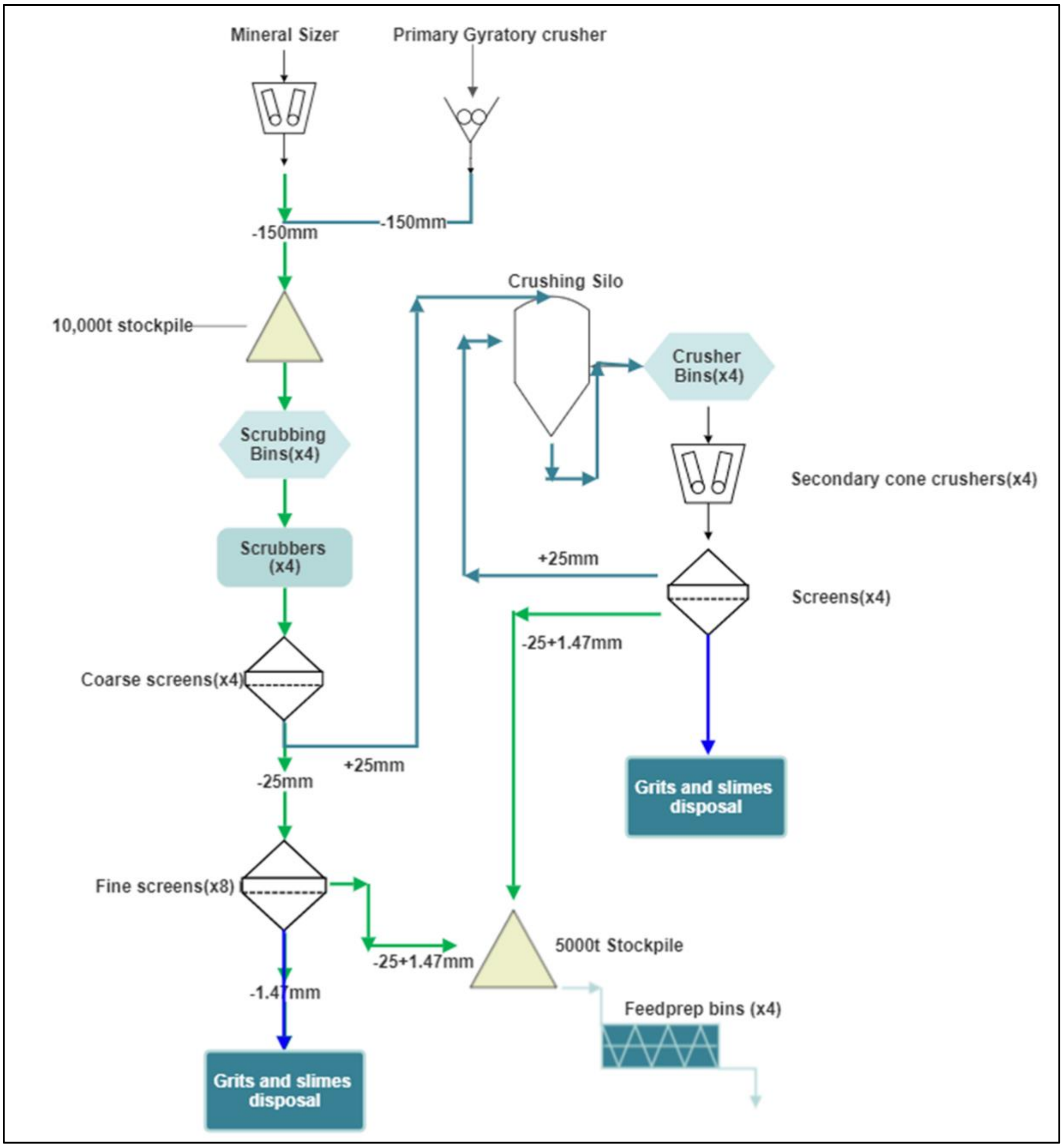

Figure 1.5: Commination section process flow

- Dense medium Separation: the DMS concentrate is fed to a sink screen to separate -25mm to +1.47mm and -1.47mm for aquarium recovery and water recovery, respectively. The DMS tailings are fed to a double deck float screen to separate -25mm to +3mm, which is conveyed to the Recrush plant. The -3mm, the + 1.47mm and the -1.47mm fractions are also conveyed to the Recrush tailings dump and the water recovery section respectively as on Figure 1.6.

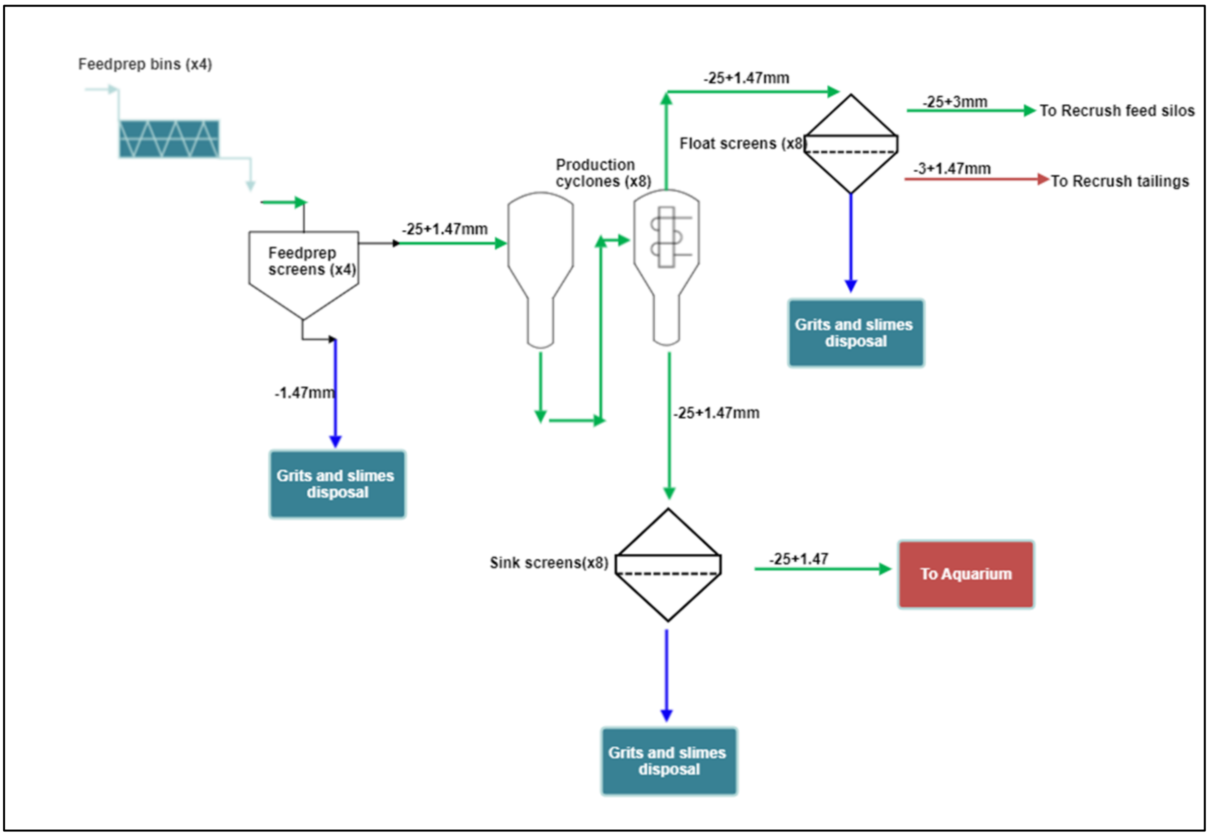

Figure 1.6: Dense Medium Separator Process flow

- Water recovery process: the water recovery section is comprises a de-gritting circuit to separate -1.47mm to +0.3mm and 0.3mm via hydro cyclones. In this process, the cyclone overflow (-0.3 mm) is fed to conventional thickeners; and the underflow is taken to the tailings disposal circuit for disposal.

1.3. Problem statement

Through the various sampling campaigns that have been conducted, the geometallurgical and geomechanical characteristics of the different kimberlite facies were established. In November 2016, Jwaneng mine, through the assistance of a second party, evaluated available data to see if it was feasible to construct a geometallurgical model for the D/K2 pipes. The Jwaneng Mine geometallurgical model could be a valuable tool in the planning process once the model completed. However, the model was not completed because of low level confidence in the essential metallurgical response variables (MRVs) of the D/K2 pipes. Once the MRVs can be correctly characterised and their role in the recovery processes identified, confidence in the model will improve.

Geometallurgical data for the creation of the geometallurgical model at Jwaneng Diamond Mine has been collected. But experience has shown that clay content is critical to process efficiency. This requires modelling of the clay so the plant can be capable of accepting clay-rich kimberlite. When it is clear what actions need to be taken to address and mitigate the effects of clay-rich kimberlite, the geometallurgical model will need to be adapted to incorporate these actions. With the clay-rich kimberlites being identified and the effects of clay being incorporated into the geometallurgical model, the appropriate steps required to be taken will be integrated into the mine’s planning processes as a predictive tool. This will lead to future utilisation of the model, which will allow for the model to be tested and validated for its accuracy.

In times past, Jwaneng Mine produced an incomplete geometallurgical model that was never implemented. For this reason, the predictive capability of the model has never been tested; and consequently, there is no confidence in the model that was produced. The aim of the mine is to establish the geometallurgical response variables that need to be updated with additional data to allow the establishment of an effective geometallurgical model. This research investigation will focus on the MRV 3 on the D/K2 pipes that measure the slurry and slime components that are directly impacted by presence of clay.

1.4. Research aim and objectives

The research aims to contribute insight about how MRV 3 is impacted by slurry and slime components in the D/K2 pipes; with the hope that the insight can be used in developing a geometallurgical model. This will allow more accurate forecasts of short-to-medium term plant throughput and recovery. Accurate forecast will then lead to identification of a feed-blending strategy that will improve plant efficiencies when clay-rich kimberlite is being treated.

The objectives of this research are to:

- Identify the different occurrences of clay in the three main Jwaneng Mine pipes;
- Investigate how the efficiency of processes in the Jwaneng treatment plant is affected by the behavior different clay-rich kimberlites; and establish the behavioral change when feeding different clay-rich kimberlites into the treatment plan, by comparing the processing efficiency trends of the different kimberlites against the mining feed mix, ; and
- Make recommendations regarding the addition of clay behaviors to the metallurgical response variables identified in the geometallurgical model.

1.5. Research scope

This research study will be based on MRV 3 which looks into slurry and slime management during mineral processing. The research to be undertaken will compare plant efficiencies against the geometallurgical data collected. The research will also identify the clay-rich kimberlites that adversely affect plant performance. Where confidence in the data requires improvement, the necessary additional sampling campaigns will be recommended to allow for all necessary data to be collected. Testing the model and validating its predictive capacity by measuring actual results against appropriate targets will then be possible in.

1.6. Research significance

Jwaneng mining will be moving to mining depths which are significantly different to the mine’s current mining depths, which means different geological units can be expected. Having a better understanding of the impact of the geological units on mineral processing will improve the understanding of what to expect from the mine in future. Having a fully predictable geometallurgical model will assist in future mine planning which will allow for usage of appropriate plant parameters that are specific to the mine’s lithology. Analysing slimes and slurry management as part of MRV3 investigation, will allow for testing of processes and perfecting the model’s capability with respect to managing slimes and slurry. As geometallurgy is a process of continual data collection, more data will lead to expanding knowledge into other MRVs, leading to completion of the Jwaneng geometallurgical model in future. The predictability of the mineral processing chain will thus be improved, leading to a reduction in revenue loss.

1.7. Research report outline

The introductory chapter provided background information, outlined the problem statement, research scope and significance for the research study. Chapter 2 introduces the geometallurgy field and explains its importance in the mineral value chain. Geometallurgy is a broad subject and it is defined by different aspects per commodity which are outlined in chapter 2. There are different approaches that are followed when creating a geometallurgical model these are also defined and assessed. A key mineral being investigated is clay e key mineral being investigated is the clays, a characterization of these minerals is defined .Chapter 2 also identifies and describes, in detail, the link between geometallurgical response variables and lithologies.

Chapter 3 describes the research methodology and the process of data collection and analysis. Historical data was compiled from JREP ore dressing study samples. Primary data was collected from daily and monthly production reports from the geology, survey and mineral processing departments.

Chapter 4 analyses the different lithologies associated with the Jwaneng kimberlites. The main occurring lithologies are then compared against the utilization of processing consumables. The Jwaneng kimberlite lithologies are further distinguished based on the type of clay occurrences within them. Conclusions and recommendations are made in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter overview

This chapter looks into the field of geometallurgy in relation to the mineral processing chain. The literature looks at the different aspects that are associated with the field, such as: the types of geometallurgy available, the different variables related to it, as well as the field's classification programs. When geometallurgy is applied, it is essential to plan to ensure the right quality of material is produced at the right time and place. The outcome of every geometallurgy program is to essentially produce a geometallurgical model that can be utilized in mine planning. Several stages are to be followed in order to have all the necessary data to fulfil the requirements for producing a model. Failure to meet these requirements leads to failure of development of the model. Case studies have been carried out to test geometallurgy programs for different commodities. From the case studies it was determined that having the relevant data is a major contributor to the success of developing a model. Primary and secondary variables are discussed in depth in order to understand the significance of data in geometallurgy.

2.2 Geometallurgy

Geometallurgy is defined by many researchers as the comprehensive characterisation of mineral deposits that: takes into account the geological and mineralogical variability within a deposit; and quantifies the associated effect on mineral processing. Dominy, S.C., O'Connor, L., Parbhakar-Fox, A., Glass, H.J & Purevgerel, S. (2018). Geometallurgy is a cross-disciplinary field with the objective of addressing some of the complexities associated with determining the value of a resource and whether or not it is economic to exploit it. (Dunham & Vann, 2007). It is a multidisciplinary, team-based approach, aimed at linking variability in the ore feed and variability of ore performance in treatment plants. The main aim of geometallurgy is to improve the processes of a mine's value chain; and to build a model for production management within a mine (Lischchuk & Pettersson, 2021). Plants perform best when their feed has known processing parameters and behaves consistently overtime when treated (Richmond & Shaw, 2009). This performance is best achieved by integrating geology, mining, planning, operational design, mineral processing and metallurgy (Dunham & Vann, 2007).

Geometallurgy is based on identifying various attributes that contribute to the realised value of the resource. These attributes are all dependent on the material's characterisation. Hence it is important to have improved material characteristics combined with the spatial modelling. Another core aim of geometallurgy as a concept is to reduce the uncertainty in a mine's value chain as it improves ore utilisation while lowering the operational risks (Claassen & Laurens, 2016). An understanding of where geometallurgy is headed will allow for a better understanding of what the best and most recent data collection processes are, which will assist in solving future questions (Richmond & Shaw, 2009).

A geometallurgical model provides a quantitative prediction of metallurgical performance. Throughout the project, the model provides predictions of things such as: the quality of the concentration, throughput, tailings recovery, and fresh water consumption. Richmond & Show (2009) demonstrated that in order to maximize the profit that a resource can achieve, models with predictive ore control strategies must be implemented. The ultimate aim of a geometallurgical model is to provide a spatial predictive mechanism which helps to optimise mineral resource utilisation (Lischchuk & Pettersson, 2021). Predictive geometallurgy requires the appropriate prediction of secondary properties of mining blocks. Thereafter it requires the proposal of suitable mining and processing plans and schedules that based on the properties of the mining blocks instead of their grade (Boogaart & Tolosana-Delgado, 2018). Prediction allows for operations to easily identify when there is a drop in performance allowing for quick corrective measures to be initiated (Lischchuk & Pettersson, 2021).

Prediction in geometallurgy refers to correctly implementing a geometallurgical program that provides an improved predictability and consistency of both mining and processing performance (Lischchuk & Pettersson, 2021). To achieve predictability, there is a need to first establish performance benchmarks for the various ore types occurring at each unique mining operation. To enhance the predictability of the process, gaps in the methods applied in geometallurgy need to be identified. The first step is the identification of the geometallurgical analysis of the ore body with respect to its primary properties. This involves grouping similar primary properties (ore related) into geometallurgical domains; followed by characterisation of secondary properties (processing related) through geometallurgical test works (Boogaart & Tolosana-

Delgado, 2018). Understanding of the gaps will identify areas which need to be developed more, leading to the collection of and implementation based on more detailed geometallurgical data, leading to increased predictability.

The complexity of the process, lack of progress in the geometallurgy program and lack of collaboration between departments may negatively impact predictability and cause other predictability issues. (Lischchuk & Pettersson, 2021). Geometallurgical models should be able to link the variations observed upstream in the process, with the performance coming from production. Understanding the extent and the complexities which come from the variations in production allows for more informed decision-making actions, resulting in better planning for production (Lischchuk & Pettersson, 2021).

Having the ability to predict mining and processing behaviour for the different feed material allows for better prediction of block values, which can be used as a strategic mine planning tool for optimal exploitation of the deposit. Predicted properties can be used to find ore partners in blending to reduce feed variability in the plant and ensure constant plant operation conditions. Blending of different ore types ensures stable feed for processing but it’s only a small decision scope as it only changes where to mine and not when and how to process (Boogaart & Tolosana-Delgado, 2018)

2.3 Types of Geometallurgy

Geometallurgy provides enhanced knowledge on the orebody to be utilised in decision-making during planning and operations. To gain knowledge on spatial variation in ore processing, responses must be embedded in a structured business process. Geometallurgy can be split into 2 types (Dominy, et al., 2018):

- Strategic geometallurgy
- Tactical geometallurgy

Strategic and tactical geometallurgy cover the project life cycle and can be integrated into a logical process flow. The process begins with the design of the process and incorporates reconciliation to the plan as illustrated by McKay, N., Vann, J., Ware, W., Morley, C & Hodkiewicz, P (2016) in Figure 2.1.

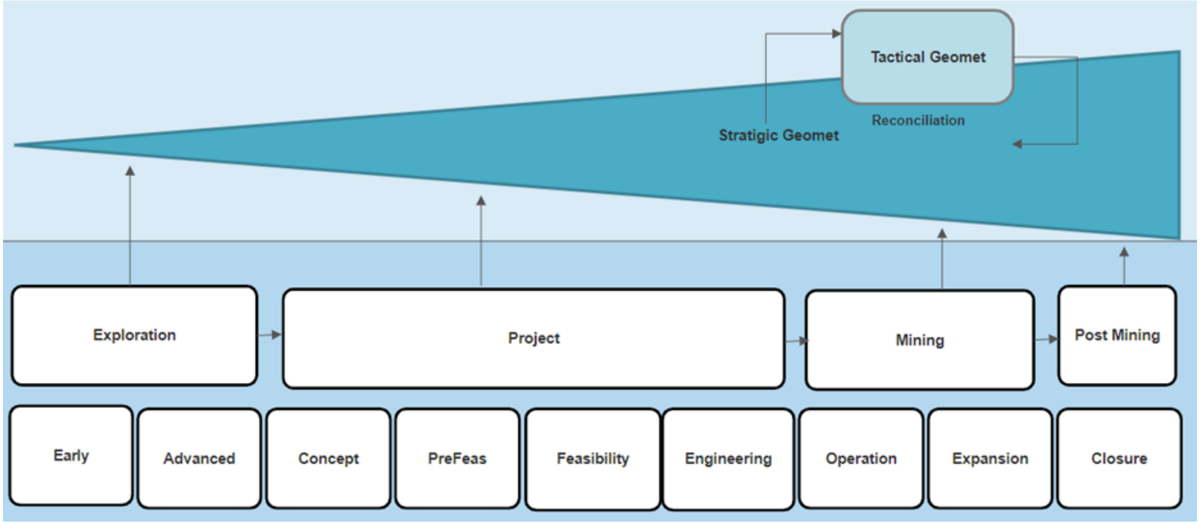

Figure 2.1: Conceptual positioning of Strategic and Tactical Geometallurgy within the Mining Cycle.

2.3.1 Strategic geometallurgy

Strategic geometallurgy delivers value to a mineral resource during the development, planning, operation and mine closure phases (Dominy, et al., 2018). It is a long-term method of using geometallurgical knowledge gained from the data collection processes to maximise the value of the mineral resource (McKay, et al., 2016). Strategic geometallurgy is achieved through collaboration by multidisciplinary teams working together to plan and put processes in place to translate geometallurgical data into useful knowledge. Through using the gained knowledge optimally, the long-term value of the resource can be increased (McKay, et al., 2016).

Exploration is the first step for the creation of a block model which includes the initial drilling phases. The completion of the model will be carried out once all the relevant spatial parameters have been collected. For the model to be rolled out into the production phases, all the relevant parameters need to have been modelled to meet the needs of production. The strategic geometallurgy model contains information on a broad range of characteristics that influence sequential realisation of value through the processing of ore at any given time. These characteristics include the grade of the resource, geological contacts, geochemistry of the ore, geotechnical structures, rock textures, hardness measurements as well as mineral recoveries. The model provides the basis for the development of an optimised reserve production schedule and critical cash flows over the life of mine (McKay, et al., 2016).

The main objectives of a strategic geometallurgical model also include creating interactive models to help guide mining and processing decisions in the context of metal production and cash flow. It is important, in the medium term, to planning time frames such as in the five year or annual plans. The strategic geometallurgy approach is to maximise value through putting in place proper collection and modelling of geometallurgical data as inputs into mine planning as illustrated in Figure 2.2

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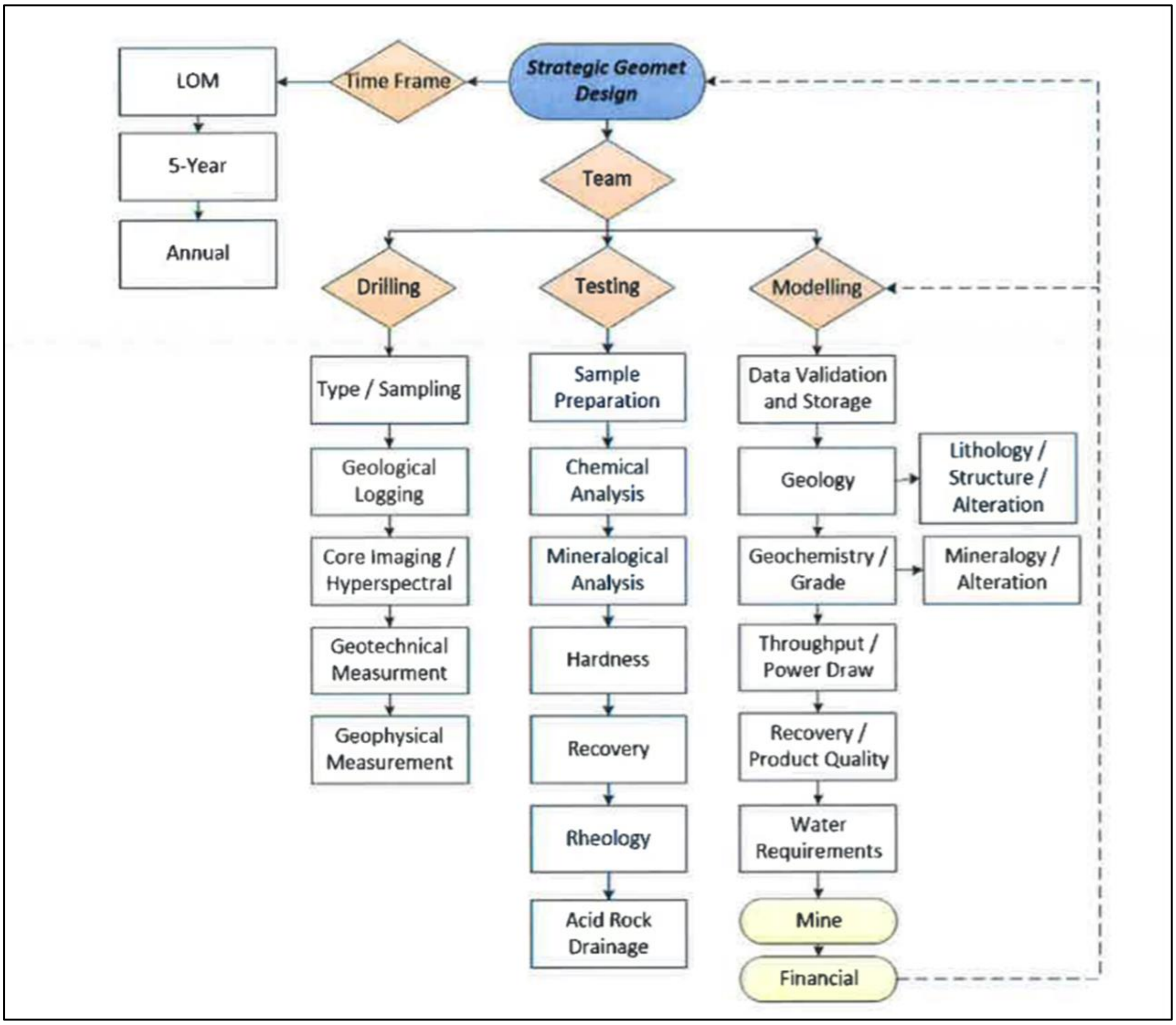


Figure 2.2: The Strategic geometallurgy framework for a mining operation (McKay, et al., 2016)

The variables which are considered in the development of a strategic geometallurgy framework have been defined by (McKay, et al., 2016) as follows:

- Design: this variable begins with knowledge on the variability exhibit by the mineral resources in the short- and long-term. With this knowledge comes requirements to better design a sampling plant to enable a better understanding of the variability of the minerals.
- Time frame: this variable focusses on maximizing the value of the life of mine. The time frames provide the highest level of flexibility in the decision making and allow the evaluation of the numerous mining alternatives that maximize value while taking into consideration other constraints.
- Teams: teams must include multidisciplinary functions which include geologists, geotechnical specialists, geo-statisticians, mining planning engineers, minerals

processing engineers and mining engineers. For the teams to work as a collaboration, objectives must be clearly outlined, information that is collected must be well managed and quality controls must be put in place.

- Drilling: the spatial locations of a drill hole must be carefully designed to provide adequate coverage of the deposit. A drill core is used to provide assays; geotechnical tests, such as fracture frequency; rock quality designation and point-load testing, which provides ore-mapping hardness data. This data can potentially be correlated with important response variables such as blastability and grinding harness. Geophysical measurements can be obtained through downhole surveys or by using hand-held tools to provide indicative measurements of rock type and quantity. With new technologies being introduced, one can obtain rapid quantitative and positional information on ore texture, lithology and mineralogy in drill core and chip samples, through hyperspectral imaging.
- Testing: numerous engineering tests can be performed to measure hardness, floatation recoveries and other parameters, given a sufficient number of drill samples. These tests require intensive, expensive and large quantities of samples that, in turn, require high-quality laboratory facilities for testing. The testing must be sufficient to specially model the process responses of the ore; and selecting spatial variability requires a sufficient amount of spatial sampling. The sampling provides large amounts of data, which must reside in a well-managed database. Successful data management must provide real-time access to all data collected; and data without reliable spatial coordinates cannot be considered.
- Modelling: the objective of drilling, testing and data acquisition is to improve the models that guide mine planning and processing strategies.

The strategic model must contain relevant attributes that represent mining and processing responses. With the increase in data and knowledge over time, the strategic model will be enhanced with information allowing it to be a more useful model.

2.3.2 Tactical geometallurgy

In tactical geometallurgy, multiple data streams are used, including: grade, mineralogy and metallurgical response information. The information is acquired from strategic block models and recent ore-control drilling. In addition to the short-term mine plan, data is collected from ore performance, equipment utilisation and plant performance.

The mine plan deals with the real-time application of the strategic model to optimise value delivery from mining processes (McKay, et al., 2016).

The objective of tactical geometallurgy is to produce a predictive ore model, based on the use of data inputs from the long-term model (the strategic model) and short-term models that are based on ore control. Ore control is the process whereby a processing plant takes blocks of ore and turns them into value through proper planning, measurements and reconciliations. Achieving value requires ore to be at a specific grade, size distribution and to have certain metallurgical performance characteristics (Dominy, et al., 2018). The process of transforming blocks of ore into value starts with understanding the ore through drilling, testing, modelling, and eventually, the delivery of the ore to a processing plant through feed strategies from mining, as on Figure 2.3. This systematic delivery is based on the knowledge of all the attributes of material feed that drives value (McKay, et al., 2016).

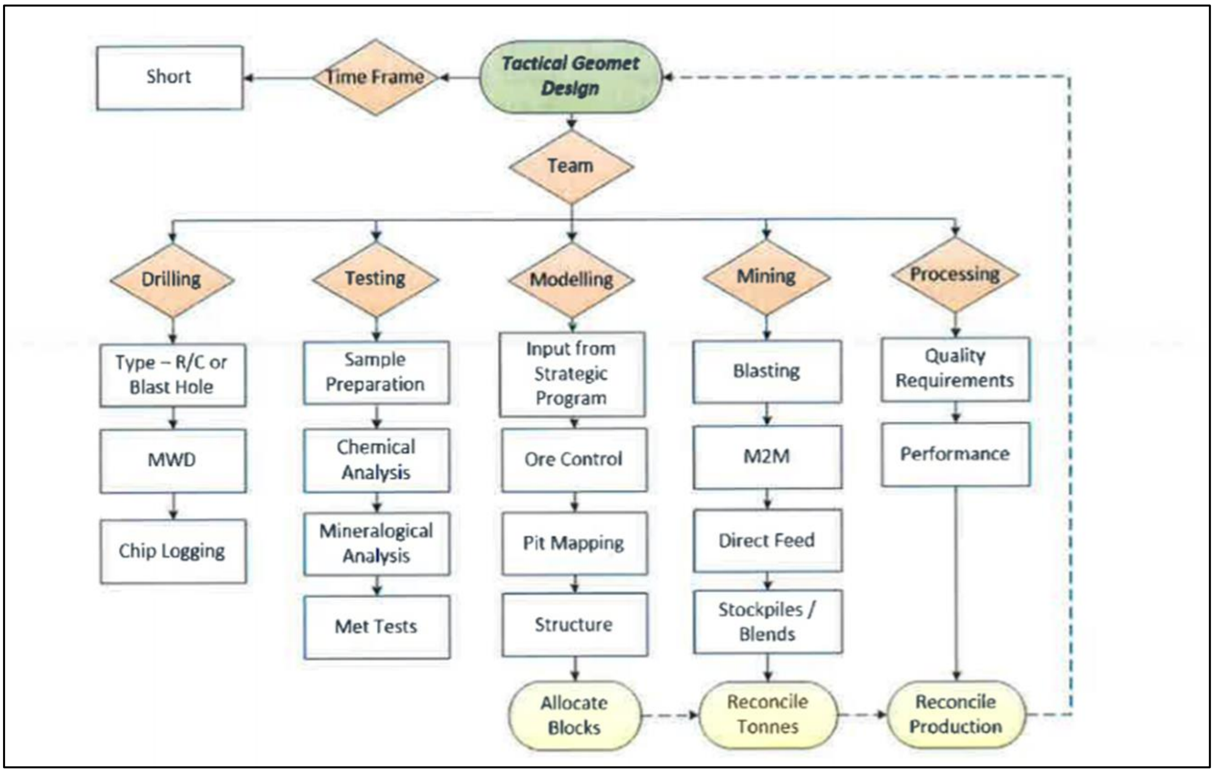


Figure 2.3: The Tactical Geometallugy Framework for a Mining Operation (McKay, et al., 2016)

The key variables, as defined by (McKay, et al., 2016), that are considered in a tactical model framework include:

- Timeframe: the model is created in the short-term and used continuously during mining activities. Overall, the turnaround time to create the model and to put it into usage is 6 months, depending on the frequency with which ore-control data is collected. The quality of planning and ore-control activities is improved as there will be more flexibility. The information used in tactical models is from the long-term geological, metallurgical and mining models that are supplemented with input data from ore-control drilling data.
- Team: the team involves multiple disciplines that are focused on the operational aspects of ore definition, mining and ore processing. In addition to data collected by the ore control geologist on the grade and geology, there also needs to be an understanding of the mineralogical, geochemical, geophysical and metallurgical characteristics of the feed. Plant operators and mineral processing engineers are critical in providing mining with feed specifications to provide feedback on issues related to feed quality.
- Drilling: this involves ore control drilling, which provides valuable opportunities to increase the understanding of localized ore characteristics and variability.
- Testing: the data that is collected from ore control data drilling and blast holes can be used to provide inputs for geometallurgical testing. An important consideration for this data to be used is ensuring correct size distribution of the drill chips and the quality of the ore control sampling.
- Modelling: the strategic geometallurgy model provides inputs for the initial framework of the geology, grade and processing performance for the tactical geometallurgical model. To get the true value of the mining block, additional data collected from the drill chips, which includes hardness information, pit maps of lithology contacts, geological structures and mineralogy, is incorporated in the model. Closely-spaced information leads to more precise estimation of special attributes.
- Mining: this is done through an ordered sequence of extracting blocks and optimally allocating the material to various destinations to maximize value. The tactical geometallurgical model enhances the effectiveness of short-term operational mining plans. This is achieved by integrating short- and long-term data to define the value of each block as waste, ore or stockpiling.
- Processing: as the plant that will be receiving the ore from mining, it’s the

> responsibility of the plant to specify their ore requirements in terms of grade, size distribution and material processing characteristics. For the processes to be a success, real-time feedback to mining is required should material not be of a required quality and should it not meet processing specifications.

Strategic models provide the initial framework of geology, grade and processing performance, the additional data that is collected in tactical geometallurgy is modelled to define the value of each block. The overall objective of tactical geometallurgy is to ensure proper support is provided to mining and processing systems through adequately allocating mining blocks to correct destinations based on their end value to achieve financial targets. The best way to achieve this is to include reconciliation processes for critical variables such as the tonnage recoveries and plant throughput. Tactical geometallurgy involves the systematic process to constantly produce predictable feed and plant performance, maximize value and provide continuous improvement. Through analysis and enhancements the model will be improved and confidence increased. (McKay, et al., 2016)

Historical approaches that were implemented to handle geometallurgical information were related to variability that was considered most critical to the metallurgical performance. With the current wide spread usage of geometallurgical data collection processes, geometallurgical modelling is becoming more prevalent (Richmond & Shaw, 2009). Geometallurgy can influence the value-adding strategic and tactical decisions in the mining value chain. Strategic and Tactical geometallurgy are interactively built processes that mutually support one another, although working in different time frames. Strategic geometallurgy provides the foundation of the information for tactical geometallurgy, which provides real-time feedback of feed through reconciliation processes. The two approaches provide the means to maximize the use of valuable information that is collected at all stages and make improvements to the system. (McKay, et al., 2016)

2.4 Framework for Geometallurgical Variables.

It is important to integrate geometallurgical models into the evaluation and the optimisation of the mineral resource to ensure that real value is realised from these initiatives. For these variables to be spatially modelled, there needs to be a number of sufficient samples that have been collected from all major domains in the resource (Coward, et al., 2009). For all geometallurgical sampling programmes that are carried out, there is need to consider the relationship between small-scale testing and operational scale performance. Also, sampling programmes must consider the implications for the minimum mass of samples required for these metallurgical tests.

(Coward, et al., 2009) Divided the variables into two groups:

- Primary variables are those which look at attributes that can be directly measured, these include parameters of mass density, grade, grain size, alteration and color. These are referred to as intrinsic properties.
- Response variables look at attributes that describe how the rocks respond to the processes they are subjected to. Examples are throughput, recovery, grindability and size distribution; and these are expressed as a response to the process or the application of energy to the rock.

It is important to distinguish the primary and response properties which are referred to as the primary response framework as illustrated in Figure 2.4.

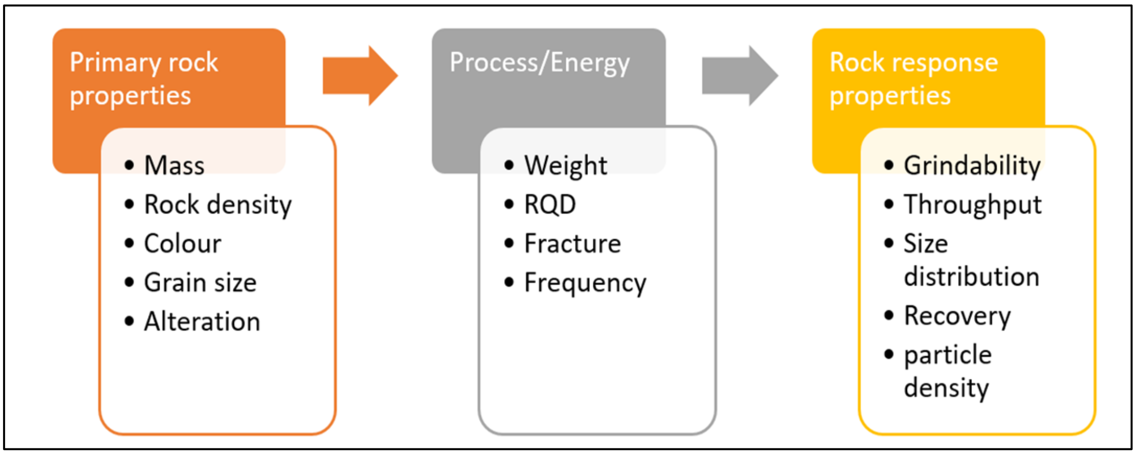


Figure 2.4: The primary and response framework *(Coward, et al., 2009)*

The primary response framework provides a useful way to classify rock variables in order to collect geometallurgical data. Variables are specific to each commodity type, deposit types, mining method as well as different processing technologies.

The basis for the primary and response variables gives an insight into how to best sample and to estimate the different types of geometallurgical variables. This is achieved by allowing one to identify, measure and model primary variables. Where a response variable can be reduced down to a primary component, this will allow control over rock behaviour under a given experimental approach. The challenges associated with sampling, estimating and evaluating will then be simplified (Coward, et al., 2009). An example of this will be of water consumption in the treatment process. Water is usually not cost driven but a strategic consideration where water is scarce. Water is a function of various variables when treating. These includes rock clay content, the degree to which the clays are altered and the liberation of the clays. In turn, these variables are a function of the fineness of the grind. A primary variable such as clay mineral content and alteration state can be estimated into the block model. A function that uses the estimation of clay content is then transferred and the resulting grind is often applied to the estimates at the block scale to urge response-variable water consumption.

The primary response framework provides a useful way to classify rock variables. To collect geometallurgical data, there is a need to identify variables that are relevant to the processes of mining and treatment for the specific operation. This will allow for the determination of variables that need to be measured. For each commodity and deposit type, mining method and processing technology, there needs to be variables that are specific to each site.

2.4.1 Selection of geometallurgical variables

In an already-existing operation, the identification and modelling of variables is assisted by the fact that there is already an existing process plant. The existing plant will be the source that provides the data that can be used to assess the effectiveness of the geometallurgical sampling and the model built from the sampling.

Selection of variables can be conducted through analysis of already-existing mining production performance by relating a period of specific metallurgical performance to a specific rock property. For this to be a success, there needs to be a good data management practice in place. Plant performance data and mine resource depletion data need to be used for a proper reconciliation process. Geometallurgical variables that are currently being considered in different mining commodities include (Richmond & Shaw, 2009):

- Ore and gangue mineralogy
- Textural and liberation properties of rocks
- Grindability, hardness and size distribution
- Bond work index
- Tons treated per hour
- Throughput
- Hydrothermal alterations to look at the clay mineralogy and abundance

2.5 Establishing a geometallurgical program

For geometallurgical analysis to occur, there needs to be implementation of a geometallurgical model, followed by a geometallurgical program. The process of creating, maintaining and utilising a geometallurgical model is called a geometallurgical program (Dunham & Vann, 2007). This program allows for the creation of a model which is used as a predictive tool linking geological properties with metallurgical responses. The efficiency of a geometallurgical program is improved through enhancing the predictability of the model. This enhancement is done through identifying gaps in the methods applied in geometallurgy. Having a better understanding of the known gaps enables the development and improvement of the model. For each commodity at various mines, it’s important to investigate the different application levels of geometallurgy as well as the different approaches that can be followed for data collection to identify the gaps. Closing the gaps identified allows for measuring and modelling of the impact of geological variability in the feed. Examples of such gaps, as described by (Lischchuk & Pettersson, 2021) may include:

- Less costly and simpler mineralogical characterisation techniques
- Geometallurgical tests, which allow capturing of variability in the process
- Process models, which could explain the behaviour of the ore in a particular stage of the process.
- Process simulation with relevant models implemented in a simulation software
- Spatial modelling methods adequate for reviewed cases

Geometallurgical models are not meant to replace already-existing mining and mineral processing models, but rather, they are meant to complement them. The amount of information collected from geometallurgical models can assist in making an informed decisions in the mining value chain.

A Geometallurgical program aims to have an organised model that can predict ore behaviour and its impact on treatability. Geometallurgical models are meant to help provide reliable forecasts for the variability in upstream processes; as knowing the magnitude and implications of the variations allows for better informed decisions (Lischchuk & Pettersson, 2021). Some steps that are undertaken to achieve roll-out of a geometallurgical programme are illustrated by Lamberg (2011) in Figure 2.5. The Geometallurgical model has to clearly outline the use of geological data, sampling strategies, testing methods and simulation outcomes. (Lamberg, 2011) Geometallurgical mapping is the estimation of the geological inputs or the metallurgical response in a spatial model.

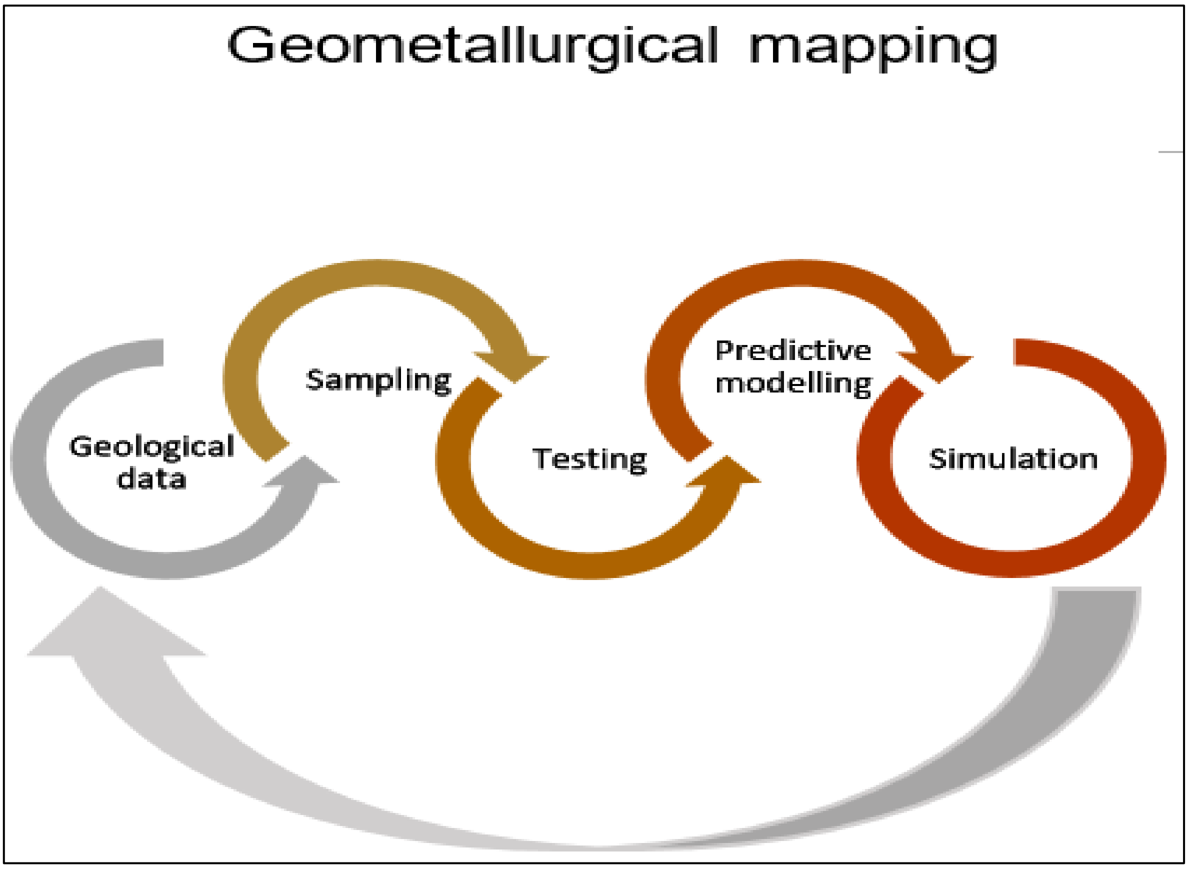


Figure 2.5: Steps of the Geometallurgical program

The following steps, as defined by (Lamberg, 2011), are taken into consideration to achieve a geometallurgical program:

- The first is the collection of geological data. Due to the variability in the geology and mineralogy of different lithologies, data is collected through drilling programs to collect information from drill-core logging, chemical analysis and other relevant measurements.
- A Sampling program is designed to define all areas to be analysed for metallurgical properties. The program needs to define the number of samples required spatially, the different assays needed and the different technologies that are needed for running tests. The number of samples needed is important to establish as having very few samples may result in having an inaccurate model; but also, having too many samples may result in a time-consuming project that is costly, although the model may have higher accuracy and prediction. For a sampling strategy to be regarded as a good one, it must consider both the geological and metallurgical variabilities. Samples used for physical testing are the same ones used for resource definitions. Selection of samples is based on drill-hole data, which is usually based on grade and spatial location.
- Laboratory testing of samples will be used to define the different model parameters. The geometallurgical model requires access to a large number of samples that are used to define ore processing properties. Defining ore-processing properties includes running small tests which characterise the metallurgical properties and give quantitative information on the variances. The method and the parameters have to be selected carefully, as the geometallurgical tests have to correlate with the selected processing technologies and compare them with the metallurgical test.
- Based on test results, a predictive model is created; and the metallurgical validity of the geological ore-types definitions are checked. A statistical relation is established for the metallurgical parameters across the geological database. A geometallurgical model is then created for the process. The model incorporates the unit operations that define the metallurgical parameters identified.

- A simulation of the geometallurgical responses is then run to investigate the different production scenarios and estimate the production risks in the mineral value chain. The information obtained from the mineralogy of the minerals forms the basis for the simulations (Tungpalan, et al., 2015). The metallurgical process model and the distribution of the metallurgical parameters are used as the data set for the simulation. When geological properties are known, metallurgical processes can be aligned to be capable to treat materials; and if these factors are unknown, the process flows will not be designed to address them adequately (Williams & Richardson, 2004). Geological factors play a big part in the way minerals behave when being processed. Table 2.1 illustrates the linkages between geological factors and the behaviour of minerals during processing, as outlined by Williams & Richardson (2004).

Table 2.1: Linkages between Geological factors and the Metallurgical properties impacted.

Geological factors	**Impacted ore property**	**Metallurgical property impacted**		
		Grindability	Floatation	Leachability
Rock type	Hardness	x		
Ore assemblage	Solubility, hardness	x	x	x
Alteration	Clays, Hardness, solubility	x	x	x
Faulting	Clays, oxidation		x	
Metamorphism	Clays,	x	x	

Geological information is used as the initial information in the classification and domain identification process. Later, the geological information is then used critically to evaluate it against results of geometallurgical tests. Campaigns such as focused mining, whereby one ore type is fed for a certain period in the plant, are used to assist with the understanding of the mineralogical characteristics of specific facie. This allows for better knowledge of the limitations of the material coming at different times (Lund & Lamberg, 2014). Such information is very valuable in the later stages of the geometallurgical model validation processes.

Metallurgical performance, such as throughput and recoveries, is also looked at as well as the environmental impacts, such as water consumption, on treating ore. A spatial predictive model is the ultimate goal that geometallurgy aims to accomplish.

Based on the predictions of the model, mining blending plans can be adjusted to try achieve optimum throughput.

Classification of data aims is to investigate different application levels of geometallurgy and different approaches to the data collection process. The overall purpose of this is to ensure all identified gaps can be closed with the aim of collecting information to increase the predictability of the process (Lischchuk & Pettersson, 2021). The type of approach is classified according to the data used in the geometallurgical program. This involves traceable components such as the chemical composition, metallurgical responses and the mineralogy which are impacted by the methods for sampling and analysis. (Lischchuk & Pettersson, 2021)

2.6 Geometallurgical program classification systems

A geometallurgical program involves classification systems that to answer the questions:

1. What type of data will be used – this is known as the approach; and
2. How will the data be used – which is the application.

2.6.1 Classification based on approach

To be able to complete the geometallurgical program, three approaches have been identified by (Lischchuk & Pettersson, 2021). These are based on the type of data that will be used to establish a geometallurgical model (Lund & Lamberg, 2014):

1. The first approach is based on using chemical composition and qualitative mineralogical information (traditional approach)
2. The second one is based on qualitative mineralogical information (mineralogical approach)
3. Lastly, the third approach is based on a combination of geometallurgical tests, chemical composition and qualitative mineralogical information (the proxy approach)

- Traditional approach

  This approach relies on chemical assays and the chemical compositions of the ore as defined by (Lischchuk & Pettersson, 2021). The metallurgical response is calculated from the chemical composition of the ore, which is collected through chemical assays of the samples. A simple recovery function is used; for example, metal recovery is a function of the chemical composition of the ore. The functions are developed by using metallurgical tests and statistical analysis to define correlation between metallurgical response and feed properties (Lishchuk, et al., 2015). This approach is commonly used in commodity types where ore grades are high and is common in the early stages of mining projects. The development of a geometallurgical program starts with the traditional approach.

- Proxy approach
  This approach relies on the metallurgical response measured by geometallurgical testing, without using mineralogy information. The approach uses geometallurgical tests and other indirect measurements of metallurgical responses. These tests and measures are used to characterise the metallurgical behaviour of the ore for a large number of samples in different processing stages. The geometallurgical test work involves running small-scale laboratory tests, which aim to directly measure the metallurgical responses of the samples. The geometallurgical test results must be converted with certain correlation factors, known as scale up factors, to give an estimate of the metallurgical results at the plant (Lischchuk & Pettersson, 2021). The geometallurgical tests need to be applied early in the ore characterisation process in order to collect information on ore variability. These tests are usually cheap and rapid in comparison with laboratory-scale metallurgical tests which usually require special equipment (Lishchuk, et al., 2015).

- Mineralogical approach
  This approach relies fully on using the mineralogy of samples. The approach uses mineral parameters such as modal mineralogy, mineral textures, mineral associations, mineral grain sizes and minerals' relation to liberation characteristics. The distinguishing factor between the proxy and the mineralogical approach is the use of geometallurgical tests in connection with elemental grades, without the connection to the mineral-related behaviour of the ore (Lischchuk & Pettersson, 2021). This is carried out by linking the data from three sub-models,

which are the geological model, the process model and the production model, as illustrated by Lamberg (2011) in Figure 2.6. A geological model and a process model, which incorporates processing behaviours such as commination and liberation, can be linked using mineralogical information, such as textural attributes (Lishchuk, et al., 2015). Collection of qualitative mineralogical data and other information must be systematic and continuous throughout life of a mine (Lishchuk, et al., 2020).

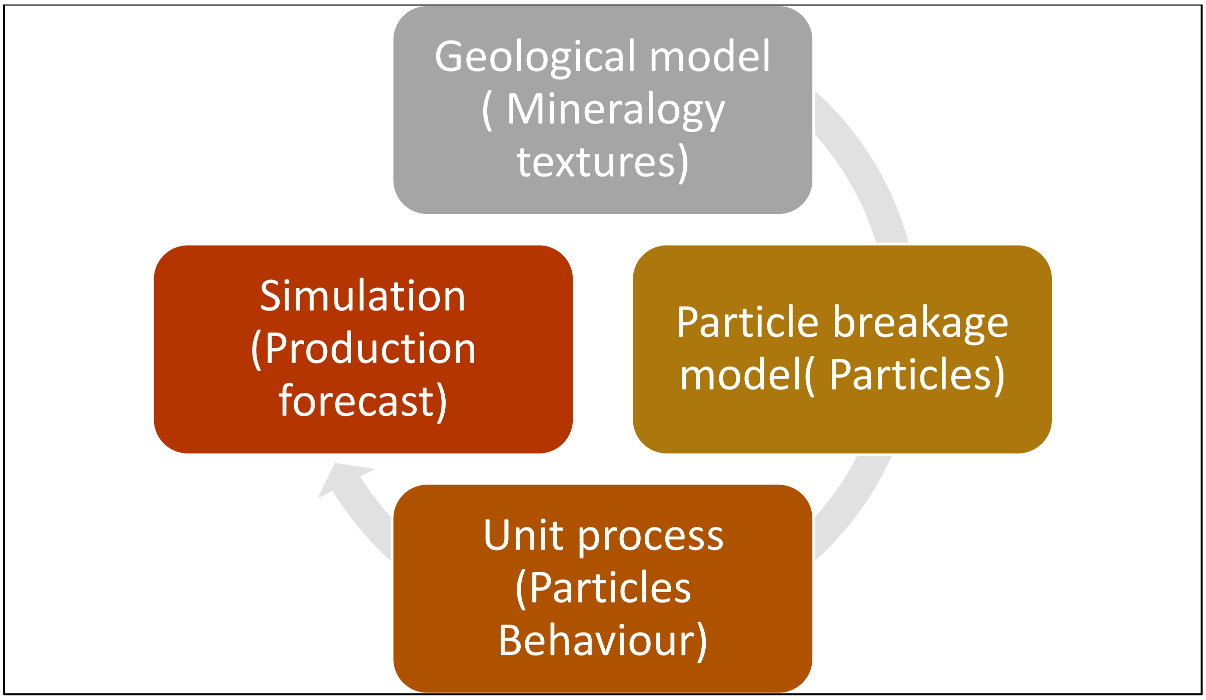


Figure 2.6: The Particle-based Geometallurgical concept

The Geological model provides ore characterisation and quantitative mineralogy data. The components of the geological model are: modal compositions, which include a mineral composition by weight per cent; and textural information, which looks at mineral association and grain size. Ores have variations in mineral grain sizes and other mineral texture characteristics, hence ore texture information is needed in the geological model parameters.

Texture is among the parameters that influence the processing behaviour of ore. The idea behind the geological model is to use information from the model to generate particles and simulate the comminution and concentration process to forecast products. Results obtained can be converted into performance indicators relevant to a specific model as a tool for mine planning and process design. (Koch, et al., 2019).

A case study was conducted by (Koch, et al., 2019) using a drill core to acquire information on texture from a porphyry copper deposit in Sweden. The Methods used to study texture at particle level included scanning electron microscopy (SEM) and optical microscopy. Measurements taken from the drill core can be used for elementary analysis such as x-ray fluorescence (XRF). The approach that was used in the case study was based on using particles and mineralogy obtained from the geological model. This was used to generate particles and to simulate the comminution and concentration processes to achieve a forecast of the product. The results obtained from this exercise were then converted into performance indicators relevant to the specific deposit and plant. Performance indicators, such as those produced in the case study, together with the geological model can be used as a tool for mine planning and process designs.

From the case study, a couple of requirements were identified that are associated with using textures, these are:

- It is important to identify the appropriate geometallurgical classes that are related to the different: rock types, and process performance from the results based of the plant survey or from estimations made through laboratory tests.
- Good knowledge of geology and variability in textures is required, together with enough drill-core images. Each geometallurgical class must be tested at a level sufficient to: build a stream file, and enable the running of a process simulation based on a feed related to the texture classifications. This is a requirement that is directly linked to the process model.

Once the drill core has been classified into different classes, the information can be used to create a geometallurgical model. The ultimate goal of the model will be to produce a spatially predictive model (Lischchuk & Pettersson, 2021).

It is still a challenge to integrate textural information into a geological model; but there are different approaches to doing this that have been studied these are:

- Textural classes can be used for process simulations
- Where drill-core chemical assays are available, appropriate element-to-mineral conversion can be selected, thus improving the quality of the modal mineralogy estimation
- With no assays collected from the drill core, the texture classes can be used to estimate the mineralogy at the surface of the drill core.

Texture carries information about both primary and response parameters.

Process models use the information from the geological model and transform it into information on metallurgical performance (Lamberg, 2011). Ore is comminuted to liberate minerals and to make particle sizes suitable from downstream process.

Integrating the mineral-processing parameters into the geological model has various approaches due to there being a variety of parameters, such as recovery, throughput, and energy and reagent consumption. When process models are solely based on ore-element properties, there is a higher chance that the accuracy reduces compared to when models are based on mineralogy. The reduction of the estimate's accuracy when using mineralogy is because the mineral concentrate is the final product of mineral processing and, therefore, it is not the pure element (Lischchuk & Pettersson, 2021). Having different geometallurgical parameters will result in different properties when the parameters are incorporated into the geological block model (Koch, et al., 2019). These variables taken on by the parameters are classified as:

- Continuous variables, such as element/mineral grade and liberation
- Categorical variables, such as lithology, ore type and textural class

The production model relies on a combination of geological and processes models to manage production so that the best possible results can achieved. The model's main aim is to integrate geological mineralogy and metallurgical information to build a special model for production management (Lamberg, 2011). A Common technique for incorporating geometallurgical parameters into the geological block model include geostatistical simulation and geostatistical interpolation (Koch, et al., 2019).

Luleå University of Technology students carried out a case study on the Kiirunavaara and Malmberget iron ores, which are operated by LKAB (Luossavaara-Kiirunavaara Aktiebolag) mining company (Lamberg, et al., 2013). These operations produce 90% of the iron ore in Europe, at a grade of 14Mt of ore produced per 43.1% Fe. The Malmberget ore field comprises 20 different types of ore bodies made up of magnetite and hematite, which are hosted by volcanic rocks. The students developed a practical way to calculate mass proportions of nine minerals using x-ray fluorescence analysis on the Malmberget iron. These calculations assumed that samples consisted of nine minerals that did not have varied chemical compositions, judging from the average electron microscope analysis. It was later found that, in comparison with modal analysis, better results are achieved through dividing calculations into four rounds in the HSC chemistry software. The relative standard deviation of the elements compared to the mineral conversion was 12%. This percentage is high while the quality is not good enough for using grades as a basis for resource estimation. This quality on the other hand is good enough to be used in defining the geometallurgical domains. A study was carried out on the applicability of x-ray diffraction using reitveld refinement. The results indicated that modal analysis by x-ray diffraction with reitveld refinement is poorer than element by mineral conversion. Through combining the various techniques and incorporating the weighted non-negative technique in the HSC chemistry software, the results of modal analysis can be improved. When the results improve, they approach the levels required when creating a geometallurgical model. The combination of these two techniques (x-ray diffraction using reitveld refinement and element by mineral conversion) gives a possible solution for a more reliable modal analysis in the Malmberget ore fields as well in other ores with relatively simple mineralogy. Ores that have minerals of interest occurring as trace quantities require further mineralogical tests to be carried out on them to get more information from their samples.

For these operations to take place, a geometallurgical model should be able to be used as a predictive tool to predict the behaviour of the ore in comminution. The comminution characteristics of the ore controls production volumes, hence it is an important variable to include. Small-scale tests, including grindability tests, were carried out to measure the communication properties of the rocks. With the results obtained, a geometallurgical model was created. The grindability characteristics have been used to find the links between mineralogy, grinding energy and particle size distribution. Results obtained from Malmberget indicate that in the grinding products, the mineral grades vary by size, which indicates a non-random breakage. Grades from magnetite are highest in the middle-size fraction, while waste is associated mostly with finer grain size.

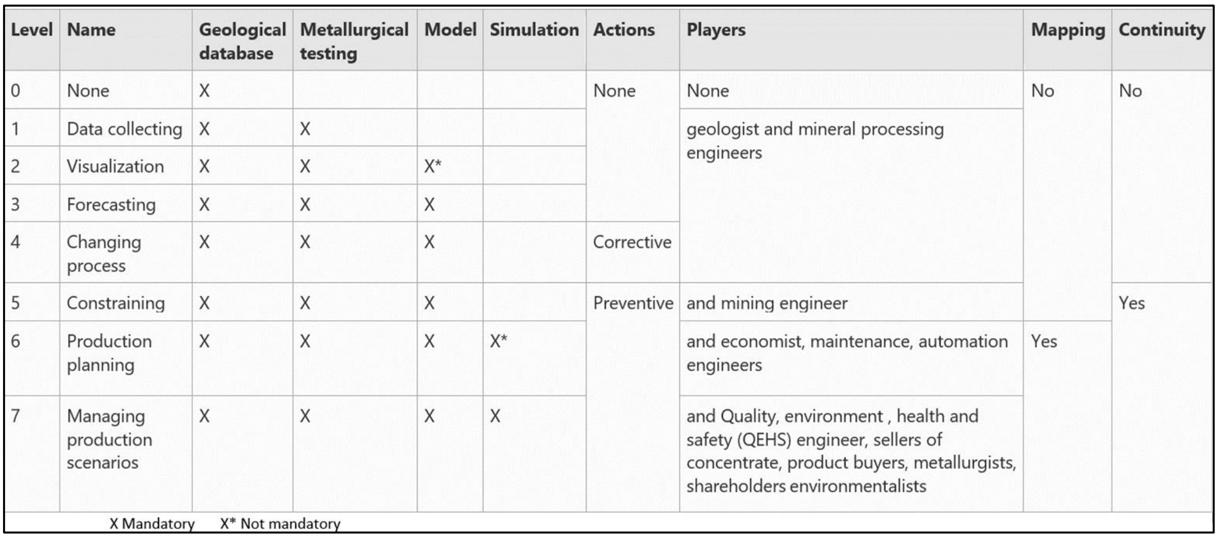
Another important variable that has to be included in the 3D geometallurgical model in these operations is the liberation characteristics of the crushed ores. In Malmberget, liberation size of the magnetite and hematite is controlled by the grain size of the ore minerals. These minerals' associations are controlled by modal mineralogy as well as by the minerals' texture. Liberation is dependent on modal mineralogy: as mineral grade increases, the degree of liberation increases. An example is the magnetite-apatite- tremolite, the mass proportion of the magnetite is associated with increase in tremolite grades. The analysis conducted on the iron ore mines in Sweden indicated that by using a mineralogical approach it is possible to achieve a geometallurgical model, but with more tests and work being carried out in order to evaluate the accuracy of the model.

More advanced geometallurgical programs tend to use a mineralogical approach, while less advanced programs use the traditional approach. The proxy approach is applied in between more advanced and less advanced programs. (Lischchuk & Pettersson, 2021). Therefore, the creation of geometallurgical models is dependent on information gathered either through: geometallurgical testing or the sampling of mineralogical data collected from the ore body (Lamberg, et al., 2013).

2.6.2 Classification based on Application

The extent to which a geometallurgical program can be used in the production space is determined by how the geometallurgical data is used in the mineral processing chain. There are levels of geometallurgy programs used to differentiate how far a geometallurgical model is involved in the production management decisions. These levels vary according to the depth of the use of the model, the key players involved, and the sophistication of the model used to solve production issues. The conditions that may be used to determine the level of application of geometallurgical model are shown in Table 2.2, as defined by (Lischchuk & Pettersson, 2021).

Table 2.2: Application levels of geometallurgical program



Level	Name	Geological database	Metallurgical testing	Model	Simulation	Actions	Players	Mapping	Continuity
0	None	X				None	None	No	No
1	Data collecting	X	X				geologist and mineral processing engineers		
2	Visualization	X	X	X*					
3	Forecasting	X	X	X					
4	Changing process	X	X	X		Corrective			
5	Constraining	X	X	X		Preventive	and mining engineer		Yes
6	Production planning	X	X	X	X*		and economist, maintenance, automation engineers	Yes	
7	Managing production scenarios	X	X	X	X		and Quality, environment , health and safety (QEHS) engineer, sellers of concentrate, product buyers, metallurgists, shareholders environmentalists		

X Mandatory X* Not mandatory

The below levels have been used to differentiate the different applications of geometallurgy programs:

- Level 0: there is no geometallurgical data that has been collected and no geometallurgical model exists.
- Level 1: geometallurgical data has been collected but it is not utilised for any planning purposes. To be useful, collected geometallurgical data requires tests to be carried out on it for either a feed forward or feedback effect to take place. A feed forward effect is examined on the variability in metallurgical responses under laboratory conditions. A feedback effect relies on the connection between variability in metallurgical responses at a plant that can be linked to geological variability.
- Level 2: this is where the variability within the ore body is visualised based on the data collected for geometallurgical purposes. A geometallurgical model may be developed in this level but not be in use for any production-related purposes.
- Level 3: geometallurgical data collected is used in production forecasts. The information collected is used to make other people who have no active role in production aware of feed related issues to look out for. The

information is taken but no actions exist to change mining or processing activities.

- Level 4: information on the variability in feed quality is used to make changes to processes. During this level, only corrective actions are taken and no preventative measures are put in place. This level is the transitional stage between passive and active applications of geometallurgy.
- Level 5: in this level, data that is collected is used to define feed-quality constraints and the production limitations of the process. The geometallurgical program must be continuous and constantly updated with improvements. This level includes combating limitations relating to feed properties. Feeding blends are therefore changed to mitigate the negative impact of the problematic components downstream. These changes may include actions such as selective mining and changing the production sequences. Hence, changing feeding blends requires a larger group of participants, besides just the geologist and metallurgist.
- Level 6: this level requires the production plans to be based on the geometallurgical data collected. Both the geological variables and geometallurgical indices are included in the block model, hence the block model needs to be continuously maintained and updated. This requires advanced online measurement tools and real time updates of the geometallurgical model, block model and mine production plans. A wider range of players, such as: engineers; economists, together with the metallurgists and geologists, actively contribute to the utilisation and development of the geometallurgical program. Involvement of economists allows for production estimation of cash flows.
- Level 7: this is the highest level; it looks at managing production and geometallurgical data that forms the basis of decision-making. Flexibility is achieved through active use of simulations and active involvement of a wide range of departments. A more effective application of geometallurgy in level 7 requires real-time collection of data and updating of: the block model, geometallurgical model and production plans.

Investigation of Anglo American Mogalakwena operation can be used to determine the level of application of the geometallurgical model of the mine. Mogalakwena platinum mine is an open-cast platinum reef that has varying rock types, with varying hardness and recovery potential. This has posed challenges to metallurgical processes as the ore is fed primarily on the basis of platinum element grades and not by rock type. (Schouwstra, et al., 2013) Pyroxene is the most abundant mineral type in Mogalakwena, with areas characterised by large volumes of calc-silicate. The calc silicate has been identified as having high variability in its mineral content, textural characteristics and colour. Calc silicate contains high Diopside, which is a reflection of containing high calcium content. There is an intermediate rock known as para-pyroxene, which occurs between the calc-silicate and the pyroxene. This rock is also characterised as having high variability in the terms of its mineral content and appearance, but with less calcium. With the different platinum reefs, varying breakage characteristics that have been identified, which have an impact on processing throughput.

A sampling and metallurgical testing program was developed based on the data that was available, which included chemical information using CaO content as an indicator mineral of importance. Where there was inadequate data, additional information for mineralogy and texture were acquired. From the results, it was established that CaO content increases from pyroxene through para-pyroxene to calc-silicate. The data collected for geometallurgical testing work also provided an opportunity to model the hardness parameters and run floatation tests against the CaO content. There was a linkage established between chemistry and the metallurgical responses of the samples, which allowed for linking of chemistry to mineralogy of the rocks. From the data, the mineralogy of each sample was first identified, followed by clustering the samples according to mineralogy. The metallurgical responses for each cluster were then identified with respect to floatation, recovery, settling rate and grindability. It was established that Mogalakwena North can be divided into 4 different rock types, but because of the wide variation in mineralogy and chemical characteristics, the four rock types are not suitable proxies for metallurgical performance. With the limitation in the data, plant performance cannot be predicted accurately, but the plant's geometallurgical model can provide an indication of changes in the concentrate grade that can be expected with changing ore types. This resulted in the failure of the process to create a 3D geometallurgical model for Mogalakwena, placing Mogalakwena's geometallurgical program at level 2 application. If more data were collected, it would increase the mine's level of application, making it easier to predict metallurgical responses from chemical analysis.

These different types of classifications of a geometallurgical programmes allow for more practical issues to be investigated. The type of analytical instruments needed are determined. The key departments required are identified and how this model can be applied in production is determined.

Operations which have complex mining, as characterised by the mine's occurrence in variable geology, mining throughput and downstream processing effectiveness is dictated by the variable geology of the mine. The chaos theory states that for any small change in a system's initial conditions, there will be divergent outcomes to the extent that the small changes eliminate the ability to accurately predict the performance outcomes of the system (Claassen & Laurens, 2016). Complex geological environments can render mining systems unpredictable due to the compounding effect it has on operational performance if not dealt with correctly and on time.

A geometallurgical approach study was carried out by Philander & Rozendaal (2011) to test the recovery process of the lithified heavy mineral resource in Namakwa Sand Mine. Namakwa Sand Mine is an open-pit titanium-zirconium, heavy-minerals mine situated on the west coast of South Africa. The mineral value chain starts with the haulage of the resource to the mineral sizer. Then the resource is conveyed to primary-concentrate plants. At the plants, further treatment occurs as material is put through the wet magnetic separation and electrostatic separation processes, producing the final product. The mine was faced with challenges which are related to concentrate-size distribution, since material of more than 1mm is considered oversized. From experience, the oversized material, which is not removed during feed preparation, causes equipment failure downstream. Also, the occurrence of oversized material in the running of a mine impacts feed preparation equipment, eventually leading to reduced plant availabilities. Due to the strengthening of the zircon market, the mine was faced with extracting a resource which contained 35% consolidated mineralised sands, which are referred to as cemented layers. The challenge associated with cemented layers is there is a lack of geological information on their material, and material cannot be liberated to sizes lower than 1mm by the plant, leading to the loss of the mineral resource.

A poor understanding of the geology of cemented layers, and poor knowledge on how to potentially beneficiate the zircon from these layers led to the introduction of a project that will close the identified gaps, called the Hard Liberation Project. Through this project, an in-house team was set up comprising different disciplines in the mining value chain. The team had geology representatives, who looked at improving the mineral resource definition of the cemented layers, and other representatives, with metallurgists looking at running liberation tests and other process simulations.

Based on the nature of the cement matrix, three-layer types were identified comparing the mineralogy, chemistry and the textural properties of the material.

- T1- contains low calcium, al-rich clay (smectite), amorphous ferruginous matter and microcrystalline quartz.
- T2- Is magnesium-rich with poor calcium and consists mostly of sepiolite.
- T3 is richer in calcium than the other two and contains minor dolomite.

The metallurgists set tests to establish the most suitable comminution method, targeting the liberation of the maximum amount of zircon from the feed that generates minimum slimes and utilises minimal power. The results indicated that a high ratio autogenous milling, aided by pre-screening and removing slimes, achieved significant liberation of highly recoverable zircon from the cemented layers at low energy consumption. This assists in improving mineral resource utilisation to levels that had not been reached previously. Samples were then produced for laboratory simulations. Results from these test works proved that it is possible to liberate zircon from the cemented layers and recover it to product specification. Applying geometallurgy proved to be important in achieving objectives of comminution in the mineral sands. This is an indication of the value add of a geometallurgical program in understanding the primary key variables impacting the metallurgical variables, in order to achieve better processing of the material.

- In the mining value chain, mineral processing is a highly energy intensive processes, which is impacted by the introduction of changes to the feed. Changes may be through a variance in the physical state of the feed, or changes in the chemical environment in which the feed is processed (Grafe, et al., 2013). Should these changes not be controlled accordingly, there will be cost implications, which will be incurred through higher energy consumption, additional labour requirements, increases in raw material inputs and high capital expenditure. One main stage in mineral beneficiation is mineral communition. Communition is a process that involves the breaking of ore into smaller particles through crushing and grinding (Forbes & Chryss, 2013). Variability in particle mineralogy and surface chemistry has an impact on mineral beneficiation in all the various stages. The presence of clay in ore causes a variety of beneficiation challenges due to the softness of clay (Forbes, et al., 2013)

2.7 Classification of clay minerals.

Clays are a mineral group that is composed of particles that have physical properties including: hardening when dry and having plasticity when wet. Clays contain particles which are below a certain size fraction; and examples include phyllosilicate (Grafe, et al., 2013). There are two types of clay classifications, based on silica tetrahedron sheets (T) and alumina octahedron sheets (O). Clay layers are formed as these tetrahedron sheets and the octahedron sheets are bonded to each other. The differential bonding of the sheets results in the formation of different types of clay formations, which contain similar structures but are of different chemical and physical properties (Grafe, et al., 2013). The type of clay indicates the type of arrangement of the clay, which can be either: a 1:1 sheet arrangement or a 2:1 sheet arrangement, as shown in figure 2.7. Clays are grouped together according to the sheet arrangement of clay layers, the interlayer bonding between them and their interlayer cations. Clays can be classified as kaolinite, illite, smectite and vermiculite

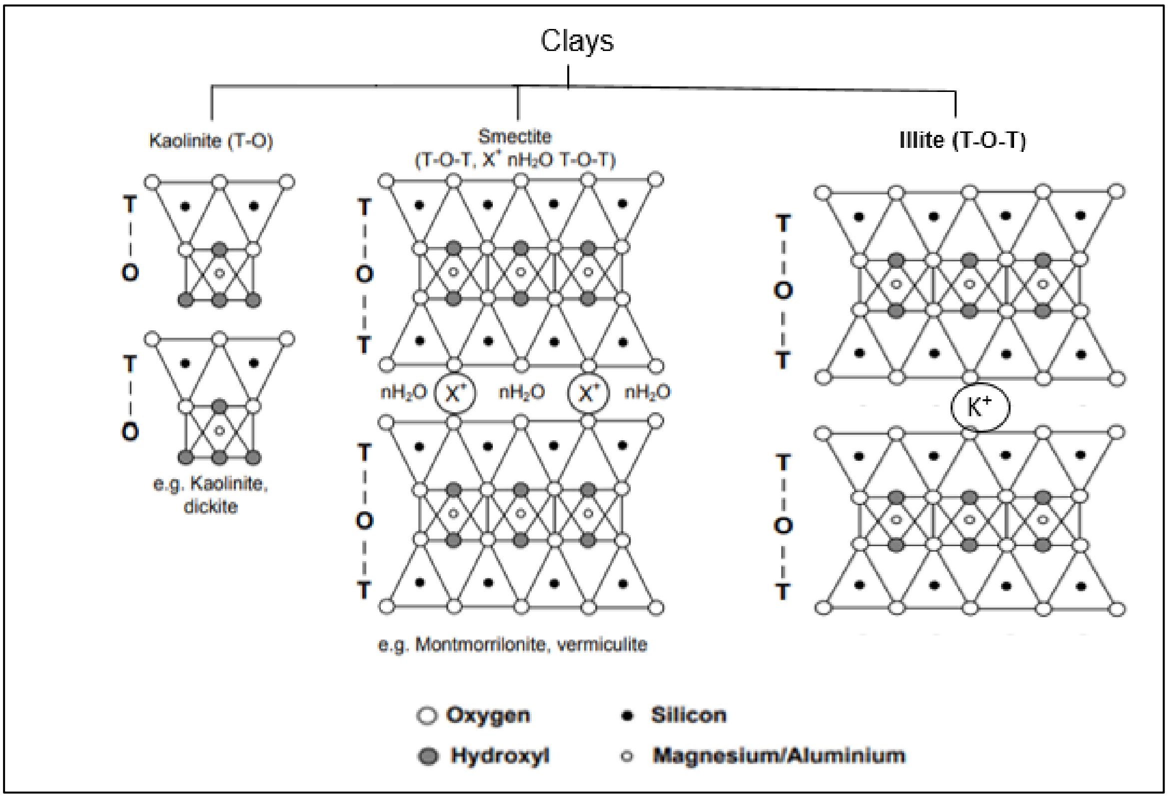


Figure 2.7: Classification of Clay Minerals

One to one (1:1) clays are referred to as a TO, which are the non-swelling clays known as the kaolinite – of the smectite group. Smectite clays are bonded to hydrogen bonds and hence water molecules are unable to penetrate through the interlayers of smectite clay particles.

Two to one (2:1) clays are referred to as T-O-T clays and occur as either illite or smectite. Illite clays are non-swelling clays with anhydrous k^+ ions as interlayer cations. The k^+ ions in the interlayers are highly bound by the clay layers leading to the water molecules being unable to penetrate to cause swelling (Basnayaka , 2018). The smectite group, on the other hand, is made up of hydrated interlayer cations, resulting in higher swelling capacity; examples include montmorillonite and vermiculite.

Kaolinite and smectite group clays contain minerals that are classified as swelling or non-swelling varieties. The capacity of these minerals to swell originates from the interlayer cations which are found in 2:1 TOT sheets of the minerals. They are responsible for the attraction to water molecules which accumulates between the sheet layers of the minerals. Swelling leads to an increase in the volumetric solid fraction of the suspension, which leads to an increase in particle-particle interactions (Forbes & Chryss, 2013).

Clay presence causes a wide range of different problems in mineral beneficiation. In the mineral-processing value chain, there are seven key areas that are impacted by clay behaviour as defined by (Grafe, et al., 2013), these include:

- Water absorption behaviour
- Suspension settling
- Suspension rheology
- Species adsorption
- Dissolution
- Clay mineral adhesion
- Clay polymer adhesion

The impact of clay on the mineral value chain can either relate to a material handling issue, which comes from the stickiness of the material and is due to chemical interference during processing. Metallurgical processes that are impacted include crushing, gridding, settling, rheological properties, comminution and solid liquid separation (flocculation) and tailings. The impact of clay varies by process, as defined by (Basnayaka , 2018) in the below processes:

- Crushing: with the presence of clay in the feed, there will be a reduction in the efficiency of crushing, as the clay sticks to the liners and blinds the openings of the crusher and the crusher plates.
- Screens: due to the sticky nature of clays, clays tend to stick to conveyor belts and blind the screens.
- DMS: the presence of clay in feed leads to a failure to achieve separation of ore, clay needs to be removed from the scrubber before reaching the DMS to minimize bad separation.
- Pumping: the presence of clays causes difficulty in the pumping of processed slurry, resulting in lower throughput rates, which impact plant performance. Clay also causes difficulty in pumping the underflow of thickener tanks, due to elevated viscosity.

- Thickeners: thickening is a dewatering process whereby water is separated from the solid through gravitational sedimentation of the particles to dewater a slurry in the tank. The slurry is the underflow and the liquid is the overflow. The presence of clay minerals reduces the efficiency of the thickening process due to the low settling rates of clay particles.
- Settling: - feed rich in clays could result in overflows of water with high solid content ending up in thickener tanks, due to clay’s low settling rates. This results in the use of contaminated water in the downstream processes.
- Slurry Rheology: this looks at the flowing ability of the slurry, as this may have a significant impact on mineral processing operations. Slurry rheology is controlled by the properties of mineral particles such as morphology, surface charges and swelling capacity. The presence of clay in feed leads to increased viscosity and yield stress. The swelling clays have a bigger influence on slurry rheology compared to non-swelling clays.

2.8 Chapter summary

Currently, the mining industry is faced with new challenges as compared to historically. This is due to changes in geological complexity, productivity, legislative environment and highly fluctuating commodity prices. If these variabilities are not clearly defined, spatially, mining projects will be at a higher risk of processing an unknown resource. Geometallurgy is a key field in identifying variabilities in a resource as well as mitigating against challenges associated with those challenges. Mineral processing is a very complex process that is impacted by any variability in mining feed. It is important to have a better understanding of the resource being treated in order to treat it according to its specific properties. For this understanding to be achieved, a better understanding of the mineralogical properties of the rocks plays a key role. This is key as certain minerals tend to behave negatively in the plant, affecting treatability and plant performance. The main mineral of interest is clay minerals, which have been discussed in this chapter. Jwaneng kimberlites are associated with clay-rich lithologies which are discussed further in the next chapters. The next chapter describes the research methodology.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Chapter Overview

This research uses the quantitative approach. The quantitative approach is defined as the use of numerical data for analysis with the purpose of describing and explaining observations using mathematical methods (Sukamolson, 2007).This chapter describes the methodology that was used to collect data. The data that is used was collected from Jwaneng resource extension-drilling sampling, Jwaneng mine production data and technical reports. The chapter describes how the data was analysed to answer the research question.

3.2 Input data and sources

For a geometallurgical model to be completed and used as a predictive tool to establish the Jwaneng clay-rich kimberlites, the confidence levels of the geological data related to the kimberlites will need to be increased. This can be achieved by adding to the model the metallurgical response variables that look at the impact of clay. The sources of data to be used for this research are obtained from the following:

- Geological data collected through resource extension projects and used in the geometallurgical modelling for Jwaneng will be used for this analysis. The data includes geological data of the kimberlites, geotechnical data and ore dressing studies.
- Ore processing and geology production data shall include the following attributes: mining blocks, ore destination, volumes moved, treated tonnes, density per rock type, mining mix and processing delays
- Metallurgical performance data collected from production will also be part of the data analysis and will include: water consumption, ferrosilicon consumption and flocculent consumption.

The data are discussed further in the next sections.

Resource extension projects geological data

In 2001 Jwaneng mine conducted ore dressing studies, during the JREP1 campaign. The studies were done to determine whether there were any changes in gangue characteristics with a change depth and facie within the North, Central and South kimberlite pipes. A follow-up evaluation of the kimberlite ore characteristics of Jwaneng mine was carried out in 2012 during JREP2. The ore dressing study sampling carried out in JREP phase 2 was done to fill in the data gaps at the lower depths of the mine. The data gaps were filled by comparing the relative ODS samples to the major geological rock units of each pipe relative to current mining levels. From the selected drill holes, the core samples were tested for: communition, concentration, water recovery and recovery characterization with regard to changes in depth as illustrated on Figure 3.1.

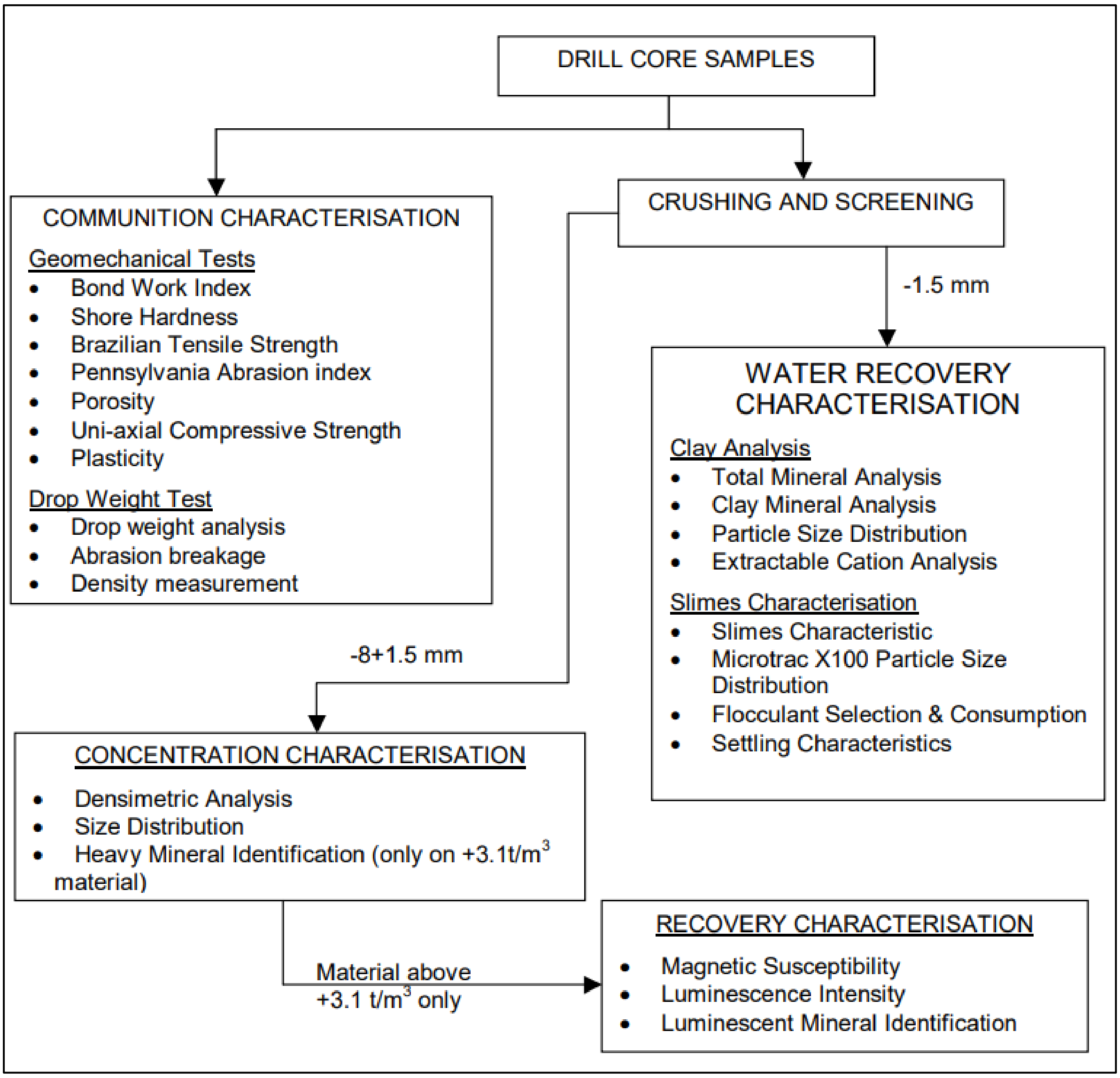


***Figure 3.1**: Test Work Conducted on the Jwaneng Drill Ore (Mhlanga, 2002)*

The objective for these ODS test works was to ensure the sampling carried out would focus on highlighting any significant change to the lithologies of the three main kimberlite pipes with changes in depth. A total of 40 geological and spatial sampling points were identified as target points on the already-existing drill core. These were sampled to obtain results for the following test requirements (Staden, 2014):

- JK SMC tests, which are carried out to provide a range of useful comminution parameters through highly controlled breakage of rock samples. For JREP2 samples, two different drop-weight tests were used: 2.0m for PQ size core, and 4.0m for HQ size. The results were used to determine the drop-weight index (DWi), which measures the strength of the rock.

- Slimes characterization tests were conducted to determine the slurry chemistry and establish settling rate based on the water at Jwaneng mine.

- Densimetric analysis was conducted at various density cuts to establish the near cut-point density distribution and the theoretical yield potential for the samples.

- Rock mechanics test works were carried out on all the samples from all three pipes to determine uniaxial compression strength (UCM), bond abrasion and the crushability index.

Combined with ODS samples collected from JREP1, the spatial positioning of the samples taken for the JREP2 tests are illustrated in Figure 3.2.

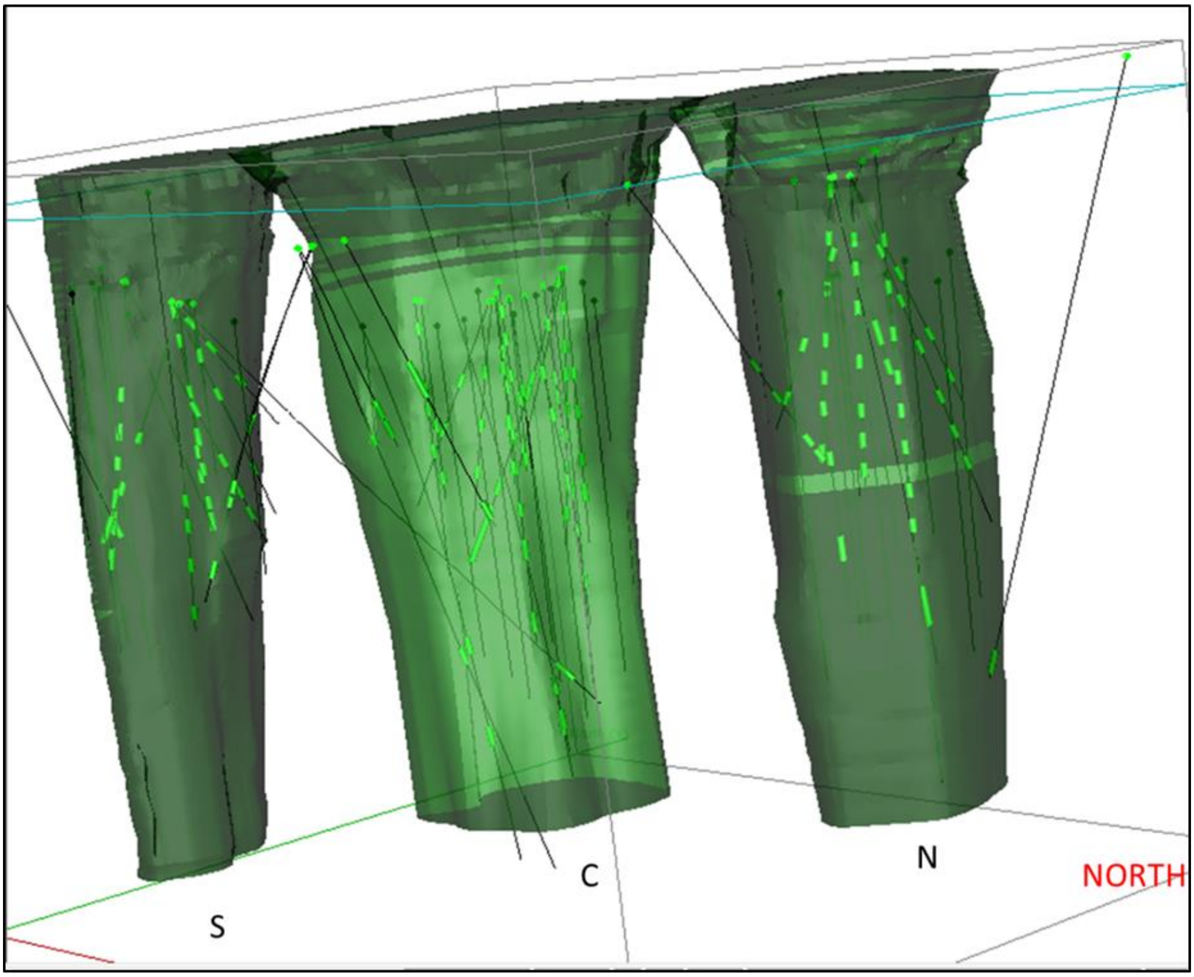


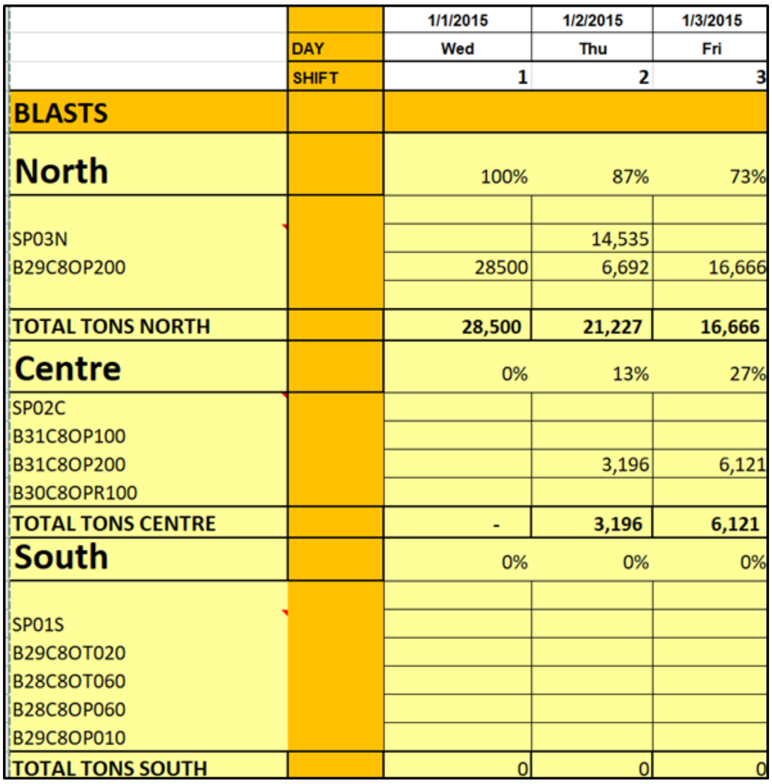
Figure 3.2: Jwaneng Pipes Indicating ODS Spatial Positioning of Sampling Points Highlighted in Light Green color

3.2.2 Geological production data

The geological production data was collected through the mining dispatch system as sampled on Table 3.1, and compiled in the daily reconciliation sheet as show in Figure3.3. The data is collected daily according to the source of the feed. At the end of every month, this data is compiled as show in Table 3.2. For this research, the data that was used was from January 2015 to December 2019. The data is plotted on a historical time series graph and an analysis was done on the variability of the ore types during the stated periods. The data was used to determine the impact of the variability that is present in the mining mix on the mineral value chain.

Table 3.1: Mining dispatch daily data records.

Shovel	(All)						
Sum of Tons	**Dump locations**						
Row Labels	**SP03N**	**SURF-CR2**	**WD06**	**WD24**	**WD26**	**WD-DAM01-02**	**Grand Total**
DK2N	**8,092**	**35,178**					**43,271**
B29C8OP400-4	8,092	35,178					43,271
Ore-ex-S/P		**1,659**					**1,659**
SP03N-2		1,659					1,659
SHLE			**48,040**	**100,899**	**57,320**	**14,686**	**220,945**
B12C9WP060-13				28,814	17,932		46,746
B13C9WP050-13				72,085	39,388		111,473
B19C8WP000-13			25,378			11,315	36,692
B30C8WP100-13			22,662			3,372	26,034
Grand Total	**8,092**	**36,837**	**48,040**	**100,899**	**57,320**	**14,686**	**265,874**



		1/1/2015	1/2/2015	1/3/2015
	DAY	Wed	Thu	Fri
	SHIFT	1	2	3
BLASTS				
North		100%	87%	73%
SP03N			14,535	
B29C8OP200		28500	6,692	16,666
TOTAL TONS NORTH		**28,500**	**21,227**	**16,666**
Centre		0%	13%	27%
SP02C				
B31C8OP100				
B31C8OP200			3,196	6,121
B30C8OPR100				
TOTAL TONS CENTRE		**-**	**3,196**	**6,121**
South		0%	0%	0%
SP01S				
B29C8OT020				
B28C8OT060				
B28C8OP060				
B29C8OP010				
TOTAL TONS SOUTH		0	0	0

Figure 3.3: Daily reconciliation sheet

Table 3.2: Monthly mining mix compilation.

Depleted Tonnes	**VK(C)**	**QVK(C)**	**KBX(C)**	**SSTBR(C)**	**ST14**	**VK(S)**	**QVK(S)**	**SP200**	**VK(N)**	**PK_BC**	**QVK(N)**	**Total**
Jan-15	98,906				165,350	302,185		204,575				771,017
Feb-15	89,465	92,482	4,074	2,300	139,871	151,547	52,683	156,844				689,676
Mar-15	79,680	98,488	19,445	11,292	70,367	197,997	45,628	128,430	2,320	117	516	655,915
Apr-15	75,463	2,343	62,708	192		200,828	129,495	40,133	3,009	2	3	514,179
May-15	290,171	150,378	22,044	8,800	21,378	86,061	51,265	12,261	13,424	990	473	659,329

Jun-15	399,279	49,388	59,820	619	49,275	33,311	22,268	114,571	34,345	73	2,058	770,343
Jul-15	143,835	8,538	19,820	316	23,234	18,986	23,772	191,012	18,966	9,779	266	458,541
Aug-15	140,346	4,120	21,296	6	123,172	84,898	60,477	42,426	9,010	205	94	486,052
Sep-15	50,355	78,146	9,062	7,096	14,158	238,993	38,564	96,987	1,262	382	452	551,122
Oct-15	210,650	16,483	1,110	544	21,734	19,769	26,554	2,886				300,023
Nov-15	98,327	7,600	4,418	57	83,458	125,388	17,029	172,792				509,172
Dec-15	128,781	71,444	11,227	215	29,585	91,246	35,120	16,412				384,072
	1,805,259	**579,410**	**235,026**	**31,438**	**741,583**	**1,551,209**	**502,856**	**1,179,329**	**82,335**	**11,549**	**3,863**	4,364,771

3.2.3 Processing production data

The data that was collected included: plant-delay analysis, which is compiled per shift and recorded in minutes as sampled on Table 3.3. The monthly consumable costs were calculated based on utilisation, as sampled on Table 3.4.

Table 3.3: Plant delay analysis per shift

Shift	Headfeed delay details for shift	Section	Type	Date	Total(min)
2	secondary silo high - high proportion of coarse material	Scrubbing/Screening	Coarse ore	12/27/2014	171
3	secondary silo high - high proportion of coarse material	Scrubbing/Screening	Coarse ore	12/28/2014	100
22	secondary silo level high - coarse material from primary stockpile	Secondary Stockpile	Hard Ore	1/17/2015	25
23	feed prep stock pile high - too much coarse material from primary stock pile	Scrubbing/Screening	Hard Ore	1/18/2015	24
26	primary crusher choking hence low throughput - wet ore from s2b	Ore Delivery	Poor blending	1/21/2015	122
27	primary crusher choking hence low throughput - wet ore from s2b	Ore Delivery	Poor blending	1/22/2015	85
1	suspended head feed -thickeners slimming feeding s14	Thickeners	Sliming	1/26/2015	118
4	low feed from primary stockpile - surface crusher chocking and boulder bridging	Ore Delivery	Coarse ore	1/29/2015	59

Table 3.4: Monthly flocculant utilization cost

Cost Element	Cost element name	Total cost	Period	Transaction Currency	Total quantity	Cost per ton
452330	Flocculent	152,744.00	12	BWP	0.000	0
452330	Flocculent	363,475.60	11	BWP	14.860	24.46
452330	Flocculent	167,477.62	11	BWP	6.847	24.46
452330	Flocculent	-176,919.18	11	BWP	-7.233	24.46
452330	Flocculent	176,919.18	10	BWP	7.233	24.46
452330	Flocculent	10,584.00	10	BWP	0.420	25.2
452330	Flocculent	284,256.00	9	BWP	11.280	25.2
452330	Flocculent	331,128.00	8	BWP	13.140	25.2
452330	Flocculent	323,064.00	7	BWP	12.820	25.2
452330	Flocculent	516,384.00	6	BWP	17.600	29.34
452330	Flocculent	489,978.00	5	BWP	16.700	29.34

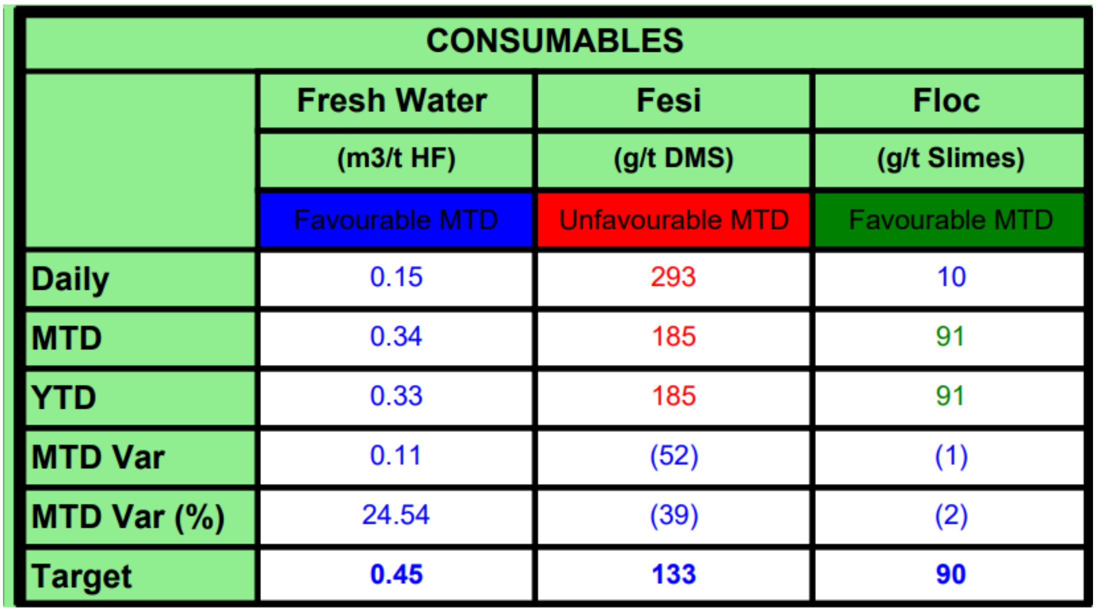
452330	Flocculent	286,945.20	4	BWP	9.780	29.34
452330	Flocculent	546,267.29	3	BWP	17.119	31.91
452330	Flocculent	554,627.71	2	BWP	17.381	31.91
452330	Flocculent	196,040.00	1	BWP	6.760	29
		4,222,971.42				24.46

Production data will be reconciled with geometallurgical information and correlated with the behaviour of material that is fed to the plant. The slurry characterisation, which is mapped out as clay content, is compared against the actual production data, particularly looking at consumables.

3.2.4 Metallurgical performance data

The consumables in this analysis will be from fresh water, flocculant and ferrosilicon (FeSi) consumptions.

- The data on the amount of flocculant usage in the plant was compiled from the ore processing daily reports as on Figure 3.4 and grouped per month as on Table 3.5. This monthly data was then plotted against the monthly ore mining mix. A historical time plot was made and an analysis was done on the changes in flocculant usage against the changing ore types.
- Similarly, the water consumption data was also compiled from the ore processing daily reports and plotted against the ore mining mix. A historical time plot was made and analysis was done on the increase and decrease of fresh water was analysed against the changing ore types.
- FeSi consumption data was also compiled from the ore processing daily reports and plotted against the ore mining mix. A historical time plot was made and analysis was done on the impact of FeSi consumption in relation to the changes in ore types



CONSUMABLES			
	Fresh Water	Fesi	Floc
	(m3/t HF)	(g/t DMS)	(g/t Slimes)
	Favourable MTD	Unfavourable MTD	Favourable MTD
Daily	0.15	293	10
MTD	0.34	185	91
YTD	0.33	185	91
MTD Var	0.11	(52)	(1)
MTD Var (%)	24.54	(39)	(2)
Target	0.45	133	90

Figure 3.4: Daily plant consumable utilization

Table 3.5: Monthly plant consumable utilization

Item	Units	15-Jan-15	15-Feb-15	15-Mar-15	15-Apr-15	15-May-15
Tonnes Treated (Wet)	t	766,464	629,110	638,190	458,011	705,114
FeSi Consumption	g/t	200		131	312	158
Fresh Water Consumption rate per ton headfeed(excluding fire water)	m3/t	0.54	1.08	0.74	0.70	0.59
Floc. consumption rate	g/t	89	102	87	74	79

The slurry characterisation which is mapped out as clay content is compared against the actual production data, particularly looking at consumables. The data sets will be compiled and correlated to a specific period from January 2015 to December 2019.

Frequent laboratory tests are carried out to determine flocculant dosage that will settle solids at required settling rates. Settling tests are conducted frequently in the plant in order to determine the flocculant dosage required during processing. Data was compiled from all tests that were run during the period between 2015 and 2019 and the dosage was calculated by Equation 3.1.

Equation 3.1: Dosage equation

$$Dosage = \frac{Solution\ Strength \times Volume\ of\ Flocculant\ Added}{Mass\ of\ solids\ (in\ ton)}$$

3.3 Practical considerations:

The unavailability of comparable data may be an obstacle, as data is collected during various drilling projects that have different project objectives which are not specific for geometallurgical modelling. Data adequacy and compatibility may also be a limitation to the project, meaning that data from different campaigns may have to be used separately to achieve comparable results. Production data is compiled by dispatchers, which introduces an element of human error; thus the data needs to be validated before use.

3.4 Ethical Consideration

A formal permission letter was obtained from Debswana Jwaneng Diamond mine to use the Company's data solely for the purpose of this research. The objective of the research is clearly outlined in the letter. The research did not involve human participants so an ethical clearance waiver from the University of the Witwatersrand was obtained (Appendix 7.21).

3.5 Chapter Summary

Chapter 3 describes how all the data was collected from the different departments of Jwaneng mine and during different resource extension project campaigns. The chapter also looked at the quantitative approach that the research will follow. The chapter further looks at reviewing available geometallurgical data against the behaviour of clay mineralogy, using the plant's production data, with a focus on consumable's utilisation data. All production data that was used was validated against signed monthly-survey reported figures to ensure correct data was used. The data collected historically through the resource extension drilling campaigns was validated against the official block model to check correct location of samples. The generated data shall allow for the correlation of predicted ore behaviour during processing with related ore block. The results are presented and analysed in Chapter 4.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Chapter overview

Variability in mineral resources impacts the mineral processing chain. It is key to identify the variability in a resource, prior to treating the ore to ensure successful throughput. Understanding the spatial distribution of minerals within the Jwaneng kimberlites allows for key metallurgical response variables to be identified. Slimes and slurry are key variables that has been identified as a key contributor to plant performance, hence the need to have a better understanding of parameters that impact it. Mineralogy, which impacts slimes and slurry, has been associated with those minerals containing fine particles from the clay mineral group. Analysis, as defined by the methodology in chapter 3, was carried out on the clay minerals impacting plant consumables. This was done to identify which lithologies need to be blended to minimize the impact on production. The three main plant consumables discussed were fresh water, flocculant and FeSi consumptions. These were compared against the mining mix-feed ratios from the period between 2015 and 2019. The correlations identified between the mining mix and plant consumable utilizations are discussed in this chapter.

4.2 Historical geological data analysis

Through the various resource extension projects, it became more apparent that treatment process efficiency could be improved significantly by improving knowledge of the different kimberlite facies that constitute the ore feed. Ore dressing studies were carried out on the kimberlite facies that would have an impact on the treatment process. These studies were intended to allow problematic ore types or trends to be identified.

A total of 40 drill-core samples were collected and tested for clay and slimes characterisation, to a depth of 547mgbl. Slimes were prepared using a -1mm-sized fraction of crushed drill core samples and process water from the Jwaneng Mine. These tests were carried out to determine the potential behaviour the clays may have during the processing of tailings containing slurry. The tests identify the potentially problematic clays that have the potential to not settle when the ore comes into contact with water. This may have an impact on processing, impacting the flocculation and thickening processes. Some of these tests conducted include, identifying the clay cation exchanged state, analysing raw water and process water quality as well as determining slurry pH and conductivity measurements.

The samples were taken as follows:

- 10 samples - Centre pipe (Samples containing VK and Dolomite breccia)
- 17 samples - North Pipe (Samples containing VK and PK)
- 13 samples - South pipe (Samples containing VK)

4.2.1 Mineralogy

With a total of only 40 samples collected, not all the lithologies that are anticipated in the life of the mine were tested. The slurry behaviour tests were conducted to examine the clay mineralogy through the XRD and glycation processes. Figure 4.1 illustrates the identified mineralogy per lithology. From the analysis of the data, calcite, smectite and serpentine were the most frequently occurring mineral across the samples, but their percentages varied across different samples. The box and whisker graphs illustrated in Appendix 7.2 indicates the smectite values to be highest in volcaniclastic kimberlites, less present in the samples containing PK (North pipe) and absent in the kimberlite breccias. The high occurrence of smectite in the kimberlite breccias indicates that the sample that was taken was more matrix supported than clast supported. Serpentine abundance, as illustrated in Appendix 7.3, indicates that it is highest in the samples containing PK (N) and lower in the samples containing VK, across all the pipes. There is no occurrence of serpentine in the kimberlite breccias. Similarly to the serpentine, there was no calcite occurrence in the kimberlite breccias, as plotted in Appendix 7.4. Calcite values were higher in the volcaniclastic kimberlites from the Centre pipe as well in pyroclastic kimberlite from the North pipe.

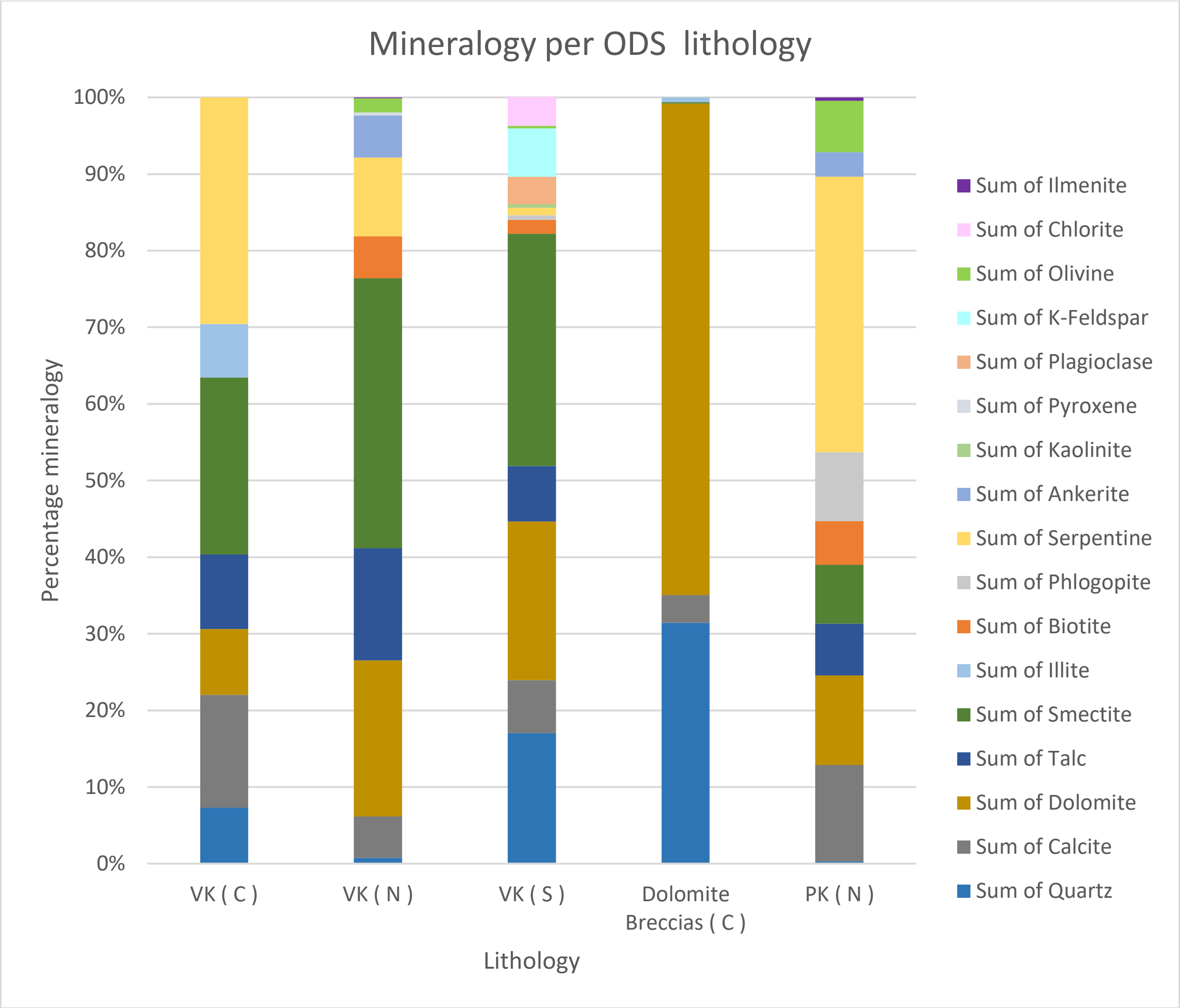


Figure 4.1: ODS mineralogy per lithology

From the ODS report, it was observed that clays are present in all three pipes with the Center pipe containing higher smectite, talc and illite. The South pipe also contained significantly high percentages of smectite, talc and kaolinite, while the North pipe contained lower smectite, talc and micas Figure 4.2. The North pipe contained the least amount of smectite, while the South pipe and the Center pipe had moderate-to-very-high amounts of the swelling clays.

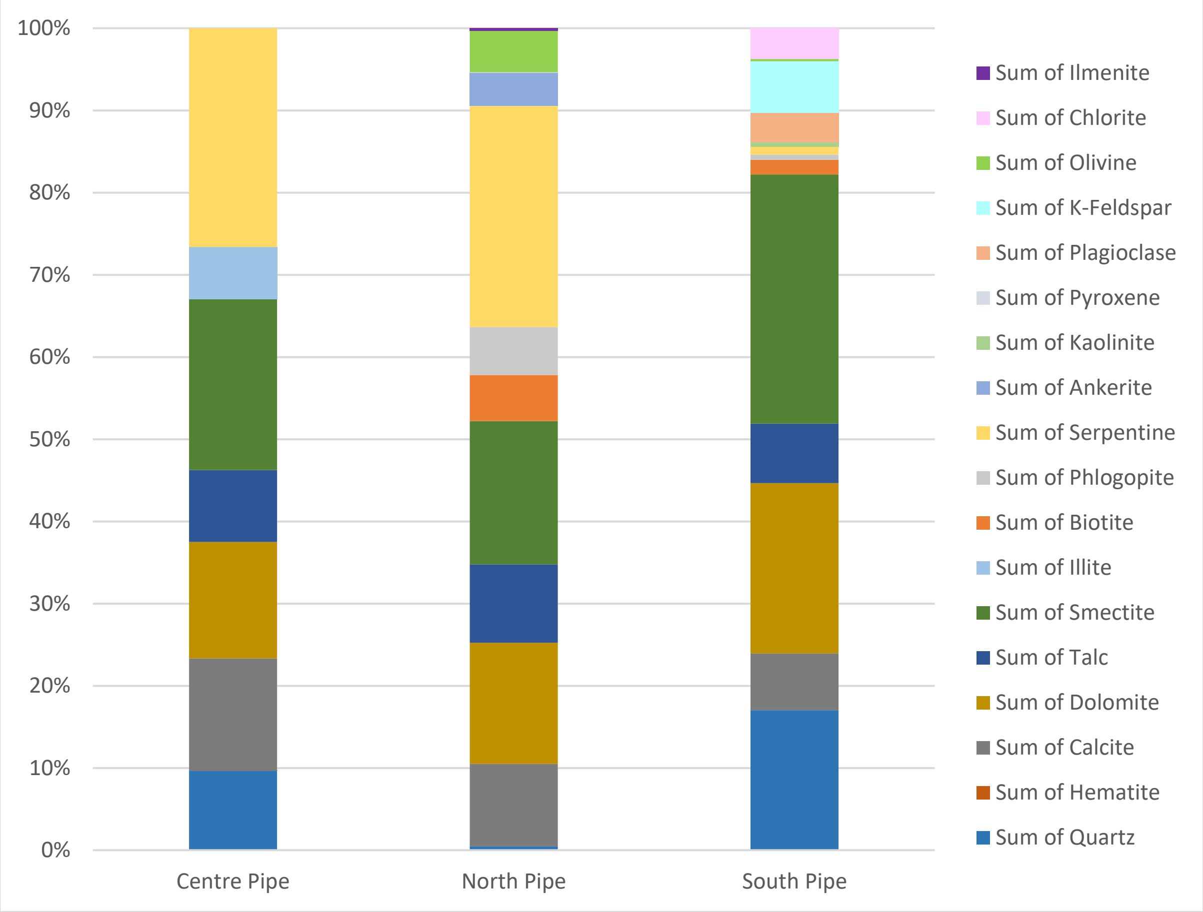


Figure 4.2: Graph of the mineralogy occurrence per lithology

Center pipe and South Pipe contained more than 50% smectite, talc, kaolinite and illite; while the North pipe contained lower smectite, talc and mica. The problematic smectite clays were found to contain high quantities of montmorillonite, which was detected in a large group of the samples. As the Center pipe contains the highest amount of smectite, the percentage of montmorillonite were also higher in the samples from the Centre pipe. The South pipe had the second highest percentage of montmorillonite and the North pipe had the least as shown in Figure 4.3.

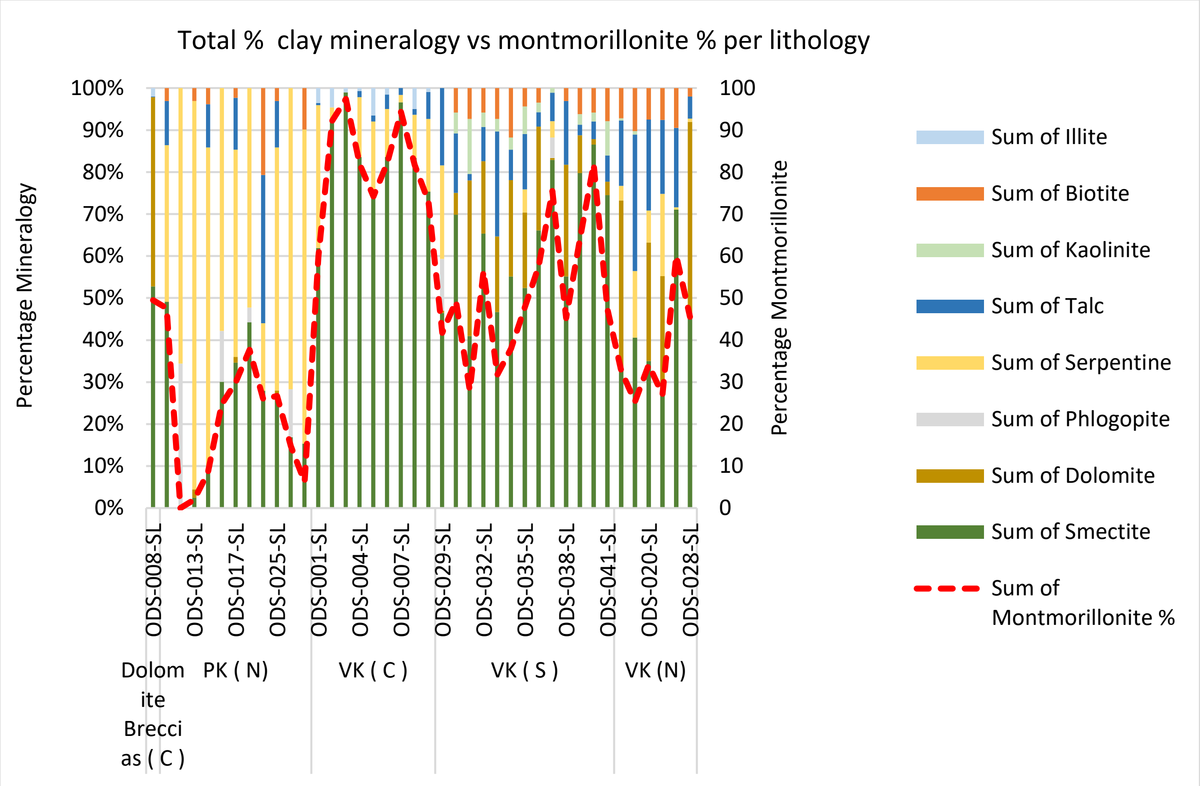


Figure 4.3: Total clay mineralogy per lithology

Based on clay classification, smectite falls under the 2:1 sheet arrangement, which is made up of hydrated interlayer cations. As a result, smectite has a higher swelling capacity. As smectite has higher swelling capacity, it is known to cause ore processing difficulties. Hence, it is important to collect this information on smectite content for geometallurgical modelling. A better understanding of the type of clay present in the kimberlites found at Jwaneng Mine will allow for better blending strategies which will improve plant performance.

4.2.2 Clay exchangeable cation

Following the JREP1 and JREP2 campaign, analysis were carried out on the exchangeable sodium percentage (ESP) of the different rock lithologies. The exchangeable sodium percentage (ESP) is a measure of the sodium cations absorbed by clay minerals (Field, 2017). These parameters are all related to the in-situ characteristics of the rocks. The ESP for a sample is obtained using the following formula:

Equation 4.1: ESP equation

$$\mathrm{ESP} = \mathrm{Exchangeable}\ \{(\mathrm{Na})/\ (\mathrm{Ca} + \mathrm{Mg} + \mathrm{K} + \mathrm{Na})\}\ \mathrm{X}\ 100$$

In this research, the exchangeable cation analysis was used to determine the cation-exchanged state of the clays within an ore. The results of determining cation-exchanged state helps to provide an indication of the potential colloidal and swelling characteristics of the clays when suspended in water. The ESP of the clay provides an indication of the degree to which the clays are sodium-ion exchanged. Sodium-exchanged clays exhibit enhanced swelling properties, while exchangeable calcium inhibits the swelling behavior of clays. When they come into contact with water, sodium-exchanged clays tend to disperse, while calcium exchanged clays coagulate. Some smectite clays swell when they are in contact with water, which may result in the generation of further ultra-fines. The high content of smectite mineral in the Jwaneng Kimberlites are an indication that the material might be difficult to settle. Highly sodium exchanged clays were found in the majority of the Centre pipe samples (VK). This was true to a lesser degree for the North pipe's samples. The South pipe's samples (VK) were mostly calcium exchanged, which would be expected to be less problematic in terms of settling Figure 4.4 shows the ESP levels of the North, Centre, and South pipes.

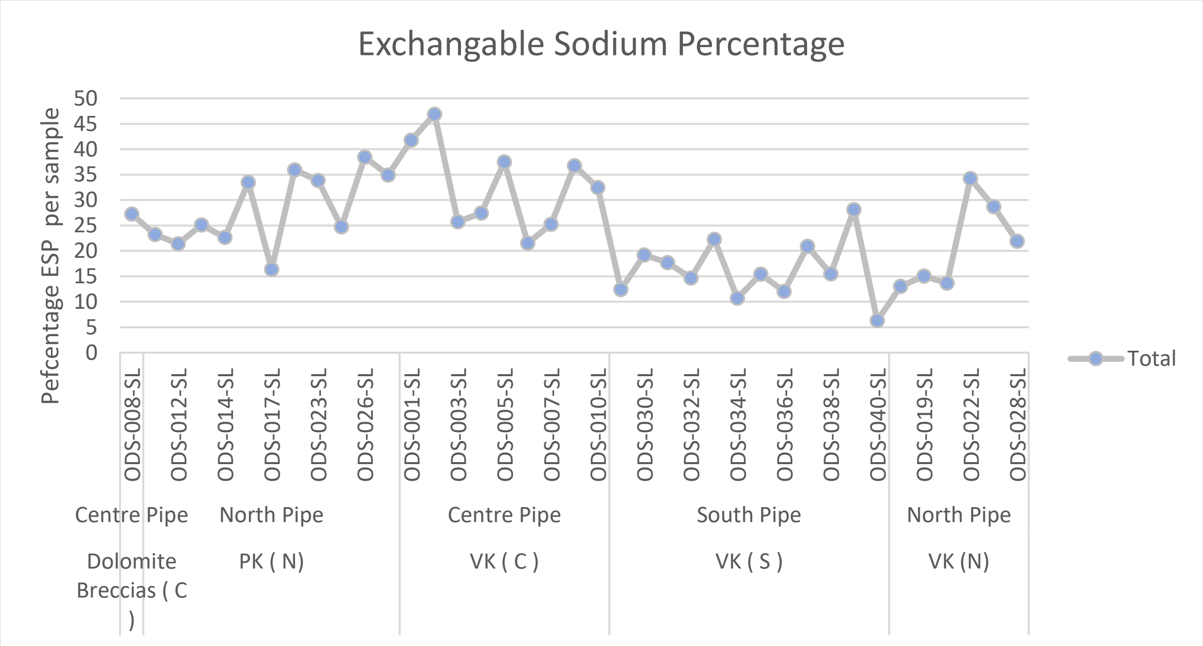


Figure 4.4: ODS Analysis on the Exchangeable Sodium Percentage per Pipe (Paterson & Cooke, 2014)

The most significant observation that was made through the analysis was that ESP values obtained from the Centre pipe's lithologies, that is VK(C), were significantly higher than those in the breccia zones. This was expected as VK is a clay-rich kimberlite, whereas all the breccia zones consist of predominantly country-rock clasts of sandstone (in the SSTBR), quarzitic shale (in the KBX(C)) and dolomite (in the KBWDM(C)), which have very low clay content. Occasional higher ESP values might occur where kimberlitic matrices may be locally common within the breccia zones. In the North pipe, there is no significant statistical difference between the ESP values from the various lithologies. This is not unexpected as the different lithologies contain slightly similar characteristics. For the South Pipe, higher ESP values are associated with: low-dilution volcaniclastic kimberlites (AVK(S) and VK(S)); and low ESP values with highly-diluted breccias (KBWDM(S) and KBX(S)). Following the patterns seen in the other pipes, these differences in the South Pipe are inferred to relate to smectite-rich and smectite-poor zones.

4.2.3 Comminution characterization

Comminution characterization involves determining geo-mechanical ore properties in relation to comminution at varying depths. Comminution is done by carrying out a variety of tests on the samples. The process of acquiring the ODS data that was acquired was more of an opportunistic sampling campaign that took advantage of other sampling programs. Due to data inadequacies, not all test results were utilized, such as the values obtained from the porosity tests and measurements of plasticity. Rock-mechanical tests were conducted on the ODS drill core samples whereby three samples from each pipe were selected for testing.

Material is classified based on its hardness through drop-weight tests, which were carried out. Drop-weight tests are single breakage tests used to establish specific breakage parameters. The tests are also used to measure the resistance of an ore to comminution by impact of forces (Field, 2017). A standard drop-weight test requires a single particle of a set size fraction to be impacted by a given weight through dropping it at a certain height, thus impacting the input energies. Material is then classified as illustrated on Table 4.1, based on rock-hardness data that is collected and used in crushers.

Table 4.1: Classification of material hardness as characterized by the t10 and ta values at 1.0kWh/t

	Very hard	Hard	Moderately hard	Medium	Moderately soft	Soft	Very soft
t_{10} (%)	<22.4	22.4-27.3	27.3-29.6	29.6-34.9	34.9-38.0	38.0-50.9	>50.9

Tests that were carried out involved single particles of various sizes being broken using specific energies ranging from 0.1kWh/t to 25kWh/t. The particle size distribution for each crushing event is recorded and a t10 parameter is determined. Sampling was completed and results for the drop weight tests, carried out on 40 samples from the Centre, South and North pipes were received. The results of the t10 values indicated that from the 40 samples tested, values range from a minimum value of 31.4% (highest resistance) to a maximum of 50.2% (least resistance), as indicated in Figure 4.5. The t10 values obtained from the samples reflected that an average of 40.7% was achieved at an energy input of 1.0kWh/t; this indicates that the kimberlites are a fairly soft ore body. A low t10 value indicates a more impact resistant sample with less fines generated from it, while a higher t10 value indicates a less impact-resistant sample with greater fines produced (Dam, 2013).

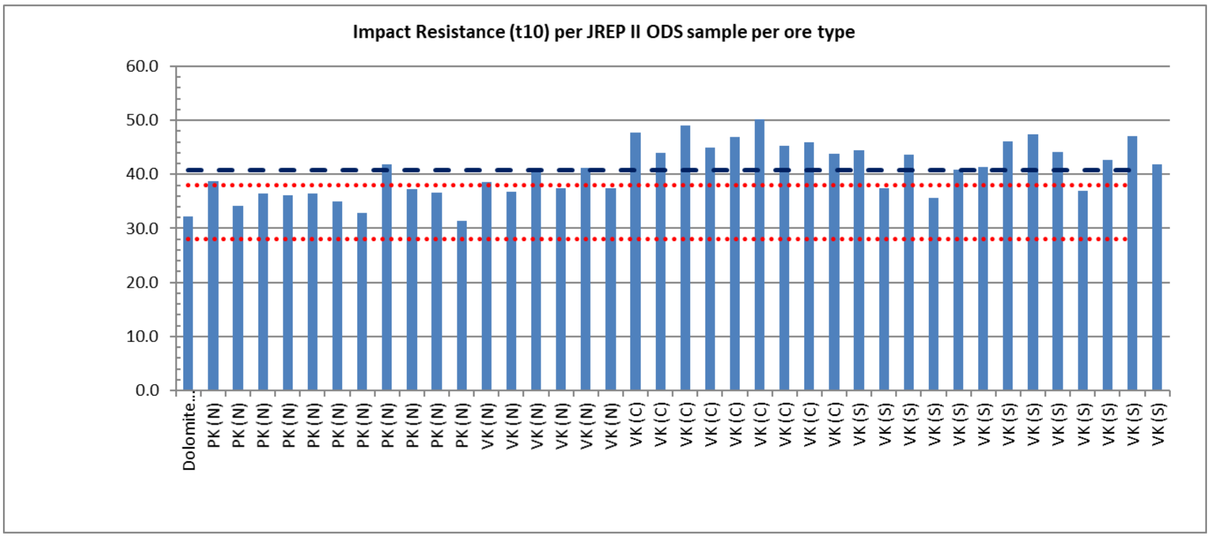


Figure 4.5: Impact resistance per ODS sample

The North pipe’s samples include 17 samples taken from PK (N) and VK (N), which had average t10 values of 36.1 for PK (N) and 38.1 for VK (N). These fall within the range of having a hardness that is moderately soft for the VK (N) and medium for the PK (N). Samples from the Centre pipe included only VK samples and all the samples were the least impact resistant, recording the highest average t10 values at 46.4. The nine Centre Pipe VK samples produced t10 values ranging between, 43.8 and 50.2, which fall under the hardness category of being soft. The remaining samples collected from the South Pipe were only VK(S) samples; these samples had an average t10 value of 44.0. Similarly to the other VK sample from the other two pipes, the VK(S) fall under the hardness category of being soft. The one dolomite-rich kimberlite breccia sample from the Centre Pipe recorded a t10 value of 32.2, which falls under the medium hardness category.

From the analysis done on the ODS studies that were carried out, the following results were obtained:

- The Centre Pipe contains rocks that are classified as soft and amenable to impact breakage.
- The South Pipe moderately-soft-to-soft rock, which are amenable to impact breakage.
- The North Pipe contains moderately-soft-to-soft rock, which are amenable to impact breakage.

The geomechanical test results indicate that the North Pipe consists of ore that varies from soft to hard. The pipe consist of either PK or VK and the ore competence increases with depth, indicating that with depth the ores may be resistant to communition by impact. The results from the Centre and South Pipes indicate that the ore is soft and that ore competence increases slightly with depth. The bondwork index results indicate that the South Pipe’s ore will require a higher energy input to crush its ore relative to the North and the Centre Pipe samples. The PEN abrasion results indicate that the South Pipe’s ore is abrasive compared to the North and Center Pipes ore samples.

4.3 Production geology data

4.3.1 Mining mix analysis

During the period from January 2015 to December 2019, the main treatment plant was fed material from the three main pipes. This material comprises material from pit mining and strategic stockpile mining. Figure 4.6 illustrates the mining mix during the period from 2015-2019.

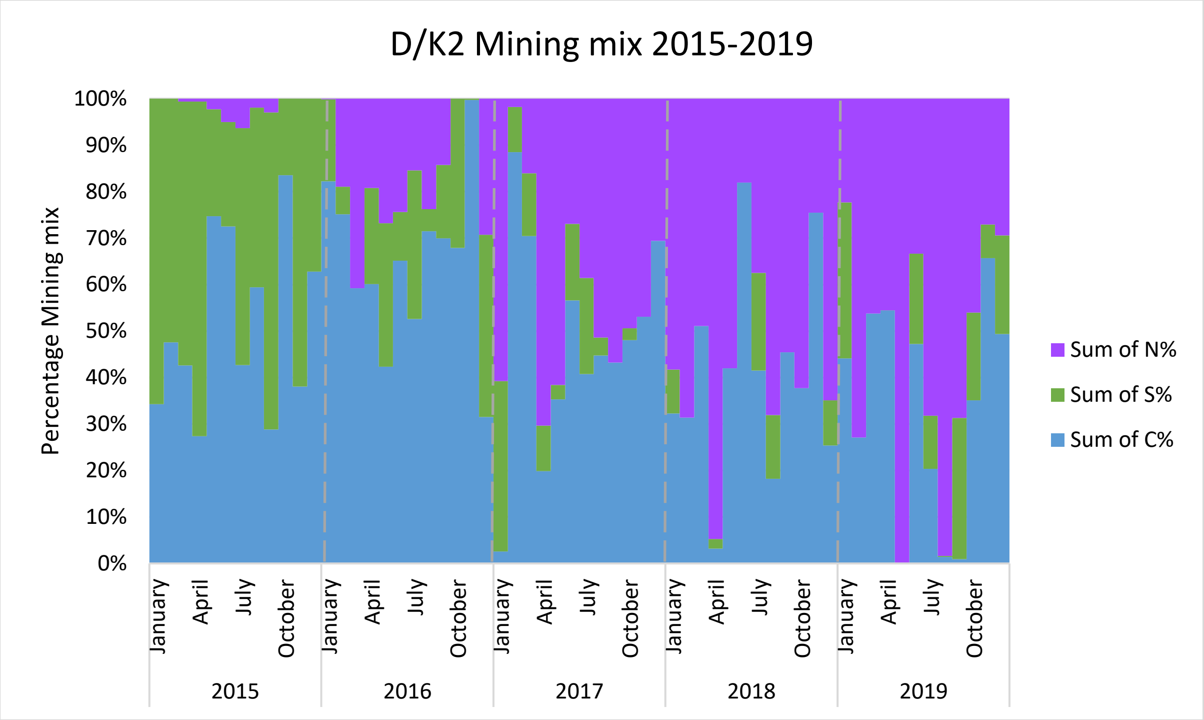


Figure 4.6: Mining mix plot from 2015-2019

In 2015 the feed was predominantly from the Center and South Pipes. The North Pipe was introduced in the mining mix at the beginning of 2016, with the Center Pipe's material being the predominant material used during 2016. There was a shift in feed towards the end of 2016, with a major increase in the usage of North Pipe's feed in the mining mix. The North and Center Pipes became the more predominant feeds in the mining mix, with little-to-no South Pipe feed being introduced until the end of 2019. Therefore overall, during the 2015-2019 period, the mining mix included 46% Centre Pipe, 36% North Pipe and 18% South Pipe feed.

The mining mix was influenced by the availability of the mining loading area and the budget for the year, as different pipes produce different grades. The Centre pipe was accessible and it was included in the mine's budget, as it has the highest grade when compared to the other pipes. During 2015 the North pipe was not accessible, hence it was only introduced towards beginning of 2016. The accessibility of the South pipe, which has the lowest grade, reduced in 2017. Hence, there was a drop in the amount of the South Pipe's feed that was included in the mining mix.

The feed material that is treated through the main treatment plant is sourced from two main areas: material that has been blasted in the pit or previously stockpiled, ex-pit material. There is no specified blending ratio that is in place between for how much material must come from the two sources. There was, however, variation in the blending ratio during 2015 -2019, as shown in Figure 4.7.

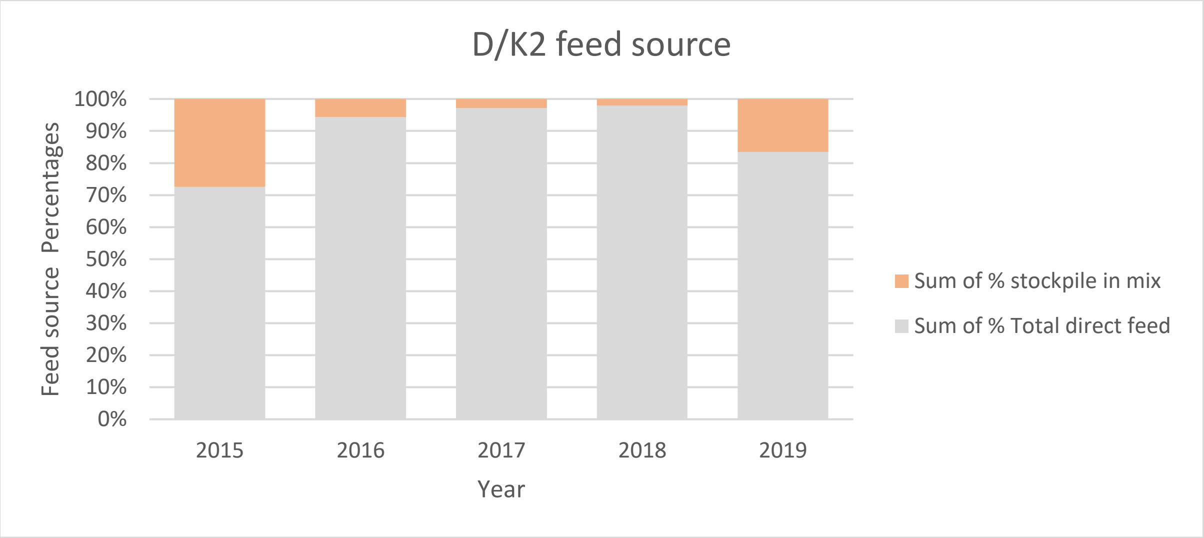


Figure 4.7 Jwaneng D/K2 feed source blending ratio

2015 had the highest feed material coming from the strategic stockpile at 29% while 2018 had the least amount of feed from the strategic stockpile at 2%. The strategic stockpile contains feed which has been accumulating over the years. As the material has been exposed to weathering, it behaves differently from freshly blasted material. The influence of the material is investigated further in the sections which follow.

4.3.2 Processing production data

The kimberlite mined from D/K2 is treated through MTP, at an average rate of 25000 tonnes per day. During processing, the plant experiences challenges that result from sources and at different processing phases, as shown in Figure 4.8. The problems experienced may be from: mechanical breakdowns, blockages, ore related issues, maintenance issues, safety related issues, etc. Plant performance data records are collected daily per shift, in minutes, to identify the time lost due to the delays experienced. The data collected on the plant's delays between the periods of January 2015 to December 2019 indicate that the plant had downtime that amounted to 21,549 minutes. The highest delays were from ore delivery, at 31%; thickener issues, at 27% and from issues in the DMS section, at 19%. The tailings section is the least impacted area with only 1% of the total minutes being attributed to it.

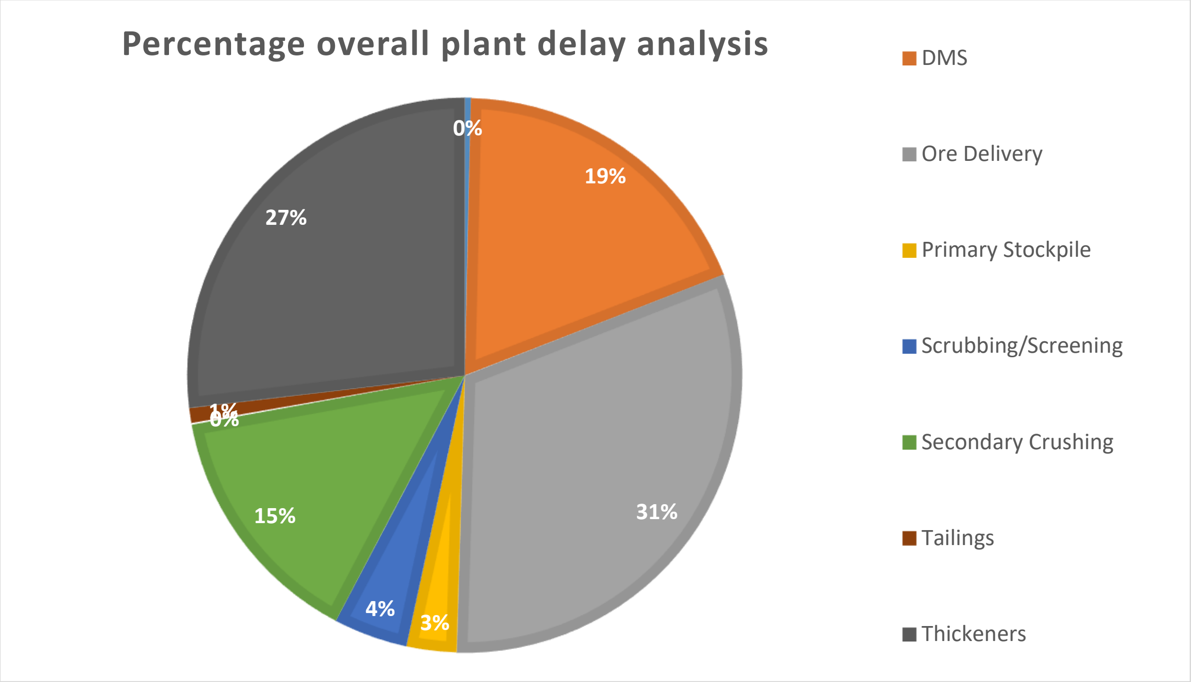


Figure 4.8: Percentage overall plant delay analysis

A review of yearly plant-delay challenges was analysed, and the delays were categorised into 12 sections, shown in Figure 4.9. These are the sections which are highly impacted by the delays experienced during processing. The sections include: ore delivery, primary and secondary stockpiles, crushing, scrubbing, silos, thickeners, DMS and tailings. A further review of yearly delays indicates there is variance in the amount of time each section was impacted each year. There were also delays that occurred annually and delays that were not recorded in some years. The two sections that showed some consistency in occurrence were: the scrubbing screens and ore delivery. Both these sections had a consistent range as compared to other sections which show inconsistencies in their occurrence.

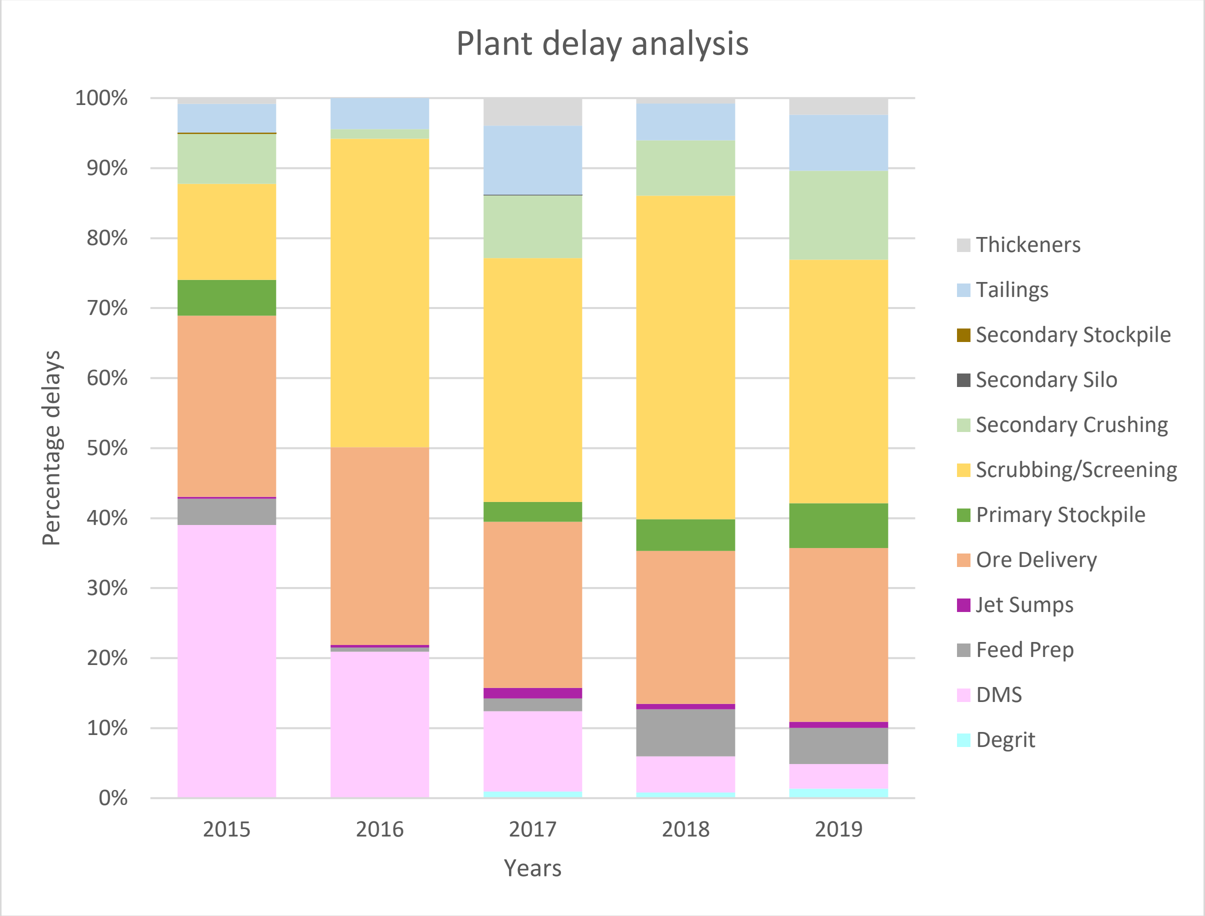


Figure 4.9: Annual plant delay analysis

Additional analysis was carried out on these delays to look at delays that were impacted by the ore, which is the feed for processing. Figure 4.10 illustrates that the delays related to ore feed are mostly from ore slimming, poor ore flow, poor blending, hard ore, coarse ore and fine ore. The thickeners are the areas which are highly impacted by the ore feed. Slimming is common in the thickeners, and it is cause by the solid matter failing to separate from the water, resulting in recirculation of dirty water. The impact of slimming is seen in the other processes as it causes more delays downstream. Poorly blended ore impacts majority of the areas when fed, which delays ore delivery to all areas of the plant. Due to the wider variance in ore densities as a result of poor blends, DMS requires more stoppages to handle the ore better for processing. Coarse ore is another factor that causes delays in the plant. The impact of coarse ore is experienced in the secondary crushers. The delays are mostly a result of silos filling at a higher rate because of the larger amount of crushed material. Hence there becomes a need to reduce feed and, eventually, to stop feed completely.

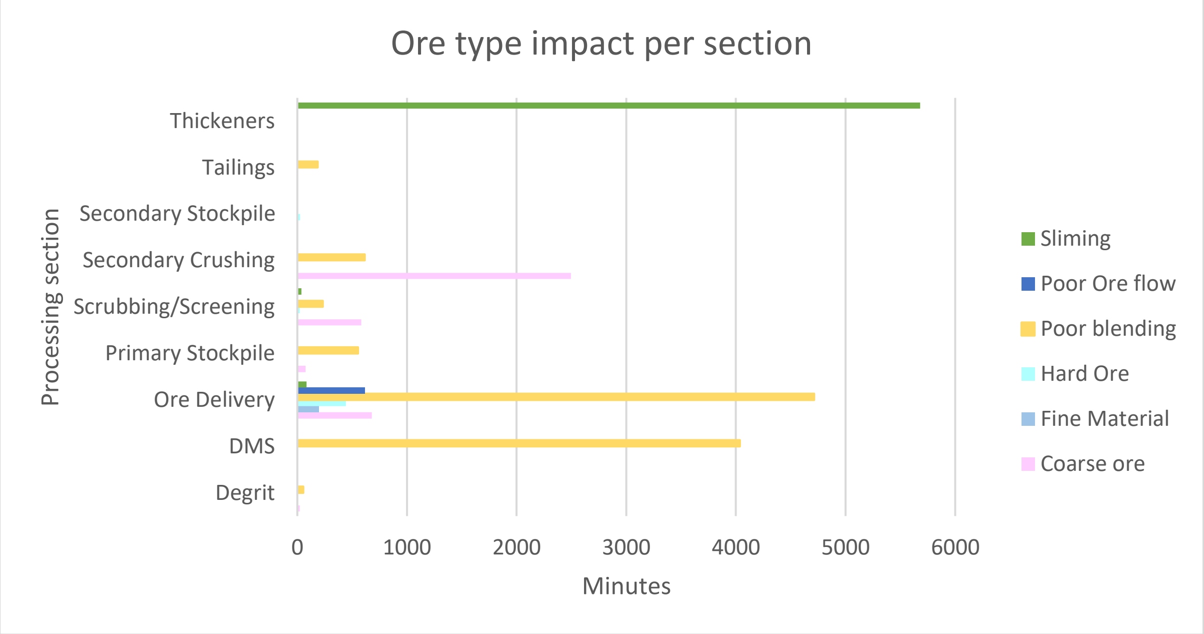


Figure 4.10: Ore type impact analysis per section

4.3.3 Mining mix against flocculant usage analysis

The Jwaneng mining mix contains lithologies from very fine to moderately fine material. The variation in lithologies indicates that flocculent doses will vary for different areas treated. Flocculant makes fine particle agglomerate into larger and heavier particles, which makes it easy for them to settle. The kimberlites were found to be slow settling to fully settling, depending on the ore type in the unfloculated state. As stated, the mining mix contained lithologies from all three pipes, as illustrated in Figure 4.11. Flocculant is one of the key consumables in the treatment process and dosage varies depending on the mining mix.

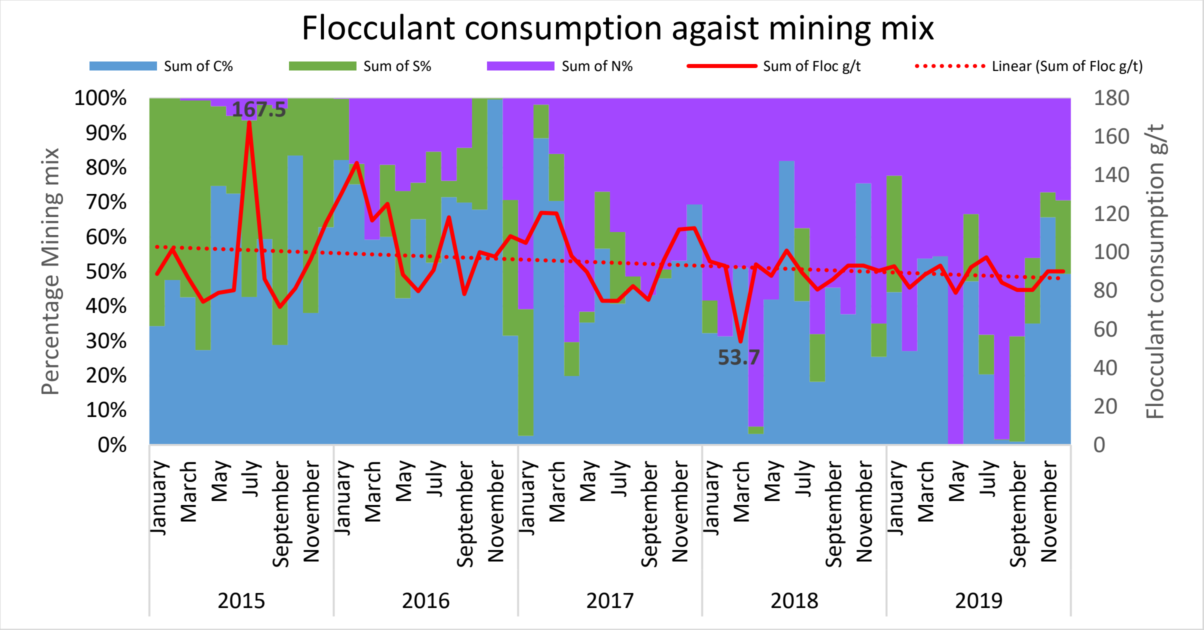


Figure 4.11: Plot of mining mix against flocculant consumption.

When comparing the annual mining mix ratios, as shown in Table 4.3, against the flocculant consumption, it can be seen that there are consumption variations depending on material treated. The year 2015 was dominated by feed from the Centre and South Pipes, with less North Pipe feed due to the unavailability of the pipe. In 2016, as mining progressed more towards the northern side of the pit, there was an increase in North Pipe feed, and a reduction in South Pipe feed. Due to pit dynamics, by the year 2017 till 2019, feed attention had shifted mostly towards mining the North Pipe. This is observed from the increase in the North Pipe's feed percentages in the mining mix compared to The South and Centre Pipes.

Table 4.2: Mining mix ratios from 2015 - 2019

	Centre pipe (%)	South pipe (%)	North pipe (%)
2015	50	48	2
2016	64	17	19
2017	47	10	43
2018	39	6	55
2019	33	12	55

The mining mix for the research period included material from both in-pit and ex-pit strategic stockpiles. The highest amount of stockpiled material that was included in the mix was during the year 2015, during which 27% of feed came from the stockpiles. The lowest amount of stockpiled material in feed was during the years 2016, 2017 and 2018, each having less than 6% of feed coming from the stockpiles. In 2019, there was an increase in feed material that came from the stockpiles, at 17%. The annual source of feed plotted against flocculant consumption do not show a correlation, as show in Figure 4.12. When comparing the monthly source of feed against flocculant consumption, the plots are as shown in Appendix 7.5 to 7.8. The highest monthly flocculant consumption was observed in July 2015, with consumption of 167.5 g/t against an average consumption rate of 91.4 g/t, for the period between 2015 and 2019. The highest annual flocculant consumption was observed in 2016 at a rate of 106.73g/t as show in Figure 4.13. The lowest annual average flocculant consumption rate was observed in 2019 with a rate of 87.33g/t, while the lowest monthly rate was observed in March 2018 with a rate of 53.7g/t.

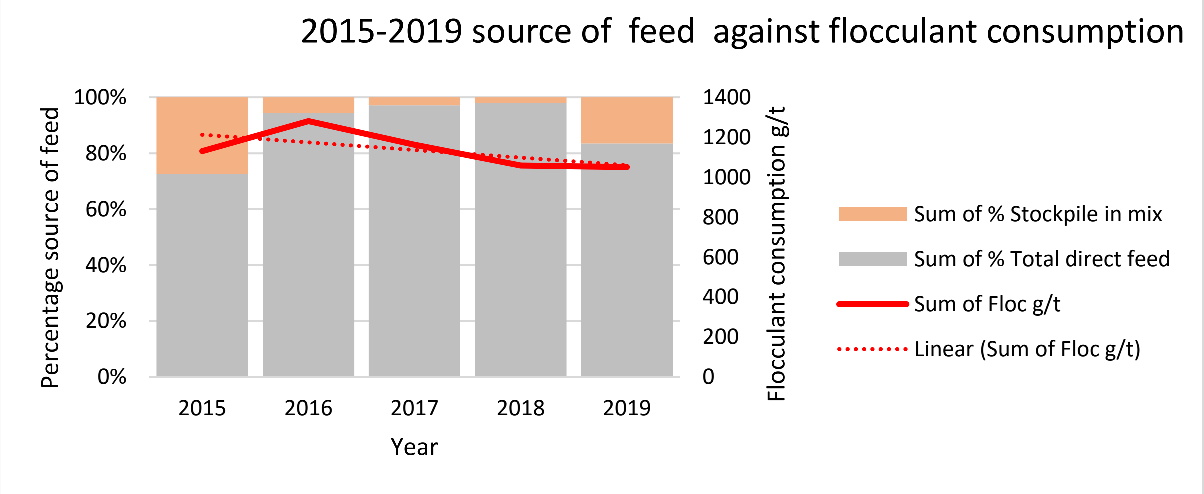


Figure 4.12: Annual source of feed against flocculant consumption

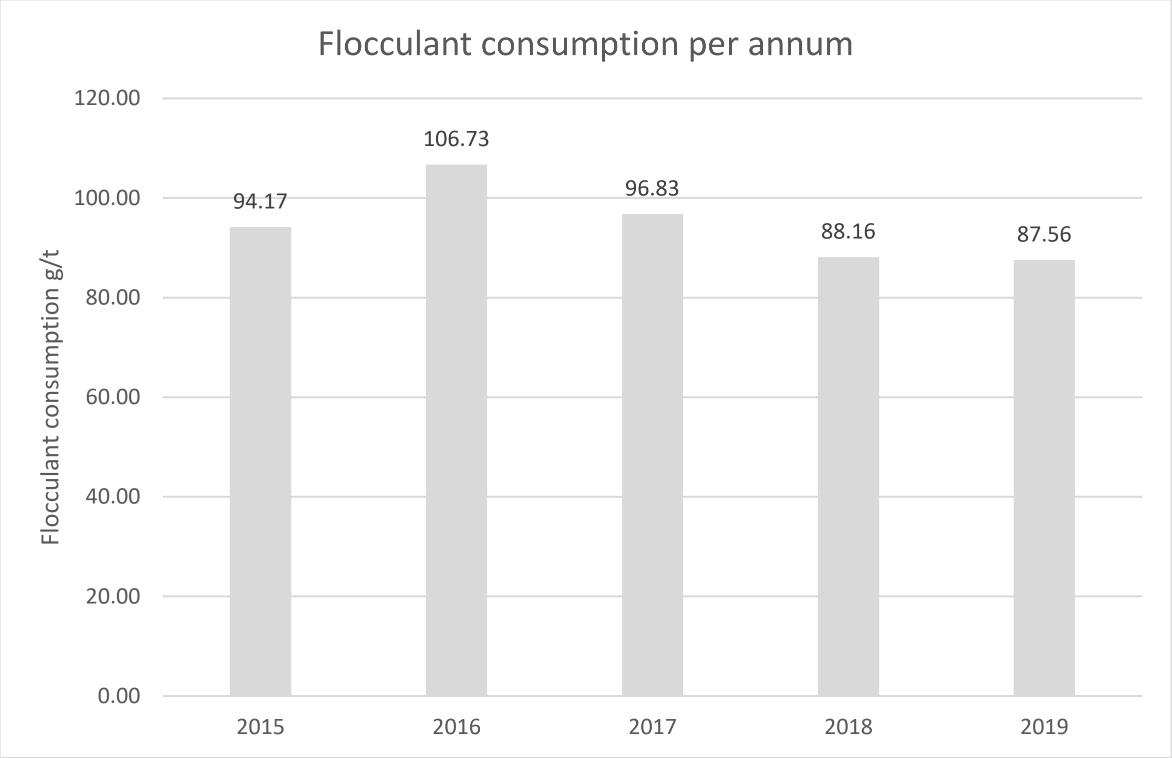


Figure 4.13 Average flocculant dosage per year

When comparing the flocculant consumption rate against the percentages of the sources of feed annually, there is little correlation compared to when analysing these variables on a monthly scale. To further analyse the data, the source of feed was investigated. Zooming into the mining mix for 2015, which included the month which had the highest flocculant consumption rate, 51% of material came from the South Pipe, 43% from the Centre pipe and 7% from the North Pipe, as shown in Figure 4.14. This is attributed to the mining blends during this period, which contained significant amounts of feed from the strategic stockpiles, which contained material from mostly the South and Centre Pipes.

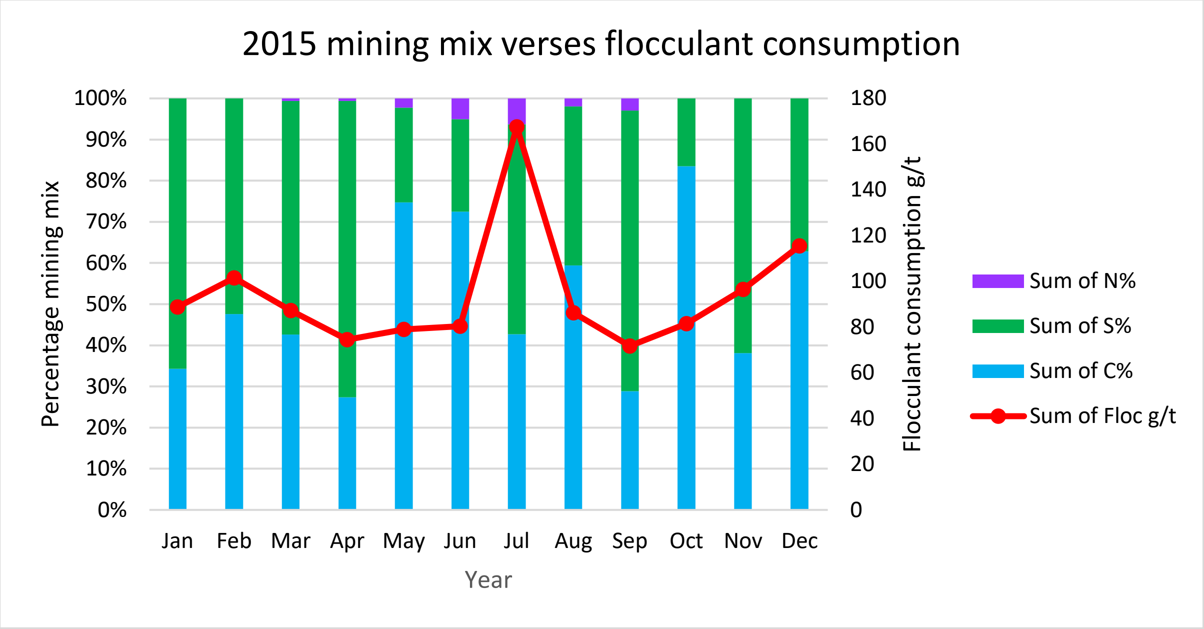


Figure 4.14: 2015 mining mix plot against flocculant consumption

The month of July had South Pipe feed predominantly coming from the stockpile SP200 and VK as shown in Figure 4.15. This is a stockpile that contains oxidised, highly weathered material from upper bench South Pipe .The predominant lithology from the Centre Pipe and North Pipe was VK, with minor material from the Centre Pipe stockpile ST14. Due to blends of high volumes of weathered fine material from the stockpiles and clay rich VK, which made up 72% of feed, the risks to the planned processing of material were higher. This highly increased settling rates, resulting in an increased flocculant dosage, and hence and increased consumption rate.

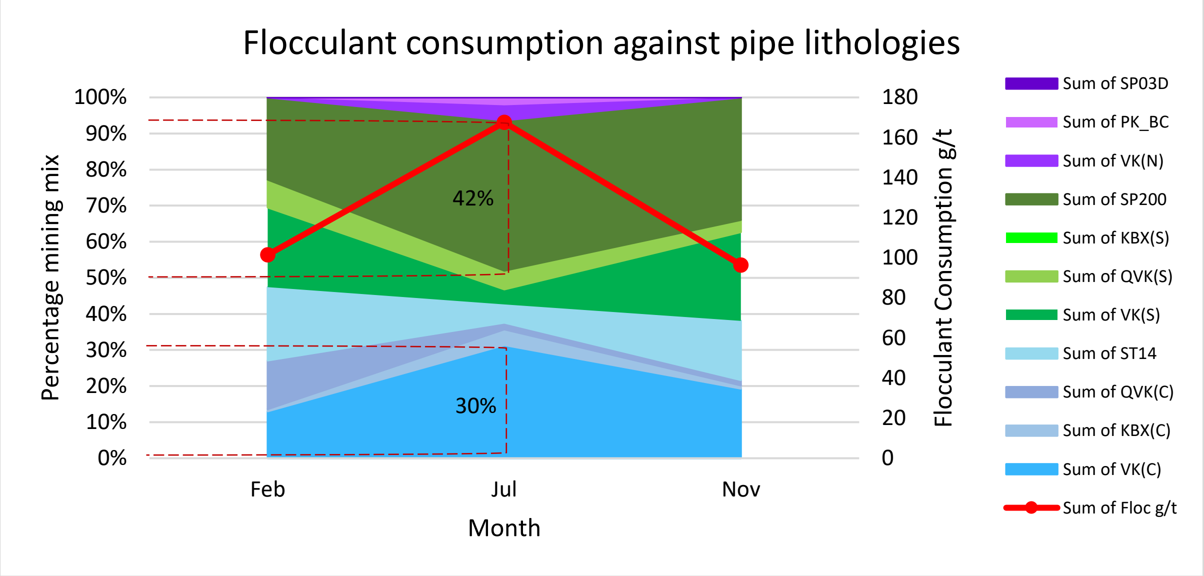


Figure 4.15: 2015 flocculant consumption against pipe lithology

March 2018 recorded the lowest flocculant consumption rate for the year, as well as the lowest for the period between 2015 and 2019, as shown in Figure 4.16. During this month, the feed was 100% from in-pit mining, with a blending ratio of 1:1 of feed from the Centre and North Pipes, as illustrated on Figure 4.17.

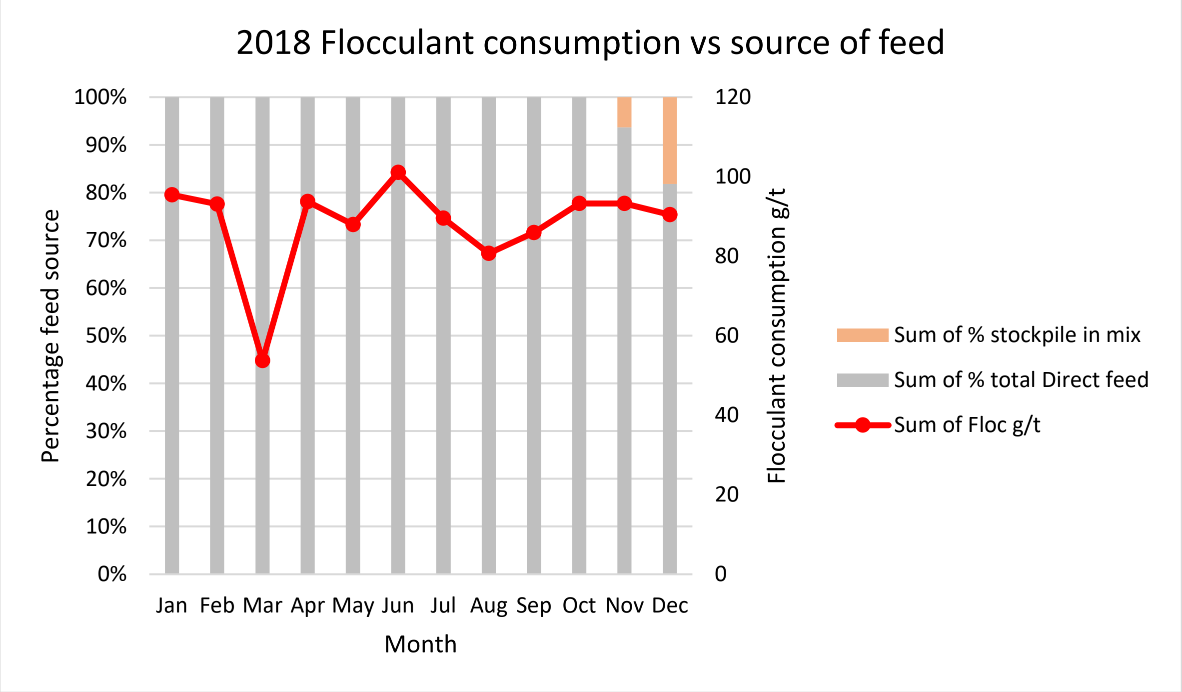


Figure 4.16: 2018 flocculant consumption vs source of feed

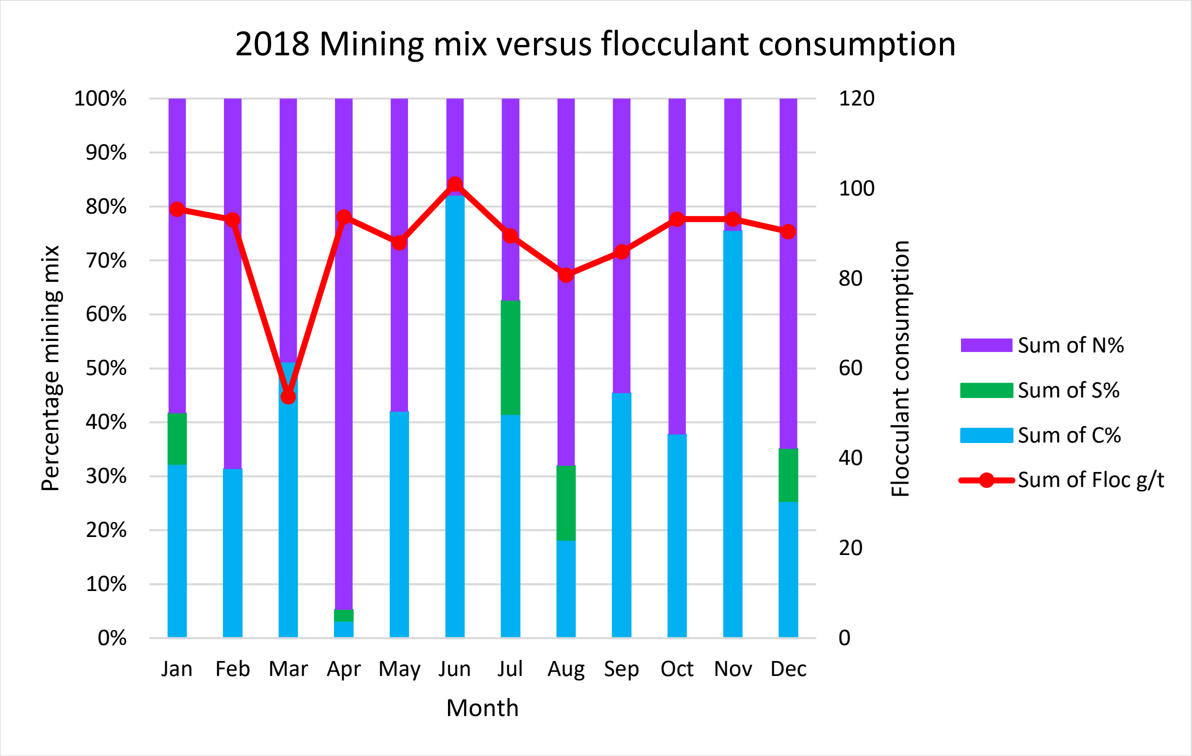


Figure 4.17: 2018 mining mix versus flocculant consumption

With an increase of North Pipe PK in the mining mix, there was lower flocculant consumption. Towards the end of 2016, PK volumes in the mining mix started increasing, while VK volumes remained constant. This is evident in the decline in flocculant usage throughout the periods with increasing PK in the mining mix. PK formed 40% of the mining mix in March 2018, together with VK from both the North and Centre Pipes (see Figure 4.18). The VK from the North pipe is less clay-rich, therefore the overall mix was made up of 50% clay-rich material from the Centre Pipe and 50% clay-poor material from the North Pipe. This resulted in a balance between clay poor and clay rich material during processing of material, hence there was less flocculant consumption for this period.

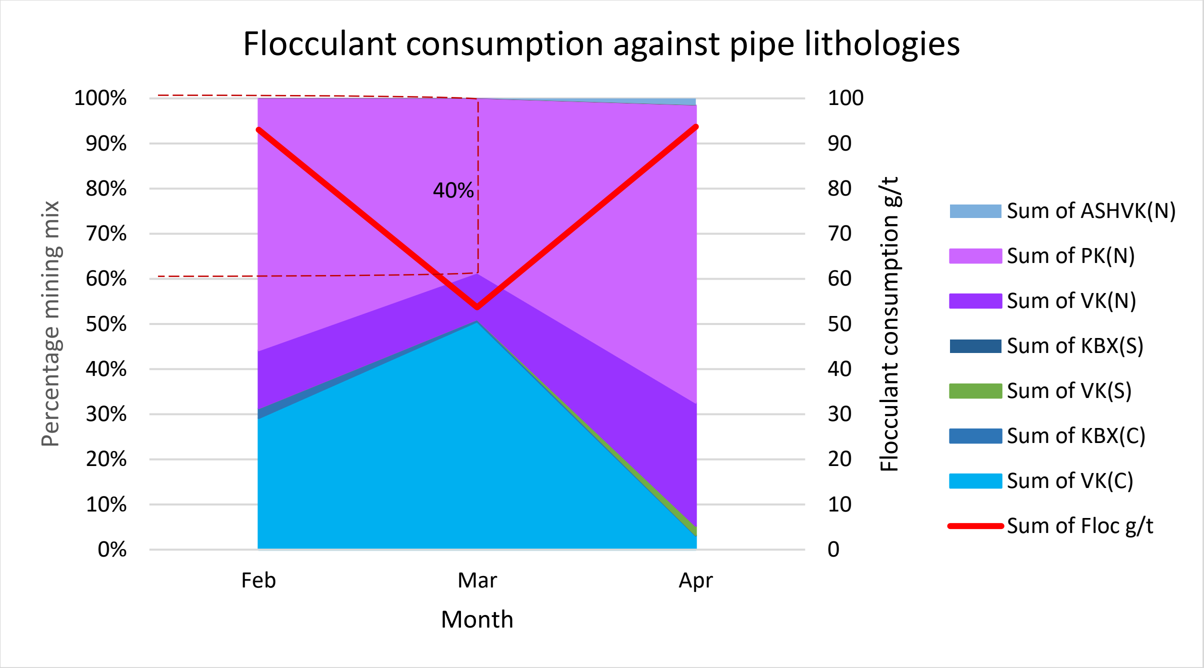


Figure 4.18: 2018 Flocculant consumption against pipe lithologies

Based on this analysis, in general there was a correlation observed between flocculant utilisation and increases in the PK and VK ratios in the mining mix. The analysis for all years is shown in Appendix 7.9 to 7.13. The more PK there is in the mining mix to blend with the VK, the lower the need to increase flocculant dosage. Comparing the volume of VK in the mining mix from all the three pipes against the rest of the lithology's as observed on Table 4.5, it can been concluded that the highest amount of VK in the feed was observed in the year 2016. The VK that was used as feed in 2016 was sourced from the Centre Pipe, at 68%; the South Pipe, at 19% and North Pipe, at 13%. The VK in the mining mix in 2016 was the highest amount of VK compared to the other years, as highlighted in Table 4.3. The high volumes of smectite-rich VK Centre and South Pipes in 2016 caused settling challenges, resulting in higher flocculant consumption.

Table 4.3: Average VK included in mining mix per pipe.

Year	Average VK (Centre) (%)	Average VK (South) (%)	Average VK (North) (%)	Total average VK in mix (%)
2015	52	45	2	52
2016	68	19	13	82
2017	63	17	20	56
2018	64	9	27	58
2019	54	15	31	50

The years 2017 and 2018 had high amounts of VK from the Centre Pipe, similarly to 2016. But compared with the total mining, the proportion of VK in the mining mix was lower, hence lower dosages of flocculant were required. This is due to the smectite-rich VK being blended with higher volumes of PK, which is clay poor. Ore that contains less smectite clays acts as a moderator to bring the overall average of clay content down, hence reducing the effect of clay on flocculant dosage. The lowest flocculant dosage was in 2019, which had the lowest total VK in the mining mix. Figure 4.19 illustrates the average VK included in the mining mix per annum.

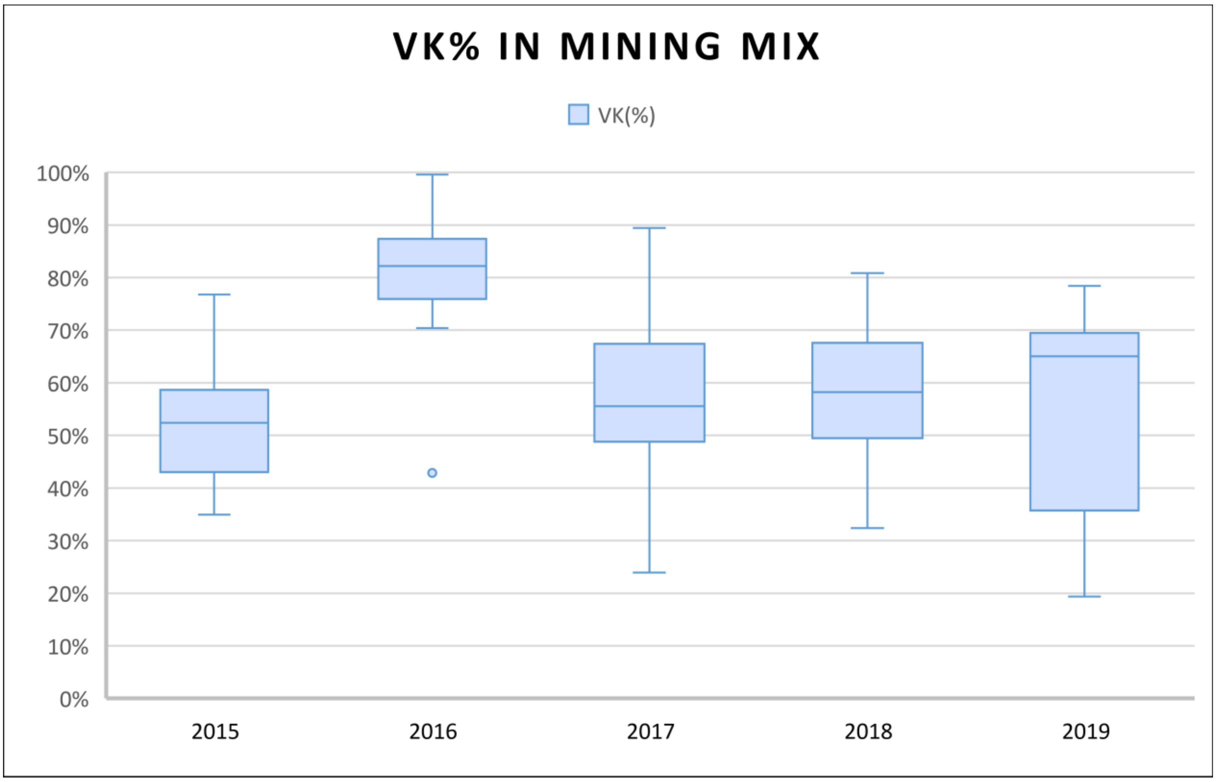


Figure 4.19: Box and whisker diagram illustrating VK percentages included in mining mix.

VK, which is higher in ESP values, made up a major portion of the Centre Pipe above 650mbgl level, when compared to expected breccia zones at levels below 650mbgl. This is due to VK containing more clays whereas the breccias consist predominantly of countryrock clasts such as sandstones, quarzitic shales and dolomites, which makes the differences in clay between the breccias and the VK notable. No major clay minerals are found in the rest of the minor rock lithologies that form part of the mining mix. The Centre Pipe VK predominantly has much finer size distribution when compare to the breccias, which have coarse clasts of country rock. The historical drilling campaigns managed to only sample few Centre pipe kimberlite breccias as shown in Figure 4.20.

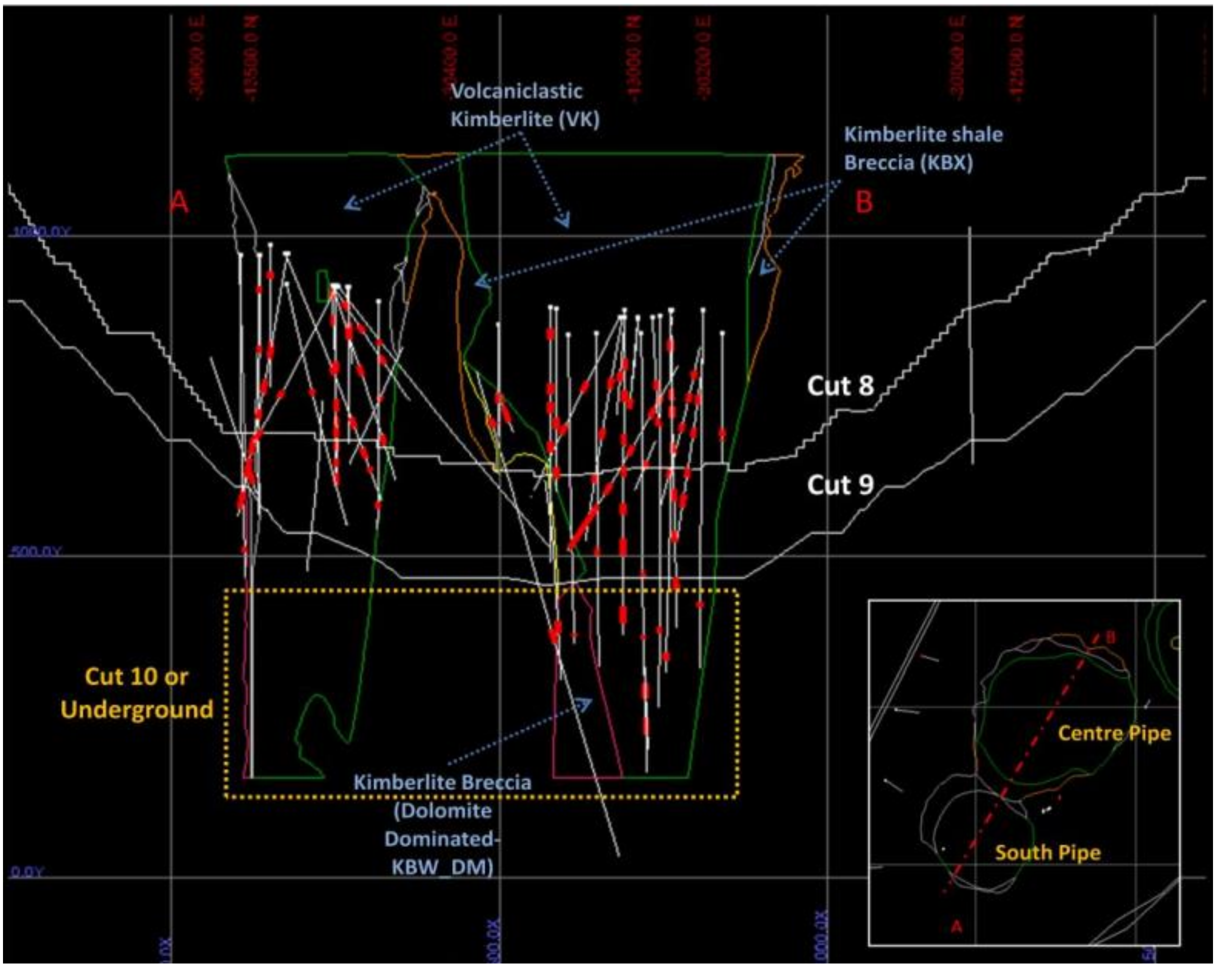


Figure 4.20: Historical drilling campaign against Centre pipe breccia

Over and above the ODS data, a test campaign was carried out to baseline the MTP head feed in terms of slurry behaviour characteristics. This was to compare the slurry characteristics and behaviour of the feed from the test campaign with the characteristics shown by the data from the two drilling campaigns (JREP1 and 2) The flocculant dosage required for VK was highest for the Centre Pipe's samples, followed by the South and North Pipes' samples, respectively, which required very low dosages of flocculant. The North Pipe is slightly coarser than the Centre and South Pipes, this is due to the North Pipe containing more talc, illite, kaolinite, micas and serpentine clays, which cause less flocculant issues.

Flocculation and thickening of dispersive slurries requires special attention that often includes conditioning of the slurry chemistry to bring the particles to a coagulated state, prior to flocculation. This is done in order to prevent thickener operational problems such as poor flocculation, poor overflow clarity and, often, low underflow density (Field, 2017). Weekly laboratory tests are carried out to determine flocculant dosages that will settle solids at the required settling rates. During 2015 and 2019 these samples were collected and measurements taken for the dosage required for settling to occur as plotted on Figure 4.21.

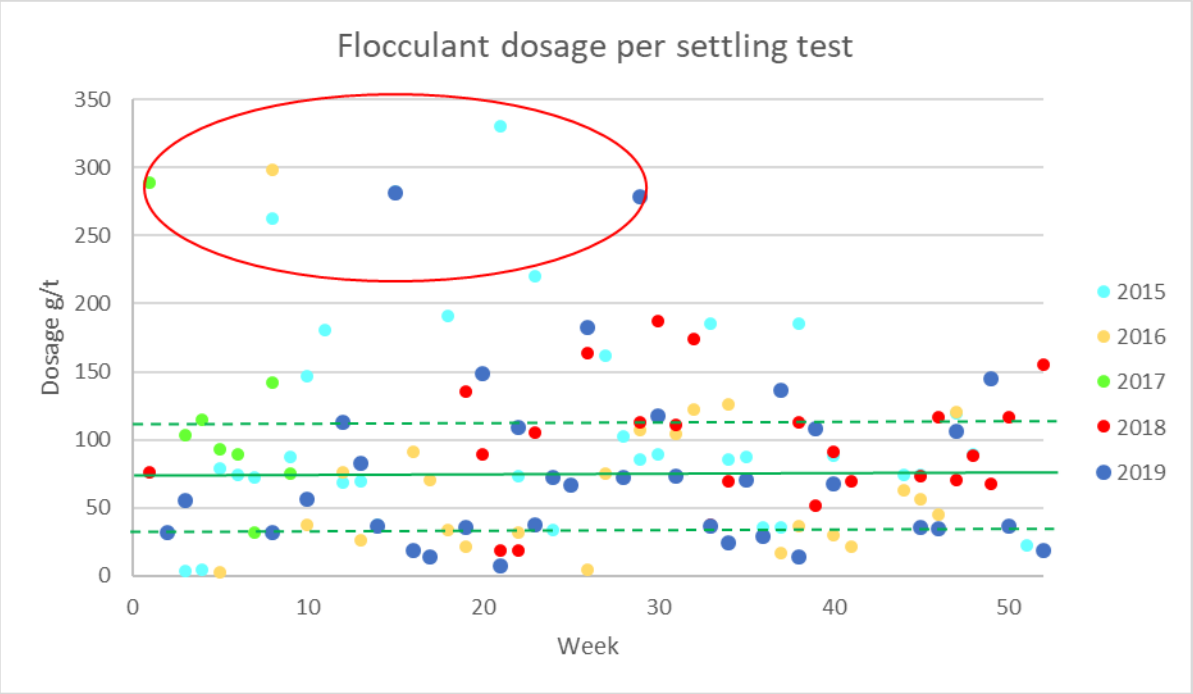


Figure 4.21: flocculant dosage settling tests

The results indicated that the average dosage required to settle the solid is 83g/t, with an upper limit of 103g/t and a lower limit of 43g/t, excluding the outliers. The data also indicated that there are extreme highs observed and extreme lows. The tests that were carried out in 2015 indicate a very wide range in the results, with extreme highs ranging above 300g/t and extreme lows of less than 5g/t. A more consistent range was observed during 2016 with majority of the data being within the average ranges. For the year 2017 and 2018, the plant did not carry out the weekly tests as required, which resulted in there being less data to analyse for the period between 2017 and 2018. For 2018, the test results obtained mostly fell within limits, with few plotting above the limits. Majority of the tests carried out during this analysis came from 2019, which mostly had results plotting within the limits, with a few extreme highs plotting above 250g/t. When comparing these results with the mining feed during the period between 2015 and 2019it is evident that where there were increases in VK in the feed, there was higher variability in flocculant dosages. 2015 had the wider variance in the results of the test due to the high volumes of VK that were in the blend. The VK that was in the mix was a combination of material from the three pipes, with almost similar quantities coming from the South and Centre Pipes, which have high clay content. Another factor that had an impact on the results was the high volumes of highly weathered, stockpiled material. 2015 had the highest amount of stockpiled feed material throughout the plant, and the stockpiled material contained more fines than fresh, inpit material. It is observed that flocculation efficiency is most affected by the ultra-fine particles found in the smectite clays which are mostly found in the Centre and South Pipes.

The impact of swelling clays becomes very evident in processing when there is an increase in flocculant consumption and a decline in thickener performance. This change is attributed to changes in the mineralogy of feed. An example of this is when there is a sudden change of clay type from kaolinite to smectite in the feed. Flocculant performance is predominantly determined by particle size, shape and the proportion of surface area available for flocculant absorption (Fawell, 2013).

It is very important to distinguish between swelling and non-swelling clays, as a significant increase in the smectite content within ore feed leads to poor thickener performance. To maintain the optimal processing environment, which is achieved when the settling rate exceeds the thickener rise rate, there is a need to increase flocculant dosages (Forbes, et al., 2013). It is important to have flocculant performance assessments to quantify feed properties as a way of predicting potential performance issues. Having said that, it is concluded that the higher the smectite content, the higher the flocculant dose expected to be used in the processing circuit.

4.3.4 Mining mix analysis against fresh water consumption

The Jwaneng Mine’s raw water is classified as good quality water that provides a conducive environment for sodium-exchanged clays to swell and generate slurry settling problems. Some smectite clays swell when they are in contact with water which may result in generation of further ultra-fines.

As shown in Figure 4.22, fresh water consumption is related to mining mix, the more fines in the system, the more fresh water is required to flush out the fines.

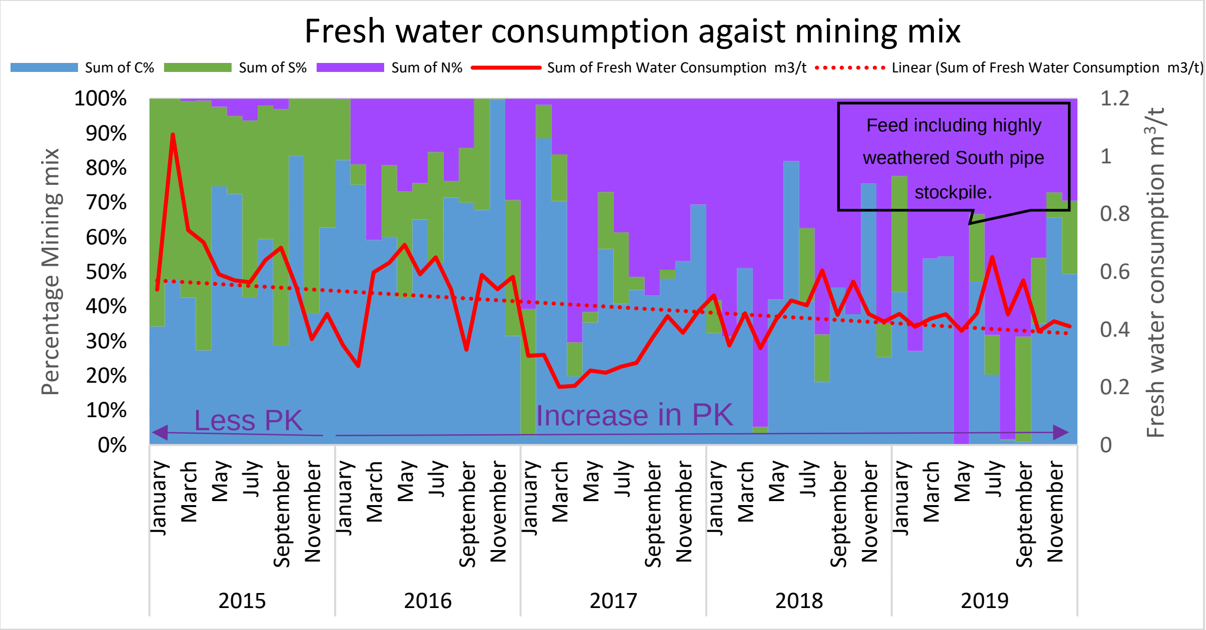


Figure 4.22: Plot of mining mix against fresh water consumption

The year 2015 had the highest fresh water consumption, at an average of 0.62m^3 per head-feed ton (see Figure 4.23). During the period between 2015- 2019, the month of February 2015 recorded the highest water consumption rate, at 1.06m^3/t. The impact of the inclusion of stockpiles in the mining mix was analysed against fresh water consumption as, illustrated on Figure 4.24. An analysis of the source of feed during 2015 indicated that the source of feed was from both in-pit and strategic stockpiles. 2015 included the highest amount of stockpile material in feed. When comparing the months which had similar sources of feed, February and July 2015 both had more than 50% of feed from stockpiles. Feed from the stockpiles is highly associated with weathered material, which usually contains more fines than in-pit feed. Where there are high volumes of stockpiled material in feed, there are chances of increased fines during processing. As high fines impact on thickeners, due to slower settling rate, more fresh water is required for downstream processes to continue.

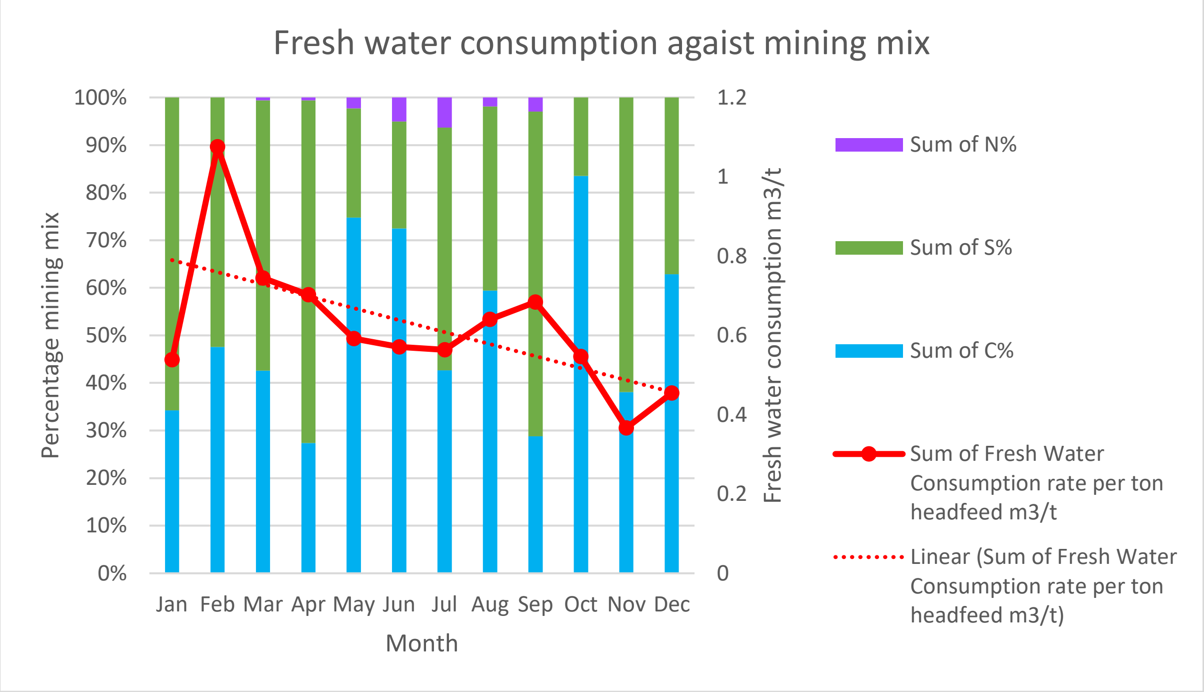


Figure 4.23 Plot of mining mix per pipe against fresh water consumption

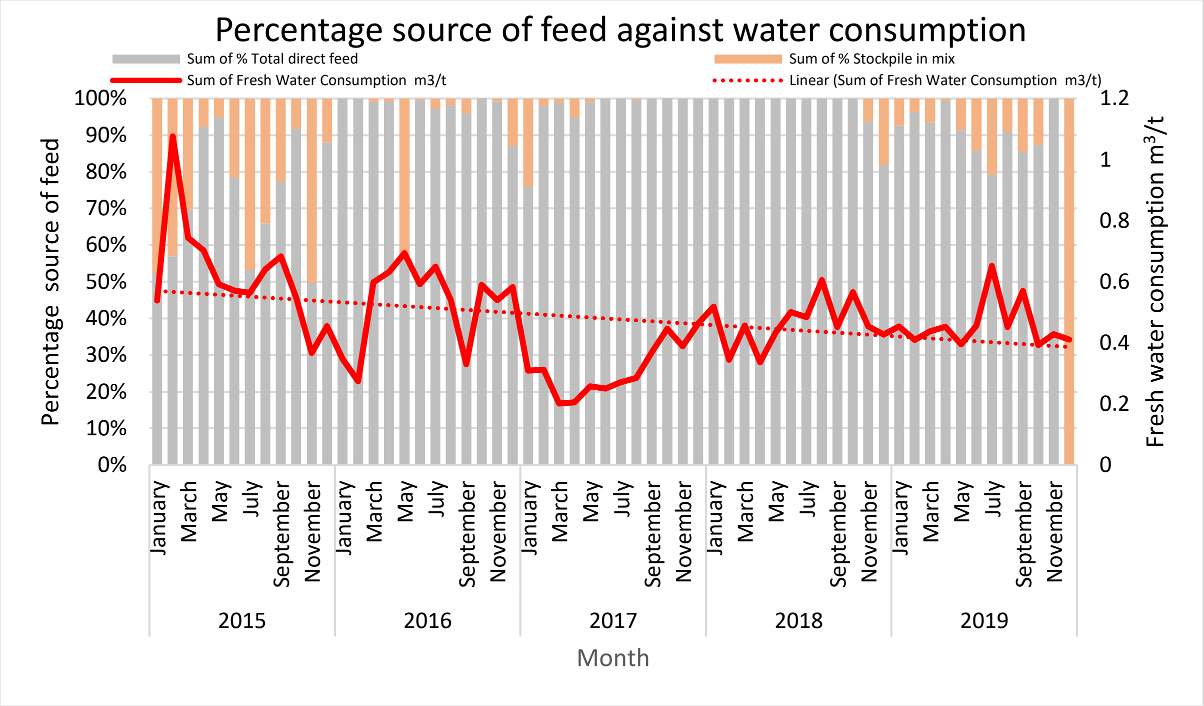


Figure 4.24: Percentage source of feed against water consumption

To investigate more into causes of higher water consumption during 2015, further analysis was done on lithologies associated with the feed during the stated months. Figure 4.25 illustrates the percentage lithology distribution for the months with similar feed-source ratios. Comparing the two months, February had the highest water consumption while July had consumption below annual average. February contained 56% of stockpile material which was partly from SP200 (undiluted South pipe stockpile) and SP14 (Clay rich Centre pipe Stockpile). A combination of this stockpile material and high VK material may have led to there being higher fines in the feed, hence the higher water consumption. When comparing February feed-source ratios with the ratios from July, there is a decrease in clay-rich Centre Pipe stockpile material in July. Instead during this period there is an increase in the fresh VK in feed. This had a positive impact in fresh water consumption as there was less fines in the feed hence less consumption.

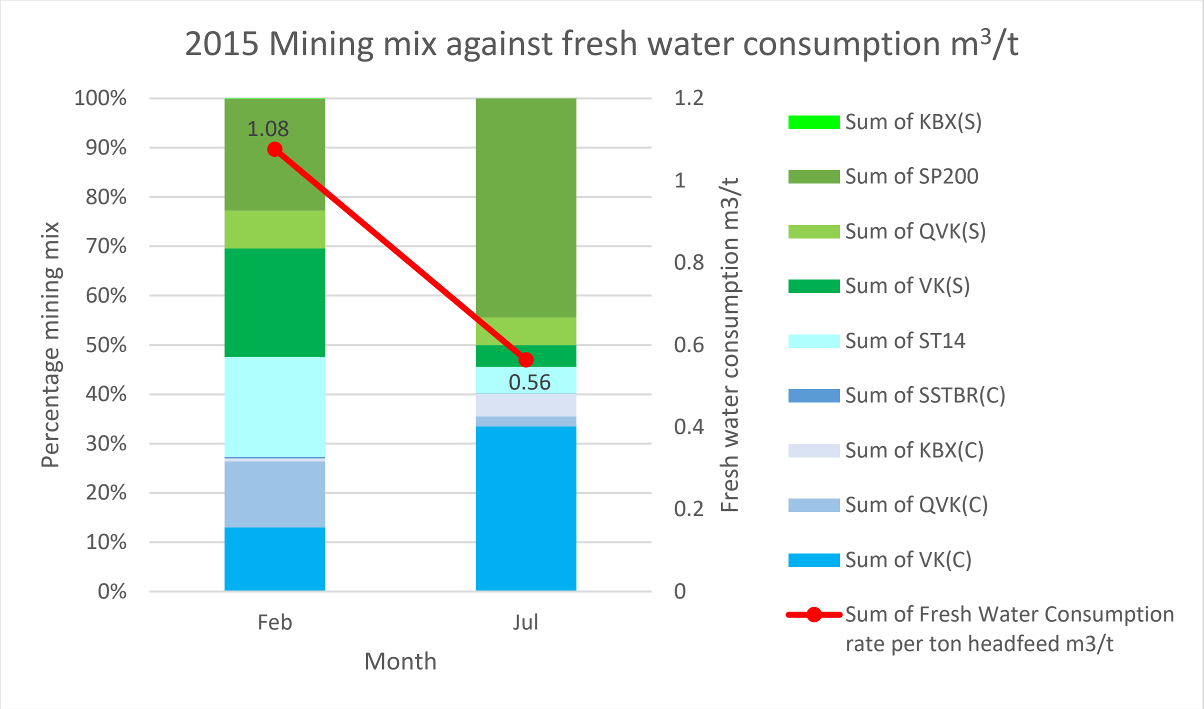


Figure 4.25: 2015 mining mix against fresh water consumption

The introduction of less clay-rich feed leads to less fresh water consumption and this was evident in 2016 in the reduction of the fresh-water consumption rate; Appendix 7.14 to 7.19 demonstrates the impact of different lithologies on fresh water consumption during treatment. There is a decline in water consumption rates as you shift from 2016 to 2019, this was due to the shift in feed from the Centre Pipe to North Pipe feed.

The introduction of minor PK in 2016 resulted in a slight drop in the consumption of fresh water at an average of 0.53m3 per head-feed ton. As more PK was included in the headfeed, water consumption reduced further to a usage of 0.41m^3 per ton. These changes occurred with the introduction of more North Pipe feed in the mining mix during the 2016 production period. PK is a hard-competent rock that is well bedded and may grade from very fine ash material to medium and clast-supported coarse beds. PK contains low content of clay minerals in its matrix as it is dominated by serpentine alteration rather than clay alteration.

The lithologies that were from the North Pipe included 56% PK as the major unit, followed by 30% of VK; the remaining 14% came from the North Pipe strategic stockpiles. PK volumes included in the mix compared to water consumption is shown in Figure 4.26. PK contains the least amount of smectite clays and more of Serpentine, Talc and Mica clays, which generally do not cause flocculation and settling problems in thickeners. These clays are often associated with less processing problems, mainly due to the ultra-fine nature of the clays and the shape of their particles, which prevents close packing compared to VK, which is more smectite-rich.

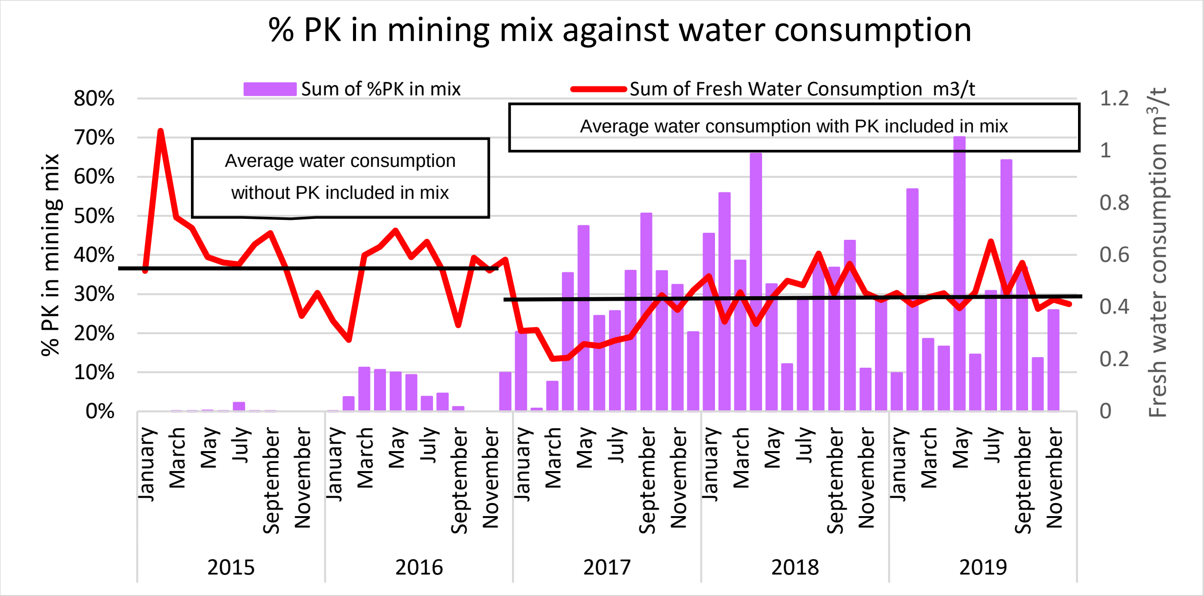


Figure 4.26: PK percentages included in mining mix plotted against mining mix.

PK acts as a moderator to smectite rich VK. The more PK is included in the mix, the less clay-related challenges will be faced. Water consumption is lower when there are less fine clay minerals in the system. The three most common factors that affect the behaviour of processing water are: the salinity of the water, its conductivity and its sodium content, relative to the water's calcium and magnesium content. The ODS studies tested the behaviour of Jwaneng kimberlites in water for the sodium absorption ratio (SAR), pH (Appendix 7.18) and conductivity (Appendix 7.19). The SAR values obtained from the three pipes indicate that the North Pipe has higher values when compared to the Centre and South Pipes, as shown in Figure 4.27.

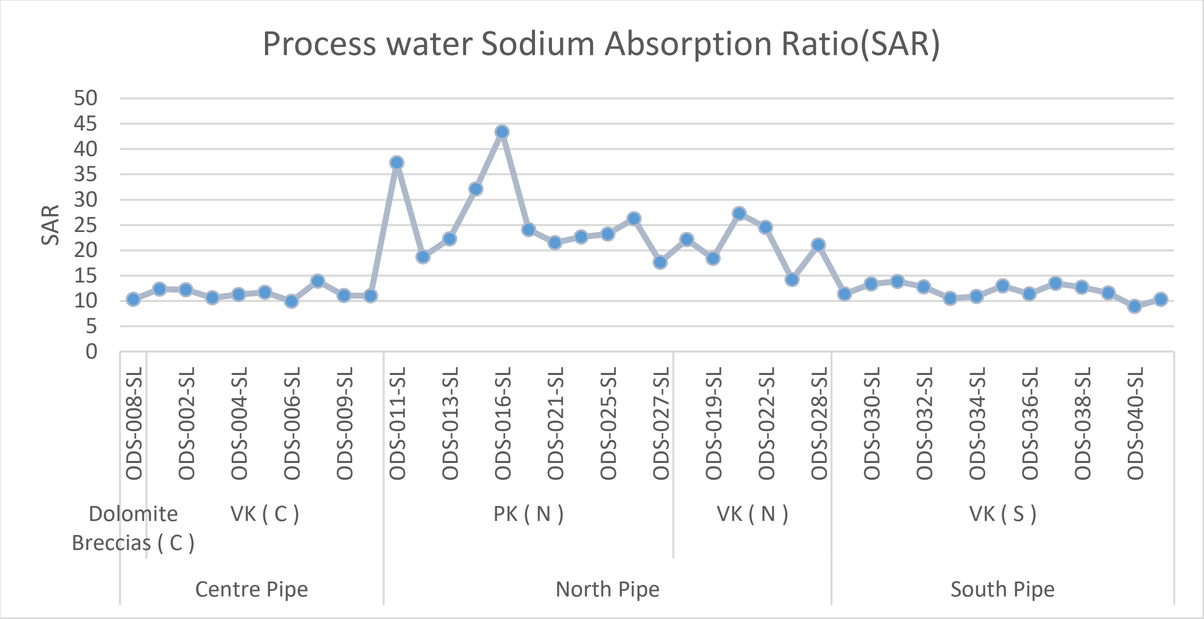


Figure 4.27: Ore dressing studies on the process water absorption ratio.

The North Pipe is expected to behave in this manner as it contains less sodium-exchanged clays compared to the other pipes. Sodium-exchanged clays tend to disperse while calcium exchange clays coagulate when they come into contact with water. Fresh water consumption varies with the type of mining mix, the more there are fine-grained, clay-rich lithologies included in the blend the more fresh water is needed. The smectite group of minerals are water chemistry dependent and they can disperse or flocculate when in different environments.

The trends observed indicate that with more North Pipe, PK-rich feed included in the feed mix, the less fresh water is required. Higher volumes of smectite, clay-rich VK being included in the blend will result in more fresh water being required during processing.

4.3.5 Mining mix analysis against FeSi consumption.

During diamond processing, there are a number of different process stages, one of the stages involves dense medium separation. This process involves using centrifugal forces to separate the diamonds from diamond bearing material with the assistance of a ferrosilicon to effectively aid the process. Dense medium separation is the first primary concentration step in diamond-processing plants. The crushed, cleaned ore is mixed with a ferrosilicon of a controlled density and passed through cyclones where ore particles are separated by their densities (Field, 2017). The particles that have densities below a desired cut-off point are referred to as the floats, while the concentrates that have particles with densities above a desired cut-off point are the sinks. By controlling the densities of the ferrosilicon medium, diamonds and diamond-bearing particles should report to the sinks.

The density of the mixture from the ferrosilicon is usually similar to that of diamonds during this process and the material will be separated by their densities. The heavier material will sink to the bottom while the lighter material will float to the top. Kimberlites, which are rich in smectite and have little internal dilution, such as VK, tend to break down more, while serpentine-rich PK and dilution-rich breccias remain intact.

As part of processing, the ferrosilicon is recovered from the process, through the magnetic separator process, and is then recycled to repeat the process. Ferrosilicon utilisation is related to the amount of ferrosilicon that is recovered and recycled during processing. The more recoveries of ferrosilicon in the process, the lower the need to re-introduce additional ferrosilicon. Ferrosilicon can be depleted resulting in poor recoveries due to many factors such as density changes and adhesion to material. Figure 4.28 illustrates the utilisation of ferrosilicon during periods between 2015 to 2019.

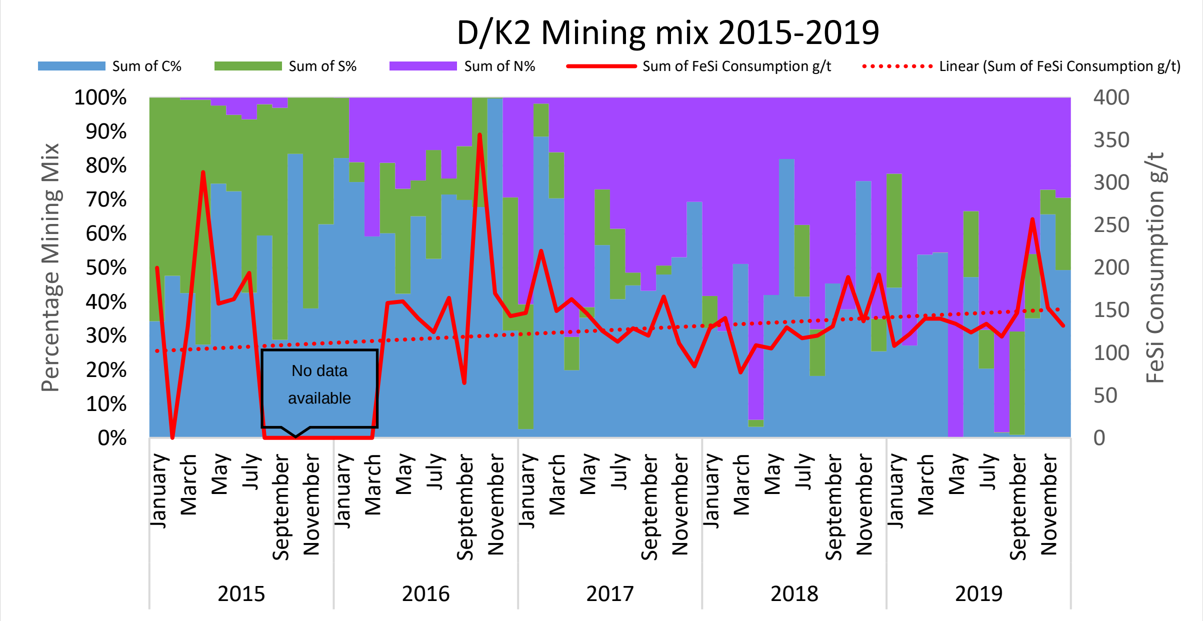


Figure 4.28: Mining mix plot against the ferrosilicon consumption

Mapping dilution, particularly the internal dilution abundance and size of the dense country rock clast, is fundamental. These clasts are most likely to cause fluctuations in the densities of the crushed rock particles. Hence dilution is important to understand. The principal diluting lithologies are quarzitic shale, dolomite mudstones and sandstones. These are mostly abundant in various kimberlite breccia domains. Of these identified lithologies, only dolomite has an average density that is likely to contribute to high DMS yields, as illustrated on Figure 4.29.

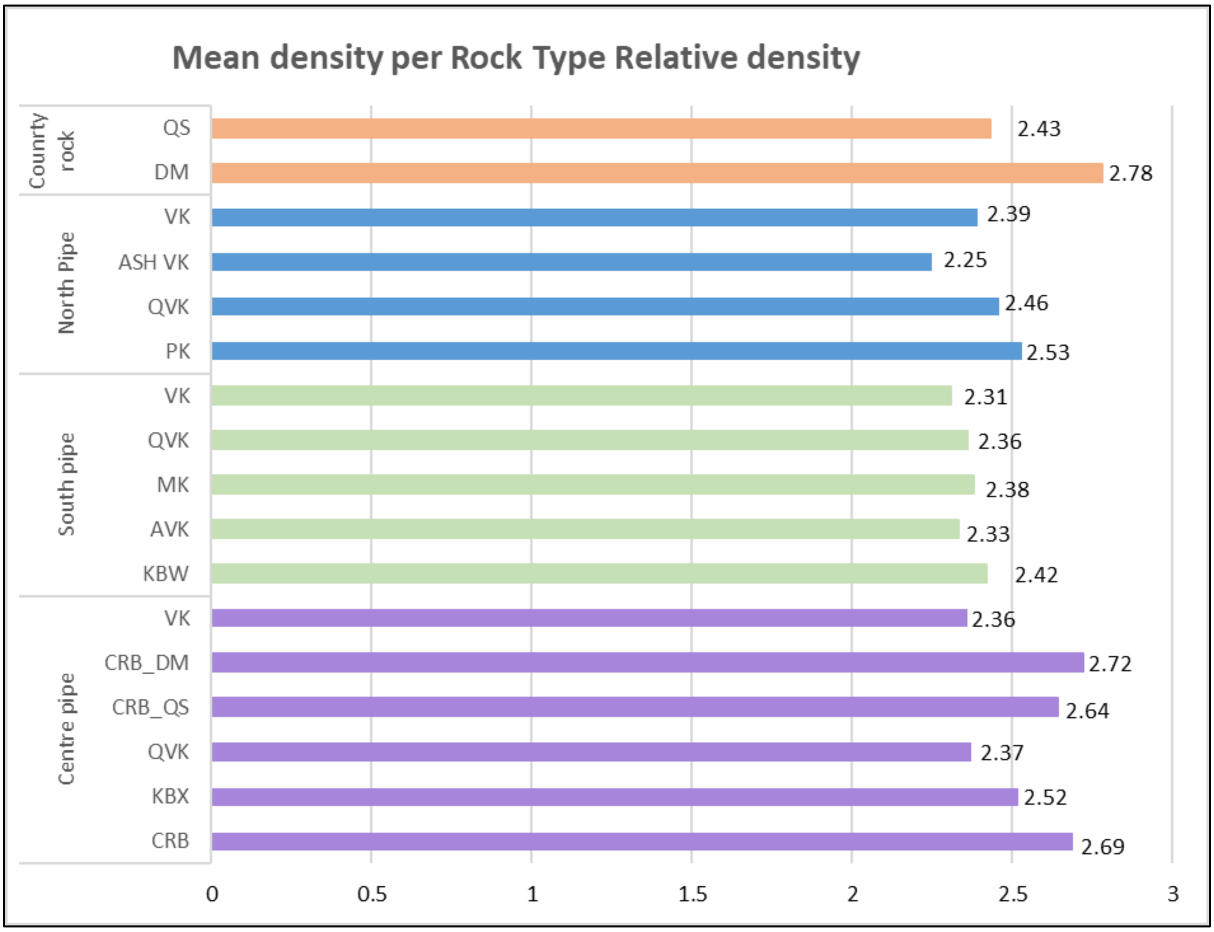


Figure 4.29: Mean density per rock type

Comparing mining mix against ferrosilicon utilisation, there is no distinctive correlation. This is due to ferrosilicon being impacted by other process activities that are not feed related, such as the general stability of the plant.

These activities include:

- Loss of ferrosilicon due to its adhesion to material as a result of inadequate washing of the material.
- Loss due to spillage as a result of leakages in pipes.
- Loss at the magnetic separators due to ineffective scrapping.
- Power failures, which lead to ferrosilicon being lost to the water circuit or passing with the gravel. Power failure also leads to corrosion of the ferrosilicon due to chemical changes.

There are also no major variations in the density of the lithologies of the feed, hence it is difficult to correlate the ferrosilicon consumption to the mining mix.

4.4 Discussion

The success of the extraction and the processing of a mineral resource is dependent on developing a resource evaluation project that will deliver a value-adding business case. The main input from the mineral resource evaluation projects is to develop a resource model which will give a spatial distribution of different rock units, grades and other geotechnical parameters (Dunham & Vann, 2007). Failure to correctly identify the variability that occurs within the mineral resource puts the business at risk. This may lead to underperformance and an increase in potential revenue loss as revenue projections are dependent on these variables (Dominy, et al., 2018). To combat poor performance, a more improved understanding of the spatial nature of rock properties is required in order to reduce the number of unknowns in the mineral value chain process (Coward, et al., 2009). Better understanding requires having exhaustive description of the rock and how it will perform under certain conditions that are imposed by mining the resource and through treating the ore. The variability in the geology of the resource dictates how the downstream processing effectiveness and the throughput will occur.

The Jwaneng D/K2 kimberlites illustrate that there are many variabilities that will negatively impact the efficiency of the Jwaneng Main Treatment Plant if not addressed.

The future mine plans indicate that the swelling clays will continue to be present in the mining mix with an increase in mining depth. An understanding of the mineralogy in these zones needs to be developed and combined with other metallurgical response data to successfully develop a geometallurgical model for Jwaneng mine.

Based on the analysis discussed in chapter 4, there is evidence that different kimberlite ores impact plant efficiency in various stages in different ways. During the years 2015-2019, volcaniclastic kimberlite from all the three pipes was the most common lithology that was treated. The ODS on the Jwaneng resources indicated the volcaniclastic kimberlite from the Center Pipe contained the highest volumes of swelling smectite clays which cause the most settling problems compared to the other two pipes. This is a result of the ultra-fine nature of the clay minerals, which lead to the formation of dispersive slurries under certain conditions. The ESP analysis gave an indication that sodium-exchanged clays, such as the smectite clays, swell when in contact with water, resulting in formation of more ultra-fines. The high content of smectite minerals in certain ore types is an indication that the material might be difficult to settle. Flocculant, fresh water and ferrosilicon are the three main consumables which are used in processing the material. The consumption rate of these consumables is directly linked to the type of feed that is being treated and addition of these consumables is a continuous process during operation; and dosage varies with any settling challenges that are experienced. The treatment plant has set daily utilization targets for these consumables, which are to be incorporated during treatment as a way to maintain plant stability. Dosages is mostly impacted by the performance of the plant as a result of feed parameters as well as mechanical challenges. Both these challenges need to be considered when analyzing the data to that delays are attributed to correct source.

High flocculant consumption rates were experienced with increases in smectite-rich volcaniclastic kimberlite volumes, from the Center Pipe, which caused settling difficulty. It is noted that the consumption rate of flocculant increases with increased smectite clays in feed. Plant stoppages attributed to settling challenges are higher and more time is lost during such periods. The stoppages are as a result of blocked screens due to the fine material, buildup of material and poor settling. All these require upstream processes to be halted in order to correct the issues that are impacting production. Having high consumption rates impacts negatively on production costs as high consumption rates lead to high production costs. During the period between 2015 and 2019, there was an upward trend in costs of flocculant, annually, as shown in Figure 4.30. During this period, Jwaneng MTP was using a standard flocculant (Senfloc 2660) which had been tested and found to be best suited for improving settling rates. To minimize the continual increase in flocculant costs, there is a need to look into having mining mix blends that reduce the amount of flocculant usage.

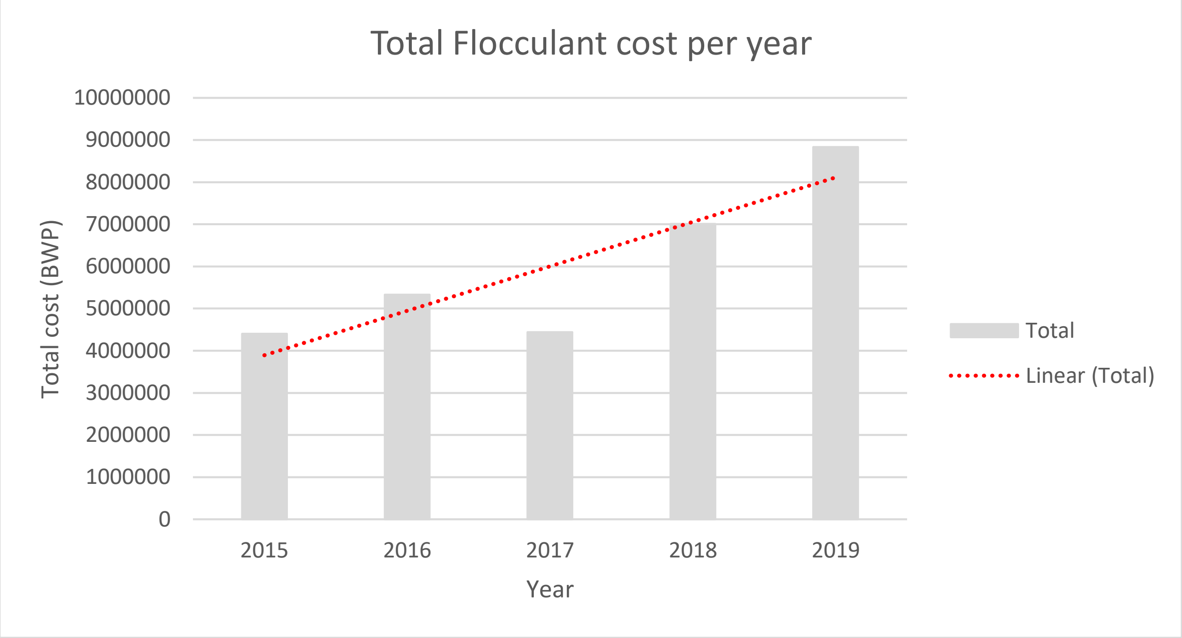


Figure 4.30: Annual total flocculant cost.

The amount of slurry and slimes that are produced is determined by the nature of the material that is being fed to the plant. The change in percentage slurry produced from MTP varies according to the geology of the mining mix. Feed that contains more fine-grained clay material results in higher slurry being produced. While less slurry is produced when there are fewer clays included in the feed. Processing of the problematic material in the plant is usually linked to the presences of the smectite clays in the feed.

The analysis of fresh water consumption indicates that the change is associated with challenges related to settling of slimes as a result of the clay behavior of the ore. Increases in water consumption is brought by feed that contains volcaniclastic kimberlite, which is rich in fine clay particles. Water consumption is lower when the dominant ore being fed contains serpentine-rich, pyroclastic kimberlite, which has less clays. The two minerals: smectite (clay rich) and serpentine (clay poor), have an impact on the competency of the rocks, how the rocks mix with water and how they respond to processing. A higher presence of clays causes delays in the water recovery of the plant, hence the need to introduce fresh water. Similarly to flocculant consumption, higher water consumption is impacted by the type of feed: the coarser the feed the less the water consumption.

To reduce fresh water and flocculant consumption, there is a need for better blending strategies to ensure the right material is fed at the right time. The blends need to incorporate the smectite-rich lithologies with more competent serpentine-rich rock that has less smectite, as Table 4.5 indicates impact of processes limitations per lithology. Due to the data gaps that have been identified, there is a need to further investigate other lithologies that occur in the kimberlite pipes as currently only two lithologies have been determined. As mining progresses to deeper depths, there is a need to have metallurgical and geological data collected in those deeper areas to enable formation of better blending strategies that incorporate all lithologies, especially kimberlite breccias. Based on the analysis of the mining mix percentages for the period, the Centre Pipe has been the highest feed pipe throughout the years, blended with lower volumes of the North and South Pipes.

Table 4.4: Ore type and impact on consumables

Ore Type	Treatability Challenges	Unmitigated Risk / Impact	Risk Mitigation	Impact on Consumables
Pyroclastic kimberlite				
• Low clay mineral content • Hard and dense	Competent material that affects secondary and tertiary crusher performance	Reduced throughput on the secondary crushers. Increased tonnages to the secondary crushers and DMS. Secondary and DMS stockpiles consistently high Increased tonnages to the RP reduces the opportunity to fully utilize the reload	Blend with VK from all pipes	Low flocculant consumption due to less fines in the thickeners Low FeSi consumption as there are less fines to contaminate the medium Water consumption not affected
Volcaniclastic kimberlite				
• Clay rich • Soft and exhibits poor competence	• Low recirculation loads • VK clay rich	• High secondary stockpile and feed prep levels leading to intermittent stoppages of headfeed thus affecting the OU • Difficult to settle at the thickeners • Causes buildup at transfer points.	Blend with PK North pipe	• High flocculant consumption due to fines • High water consumption due to contamin

				ated FeSi

For lower fresh water and flocculant consumption, the blending ratios need to include less smectite rich Centre pipe and a combination of North pipe and smectite poor South pipe lithologies. With these blending ratios the consumption rates will be moderated as the smectite rich lithologies will be balanced out by the smectite poor lithologies.

Ferrosilicon consumption analysis could not be conclusively correlated to the lithologies fed during the period, this is a result of other processing challenges experienced and having densities which are within the same range. The mining mix at current pit depths did not include major kimberlite breccias which have a higher density when compared to the rest of the kimberlite lithologies. Current mining level is at 594mbgl (meter below ground level), as mining extends below the 650mbgl there will be a change in mining mix feed per pipe as illustrated in Figure 4.31. South pipe and Center will have additional Kimberlite breccias included in the mix, these are the Kimberlite Dolomite Breccia (KBW_DM) and the Country Rock Breccia. North pipe will have an increase in the VK as PK will be decreasing with depth

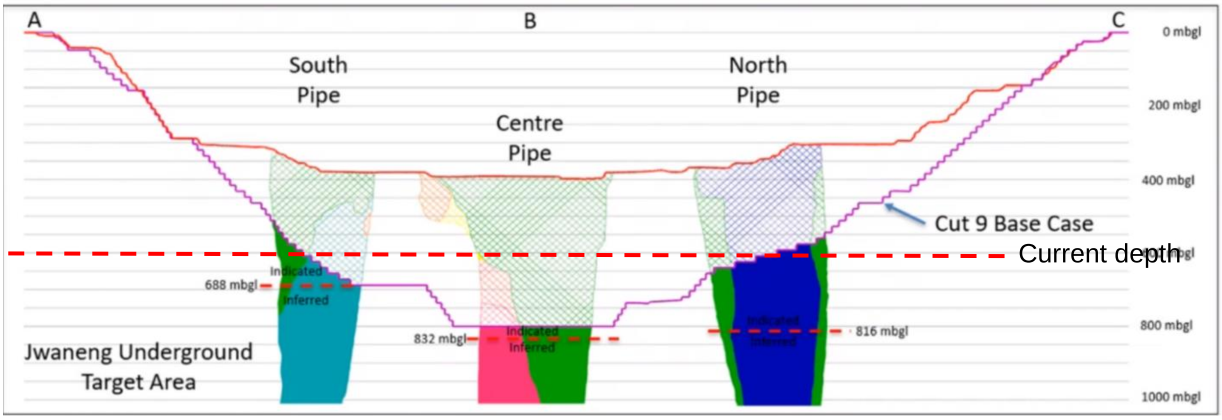


Figure 4.31: South-North Section of D/K2 kimberlites

Density and rock hardness increase with pipe depth; and this will have an impact on ore treatability. As a result, mining at deeper levels will have an impact on the slurry and slimes fractions that are produced, and will also impact comminution. Knowledge about the impact of all breccias on the treatment process is vital and should be investigated further to get a full understanding of their behaviour. South Pipe feed will have a slight change with the introduction of the kimberlite breccia, which was previously not part of the feed. The North Pipe will not result in major changes to the feed as the lithologies that are currently mined will be intersected in future mining and no new lithology will be introduced. The predominant lithology, as mining moves to levels below 650mbgl, will remain as the volcaniclastic kimberlite from all the three pipes. Another additional dominant lithology will be the kimberlite breccias. With minor sampling carried out on the expected kimberlite breccias there will be no geometallurgical information available. This will increase the risk to processing and may have a negative impact on treatment processes.

Table 4.5: Density measurement variations above and below 650 mgbl

	Facies	**Density above 650 mbgl**	Density below 650 mbgl
South Pipe	**VK**	2.30	2.38
	QVK	2.36	2.45
Centre Pipe	**VK**	2.37	2.56
	QVK	2.31	na
	KBW	na	2.67
	KBX	2.38	na
North pipe	**VK**	2.37	2.46
	QVK	na	2.46
	PK	2.46	2.60
	KBX	2.62	na

The density and hardness of rock increases with pipe depth and this will have an impact on ore treatability. More information needs to be collected that will assist in the characterisation rock lithologies that are expected in mining in the future. Collecting this information will ensure that the predictability of resource treatability is better managed. All the anticipated problematic smectite rich areas in the pit also need to be identified as well as those that are not as problematic. This information can be used to inform tactical decisions on blending ratio strategies. For better understanding of geometallurgical parameters beyond levels of 650mbgl, more drilling and sampling is required. The data collected can then be used to create a geometallurgical model, which mine planning could take into consideration when planning future mining mix blends. As part of ensuring all parameters for MRV 3 are collected and modelled in the Jwaneng Geometallurgy model for future mining depths, more specific sampling is required. For the slimes and slurry parameter, daily data needs to be collected from total MTP slimes and grits behaviour. More drilling samples must be collected for ESP % calculations as well as direct weathering test data. This information is vital as mining moves to lower levels, because the kimberlite breccias are included in the future Cut 10 or conceptual underground mining plans. The geometallurgical model should incorporate estimation of all the minerals, looking at both relative abundance and location.

4.5 Chapter summary

The presence of clay causes a wide range of mineral processing challenges, as a result of its soft nature. To guard against the impact of clay in the mineral processing chain, there are requirements to use chemical reagents such as flocculants, density/magnetic separators (to aid separation of feed); and to have suitable water requirements. In future, processing of clay containing kimberlite will not be avoided with the increase in mining depth. From all the three Jwaneng kimberlite pipes, there will be a change in mineralogy and the extent to which clay influences processing will vary according to the clay type intersected. To prepare for the change in mineralogy at greater depths, a better understanding of the geology and mineralogy of the ore is required. As kimberlite is a unit which is made up of a matrix and country rock clasts, it is required to have an understanding of the clast material, through waste dilution measurements, as clast material also impacts the process. Analysis has indicated that the key metallurgical parameter that influences performances is the type of mineralogy which is present in the feed. Flocculant and fresh water consumption trends are mostly impacted by treating high volumes of smectite-rich volcaniclastic kimberlite as well as smectite-poor kimberlites. To always maintain good plant efficiencies there needs to be a balance in the feed blends of the two. Due to other treatability issues experienced by MTP during treatment FeSi consumption couldn’t be directly linked to feed. More tests are required to draw a conclusion on this variable. Chapter 5 presents a summary of the research and concluding remarks. The recommendations on how best the slimes and slurry variable can be incorporated in the Jwaneng geometallurgy model is also discussed.

CHAPTER 5: CONCLUSIONS AND RECOMMENTATIONS

5.1 Chapter Overview

From the research analysis, findings regarding impact of the presence of smectite-rich clay in feed were determined. The impact of the occurrence of clays on slurry and slimes which are generated during processing are discussed in this chapter. Also highlighted is the importance of having spatial knowledge on clay occurrences. This chapter concludes by giving recommendations.

5.2 Summary

Geometallurgy is one field which is growing in the mining industry as discussed by many authors in the literature review. This field incorporates all key stakeholders in the mineral value chain which includes geology, mining engineering and metallurgy. The importance of identifying primary and response variables within any operation is key as each operation has different variables that are key for the mining value chain. Jwaneng mining has established three primary variables through various drilling programs, which have resulted in the collection of data for a variety of parameters. These included data collection for mineralogy of rocks, textural properties, and geomechanical properties. From these primary variables, response variables were determined to see how the rocks will behave in a processing environment. The key stages of geometallurgical model establishment involve identifying these variables and collecting all necessary information associated with them. The main objective of having a successful geometallurgical model is to eventually have the ability to include the model in mine plans as a predictive tool for production reconciliations.

From identifying the current position of the Jwaneng geometallurgical model, the research aimed at testing for the main metallurgical response variables (MRV3), looking specifically at slurry and slimes management. The key parameter that was identified as the main cause of the challenges associated with slime and slurry the mineralogy of the rocks. The type of mineralogy a rock exhibits impacts on how it will behave when treated. This was tested against how processing consumables are impacted by rock mineralogy; and it was evident that Jwaneng kimberlites have mineralogy which impact processing, if not controlled. One mineral identified as a problematic mineral to processing was smectite. Smectite is a swelling clay that causes poor settling during processing. This causes an increase in the utilisation of flocculant, as flocculant is required to assist with settling. Poor settling results in failure of processing water to be cleaned and re-circulated, resulting in the need to add fresh water. When the utilisation of consumables such as water and flocculant is not controlled, production costs will rise, which will increase daily operating costs. Ways of controlling the processing challenges were discussed in chapter 4, and included putting better feed-blending strategies in place. Variations in mining blends tend to impact different parameters in various processes in the plant. The parameters to be incorporated must include spatial-smectite percentages, serpentine and calcite occurrences as well as the distribution ESP values, which contribute to predicted slurry and slimes behaviour. The purpose of this is to ensure optimal resource utilisation at all times and to allow for economic profits to be achieved.

The metallurgical response variable looking at slurry and slime management is an important variable because if it is not controlled it will cause processing delays, both upstream and downstream. Through the research this analysis, the most challenging minerals for processing have been identified and linked to spatial locations within D/K2. For future mining operations, there is a need to extend the knowledge on the geology of depths that go beyond current mining levels. This will allow for continual predictability of challenging minerals for treatment through the implementation of a geometallurgical model.

5.3 Research findings

The nature of the material being fed to the plant is a major contributor to the amount of slimes and slurry that are produced. The aim of the geometallurgical model MRV3 is to model material that will have behavioural impacts on the plant; and to model processed material that has a natural tendency to produce slime. Slime is a major problem during the processing of kimberlite, especially when the material being treated contains a high clay content. A major stage during processing is the removal of this fine-grained material from process water. The process water generated during the recovery of diamonds from kimberlite is mixed with the fine and very-fine grained clay-rich fractions to produce a slurry. Recovering as much as possible of the process water from the slurry for reuse is a major challenge. This has an impact on fresh water consumption as failure to reuse water requires introduction of fresh water. This process increases the cost of fresh water consumption, increasing operation costs. Another consumable that is highly utilised in the process of separation of slurry and water is the flocculant. Flocculant is added to the process water to hasten the settling of the slurry and recovery of the process water. Once the slurry has settled to the bottom of the thickening tanks, it is pumped to the fines residue disposal dams (Field, 2017). To minimise the amount of flocculant used in the process and maintain effective re-use of the process water, detailed characterisation of the kimberlites being fed to the plant is vital.

Although it is always ideal to have a geometallurgical model during the feasibility study, it can still be developed in an existing mine.. The following are justifications for the benefits of having a geometallurgical programme in a mining operation:

- There is a better utilisation of the ore resource, because boundaries are defined through the delineation of the ore waste contact as data is collected by different methods such as floor mapping and deep-drilling programs.
- The more comprehensive knowledge acquired on the ore the better controlled the mining processes will be.
- Metallurgical performance improves because it is possible to control the process activities as information on the plant feed will be received beforehand.
- There are better changes in plant optimisation because variation in plant feed is better controlled and very low.
- It allow for better changes in new technology solutions because ore derived problems are identified well ahead and research programs can be more focused to solve them.
- Through a better understanding of the mineral resource, there is a lower risk in the operations.

Analysis of plant consumables against mining blends has indicated a correlation of the two. Feed that is associated with finer particles tends to result in a higher consumption rate of fresh water and flocculant. Problematic processing behaviours in thickeners are usually linked to the presences of smectite clays in the feed. This is due to the tendency of these clays to generate dispersive slurries under certain processing conditions, such as having low conductivity water and having ore that is rich in sodium content. The smectite clays are often associated with low thickener underflow density. This is mainly due to the ultra-fine nature of the clays and the shape of the particles preventing close packing. Flocculation tests carried out indicated that high VK in the feed from the Central and South Pipes required higher flocculant doses than the feed from the North Pipe feed. This is due to high ultra-fines content in the Centre and South Pipes. The test work indicated significantly high occurrence of smectite clays, coupled with high ESP in the Centre and South Pipes. If the smectite content is higher than five percent of the total mineral content, the clay is considered to have a high degree of non-settling material.

5.4 Conclusion

This study indicates the need to increase knowledge on the Jwaneng Mine's mineral resource to enable all identified metallurgical response variables to be incorporated into the development of a complete geometallurgical model. Through the different drilling campaigns, sampling and tests conducted, geological and metallurgical data has been collected for various objectives. There was no sampling that was specific to the purpose of creating a geometallurgical model, but the geometallurgical sampling was more opportunistic sampling from the other campaigns. For a geometallurgical model to be created and put into usage in the short-term plan, it needs to incorporate all important relevant variables that need to be tested for confidence in the model to be increased. The current Jwaneng geometallurgical data collected shows gaps; and there is a need for additional purposeful sampling to collect data for the model to be created.

The mineralogy of the Jwaneng rock types demonstrates that there are variations that will affect slurry and slimes fractions produced. The two main mineral species: smectite and serpentine, have a profound effect on the competency of the rock and how the rock responds to comminution and mixing with water. For this reason, it is important to incorporate the two minerals into the geometallurgical model, both in terms of their relative abundance and where they occur. The smectite clays' mass percentages show that the Centre Pipe contains the most clay-specific fraction, followed by the South Pipe; while the North Pipe contains the least amount of clay fraction. The combination of the sodium-exchanged Centre Pipe's smectite clays and the low conductivity of raw water leads to dispersive slurries, poor flocculation and thickener operational problems.

The main input into planning is a 3D geometallurgical model, which should be used in the reconciliation stages of production to test the trueness of data collected. The output of planning is the plans and schedules developed, which should incorporate information on the quality of the blend to be used. The blends must indicate information of the location to be mined as well as when it should be mined.

Although the main interest of mining is the metal grade, mineralogy, texture and grindability are decisive parameters (Aasly & Ellefmo, 2014). Where processing of material is affected by the properties of the rock, blending is required to ensure continual operations. Modern scheduling and optimisation of the dollar per carats used as the input for planning instead of the grade. The value is based on an estimate from a size of the mining block, the grade, recovery, commodity prices and the operation costs. The recovery value is dependent on the grindability, texture and mineralogy, which are key components in the geometallurgical variables. Instead of using dollar values, the life of mine is usually used to find optimum schedule and blends. The schedule and the blend is what maximises the life of mine and produces products that are within specifications (Aasly & Ellefmo, 2014). Mine planning requires good knowledge on mineralogy, geological knowledge and an embrace of geometallurgical elements to allow for informed blending strategies.

5.5 Research limitation

The production data indicates there is evidence of geological influence on the diamond by weight percentages. Due to complicated flow sheet and residence time the material takes between head feed point to processing, it was difficult to link. As a lot of information is unknown on the current lithology of the stockpiles, it will be of great assistance to understand the material on the stockpiles in order to build a geometallurgical model with all variables.

5.6 Recommendations and Suggestions for future research work

Based on the application level of geometallurgy, Jwaneng mine falls within the same level as Mogalakwena Platinum, which is level 2. Both these operations have identified the variabilities that occur in the ore bodies on their mines based on previous geometallurgical data collection processes. Due to data gap constraints, a geometallurgical model has not been developed; but treatment-of material-guidance may be given for production related purposes. When comparing Jwaneng Mine with other operations that have successfully developed a geometallurgical model, the following steps need to be taken to move from where the mine is to higher levels:

- Available data has to be assessed and data gaps identified. The first step would be to build a geometallurgical database from current geological and metallurgical data available. Geostatistical modelling, which depends on having sufficient numbers to be accurate, can be used. Estimates based on small numbers, as is currently issue with Jwaneng data, results in higher degree of uncertainty.
- Assessments must be made of all constraints that hindered the development of the geometallurgical model, based of the available data. These should include the sampling deviations which were identified.
- The mine must develop a sampling-for-purpose program that is specific to geometallurgy, aimed at closing data gaps identified by the previous campaigns. The sampling programs must target the five MRVS identified and ensure it covers all the current and future lithologies expected in the life of mine.
- The mineralogy of the expected lithologies in the life of mine must be determined to allow for better understanding of the resource; and plant simulations but be ran to test the compatibility of the material with the processing plant.
- A geometallurgical model must be developed.
- As geometallurgy is a continuous program, after the mode is developed, it would need to be tested and improved through additional sampling campaigns, as more data collection initiatives arise. With the number of different metallurgical response variables already identified, it is evident that geometallurgical information is becoming more main stream.
- Once developed, the model should be used in strategic and tactical planning to maximise the profits of the resource.

The development of a geometallurgical model, which includes all critical response variables, will allow for better processing problem-solving in the future. Through this analysis a better understanding of the mineralogy of the resource impacting slimes and slurry has been identified. The swelling clays which are the most problematic in treatment have been identified to occur within the major kimberlite units. Spatially locating these kimberlites and the associated mineralogy leads to mapping out smectite-associated lithologies, allowing for a more predictive utilisation of consumables. Spatial mapping of clays allows for better understanding of ore, leading to better blending strategies. Blending strategies would not only be based on grade but would incorporate other important factors, such as clay occurrences, as they have an impact on throughput and operating costs through the utilisation of consumables. The geometallurgical model of Jwaneng would then be ready to be utilised to provide predictability on mining mix behaviour in the value chain.

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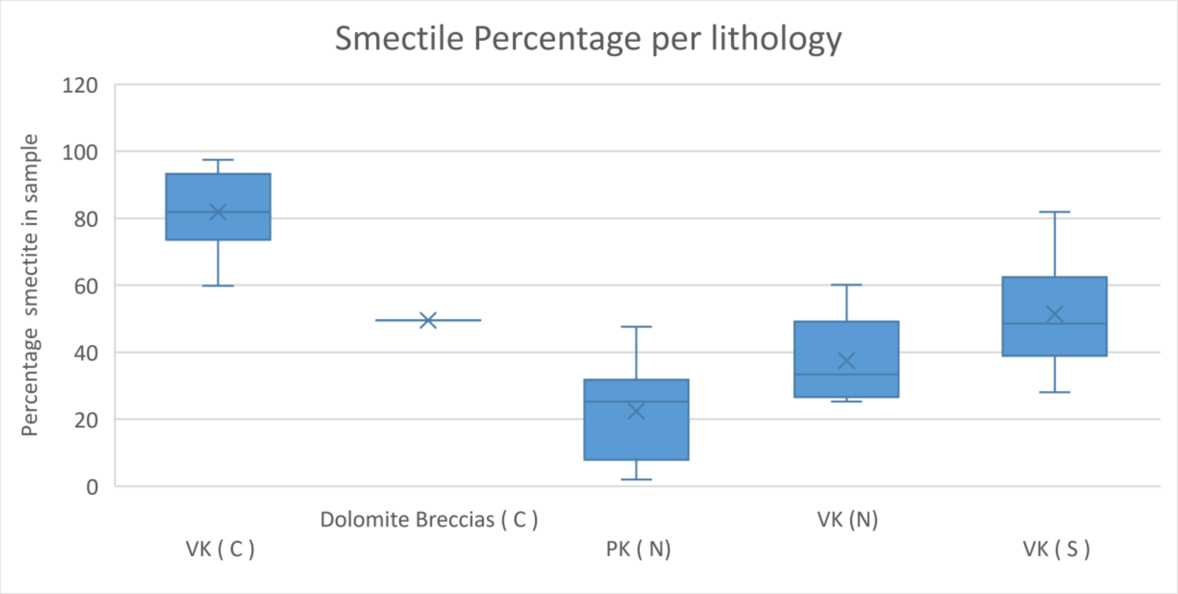
7 APPENDICES

7.1 D/K2 Modelled rock types and estimation domains

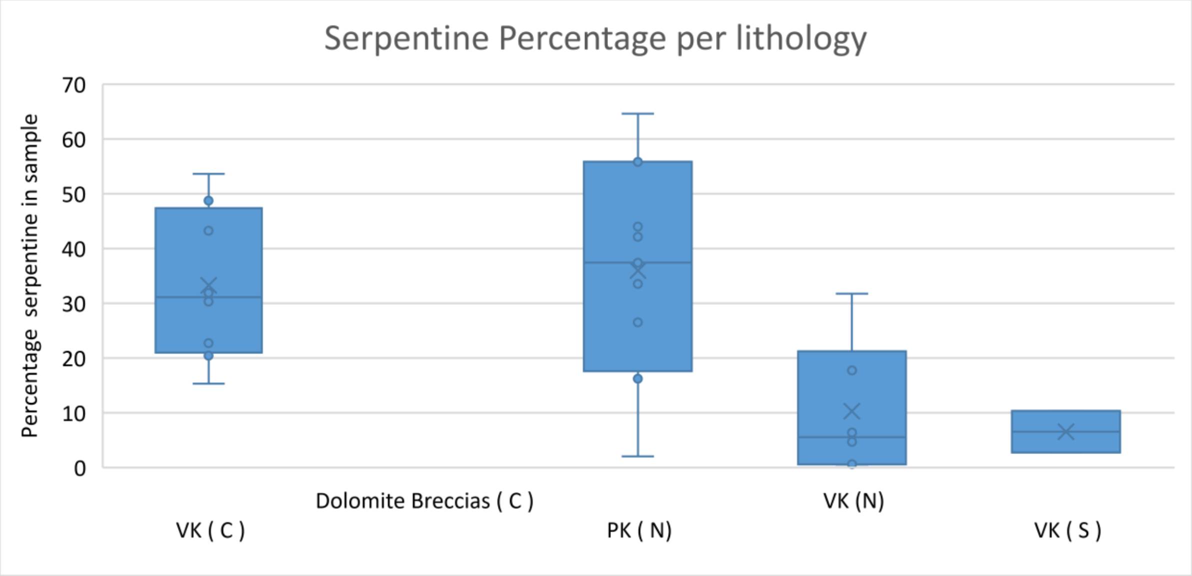
Pipe	Rock Code	Rock Type description
North Pipe	OK (N)	The Oxidized Kimberlite (OK) is a highly oxidized fragmental Kimberlite in the upper parts of the pipe. Characterized by the red color, advanced degree of weathering and alteration seen in the olivine constituents. The OK has been mined out.
	RVK (N)	Resedimented Volcaniclastic Kimberlite (RVK): Defined by a bowl-shaped morphology terminating at elevations above 200 mbgl. Presence of fine reddish shale clasts which are absent at depth (5-15%), a tightly packed clast-supported texture, and strong features of reworking. The RVK has been mined out.
	PK (N)	Pyroclastic Kimberlite (PK) with two end members: 1. Competent dark green to black Kimberlite with a high abundance of macrocrystic and phenocrystic olivines. Contains low lithic content 2. Pale grey-green Kimberlite with high lithic content. Units are well bedded and may grade from very fine bedded ash material, to medium and coarse bed intercalations
	VK (N)	Volcaniclastic Kimberlite (VK): Has a clay-rich matrix and a light green-grey appearance with lower competence compared to the pyroclastic facies. Olivines highly altered and less abundant.
	QVK (N)	Quartz-rich Volcaniclastic Kimberlite (QVK): Dark grey to black Volcaniclastic Kimberlite with elevated levels of free quartz (10-30%) and carbonaceous material (often with fossil wood). Occurs at the pipe margins in intercalation with sandstone/ mudstone breccia.
	AshVK (N)	A very fine grained, well sorted, in places thinly bedded, and ashy Volcaniclastic Kimberlite which in most cases is almost devoid of coarse clasts. The Kimberlite is incredibly fine grained and clearly distinct from the typical VK and may contain finer diamond distribution.
	SSTBR (N)	Sandstone Breccia (SSTBR): Breccia comprising intermixed Kimberlite and either sandstone or mudstone. Kimberlite content varies from 5 to 40% by volume.
Centre Pipe	VK (C)	Volcaniclastic Kimberlite (VK): Constitutes 75% of Centre pipe by volume. Kimberlite is variably altered, with olivines altering to serpentine and Mg-rich clays. Two types exist- a pale greyish-green, less competent, clay-rich unit and a minor dark green, clay-poor, more competent, juvenile-rich unit
	QVK (C)	Quartz-rich Volcaniclastic Kimberlite (QVK): Volcaniclastic Kimberlite containing abundant free quartz fragments (10-40%) normally in a clay-rich matrix. Generally forms a discontinuous rim around the pipe margin.
	KBX (C)	Kimberlite Shale Breccia (KBX): Contains abundant country rock waste material constituting 70 to 95% by volume. The country rock xenoliths range from less than 10 mm up to boulders as large as 2 m in diameter.
	SSTBR (C)	Sandstone Breccia (SSTBR): Breccia comprising intermixed Kimberlite and either sandstone or mudstone. Kimberlite content varies from 5 to 40% by volume.
	KBW_DM (C)	Kimberlite Dolomite Breccia (KBW_DM): Comprises >50% dolomite lithic clasts, mostly angular and set in a minimum of 5% Kimberlite matrix. Mainly occurs at pipe elevations below 600 mbgl, below the stratigraphic transition between the shales at the top and dolomite below.
	CRB_QS	Country Rock Breccia (CRB_QS): Unit containing very little kimberlitic material (< than 5%) within the Kimberlite wall rock breccia zone. Occurs as brecciated Quarzitic Shale (QS) blocks intercalated with the KBX. Forms a discontinuous sliver of strongly brecciated wall rock zone varying in width from 10 to 50 m.

	CRB_DM	Country rock breccia: The dolomite-rich equivalent of the CRB_QS described above. The Kimberlite content is < than 5% and the unit is extensively brecciated.
South Pipe	VK (S)	Volcaniclastic Kimberlite (VK): Dominant facies, grey-green clay-rich highly altered rock exhibiting variable textures and structures. The juvenile content is low due to advanced alteration of olivines and the abundance of mantle xenoliths is very low. The VK occasionally exhibits a competent dark greenish-blue juvenile-rich, autolith-rich unit with abundant mantle xenoliths.
	AVK (S)	Occurs dominantly at deeper levels of the South Pipe at elevations below 600m where VK gradationally transitions into AVK. Compared to the normal VK, it is relatively darker, lithic-rich, and characterized by large and dark macrocrystic autoliths and high abundance of large-sized mantle xenocrysts. It is also dominantly poorly sorted and massive to poorly bedded. It occurs in close association of intersections of dark coherent magmatic Kimberlite.
	MK (S)	Magmatic Kimberlite (MK): A dark grey, dark brown or black Kimberlite that may have formed from direct crystallization of unfragmented Kimberlite magma. Rich in juvenile components (olivines and mantle xenoliths). The basement fragments constitute <10% of total rock volume. Makes up less than 1% pipe volume.
	QVK (S)	Quartz-rich Volcaniclastic Kimberlite (QVK): Characterized by the presence of visible quartz grains exceeding10%. Often clay-rich and intercalated with mudstones. The color can vary from green to brown. Significant presence of carbonaceous material (5-20%).
	KBX (S)	Kimberlite Shale Breccia (KBX): Brecciated Kimberlite comprising quarzitic shale fragments (>50%) that are generally clast-supported and angular in shape.
	KBW_DM (S)	Kimberlite Dolomite Breccia (KBW_DM): Comprised of a high abundance of dolomite fragments (>50%) that are generally clast-supported and angular in shape. The KBW_DM is similar to the units described above for the Centre pipe.

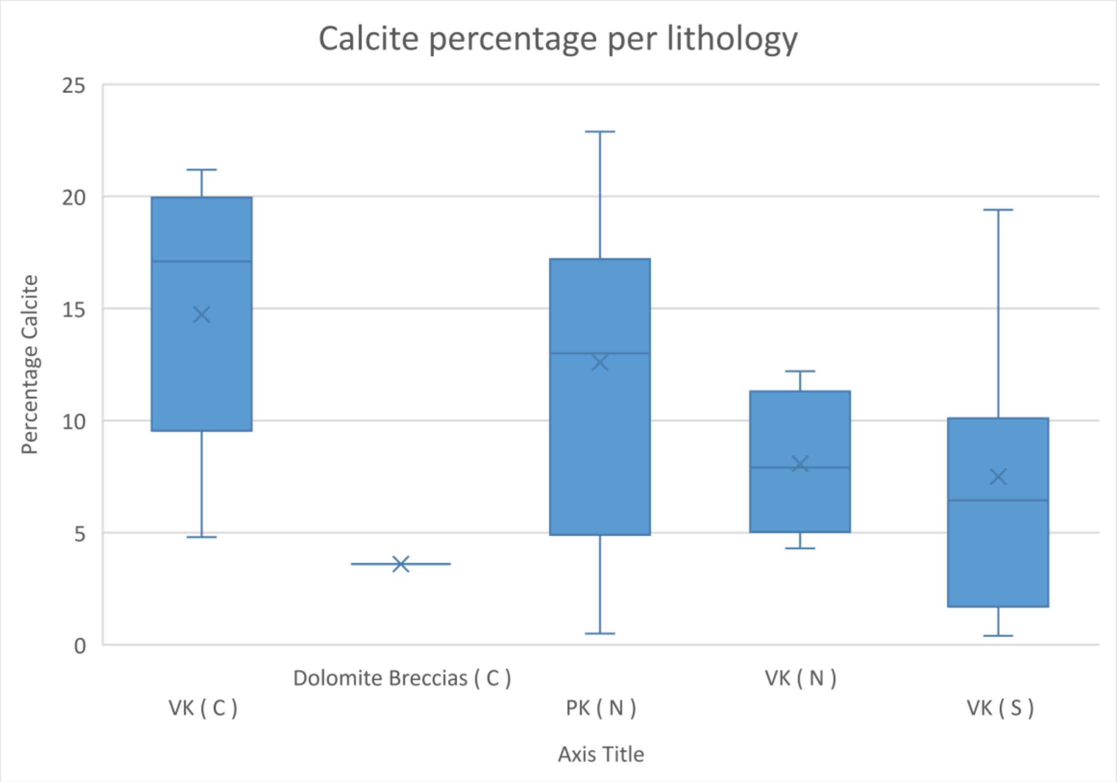
7.2 : Box-and-whisker plot of Smectite percentage per lithology after



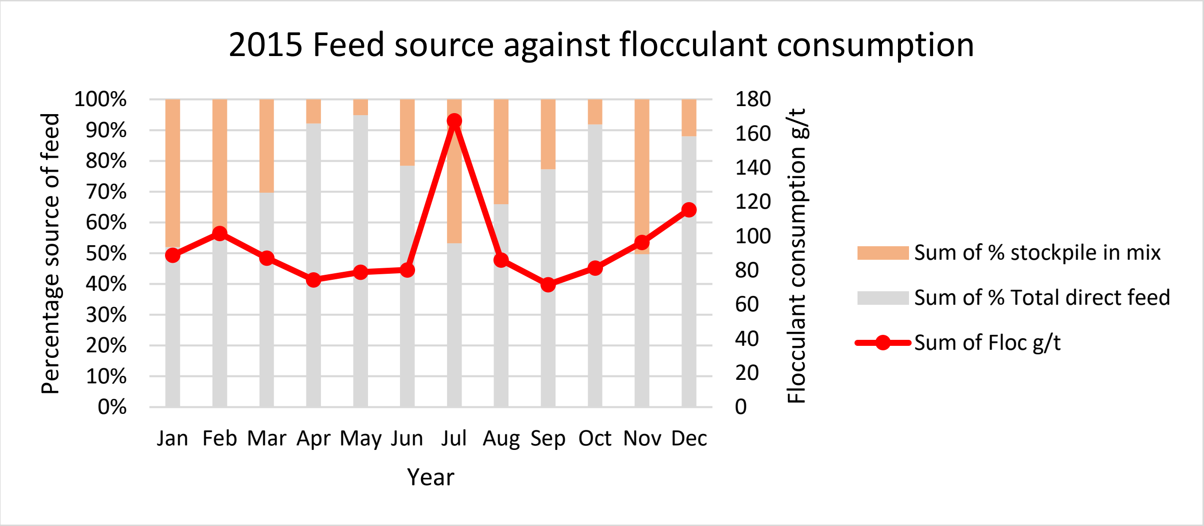
7.3 : Box-and-whisker plot of Serpentine percentage per lithology



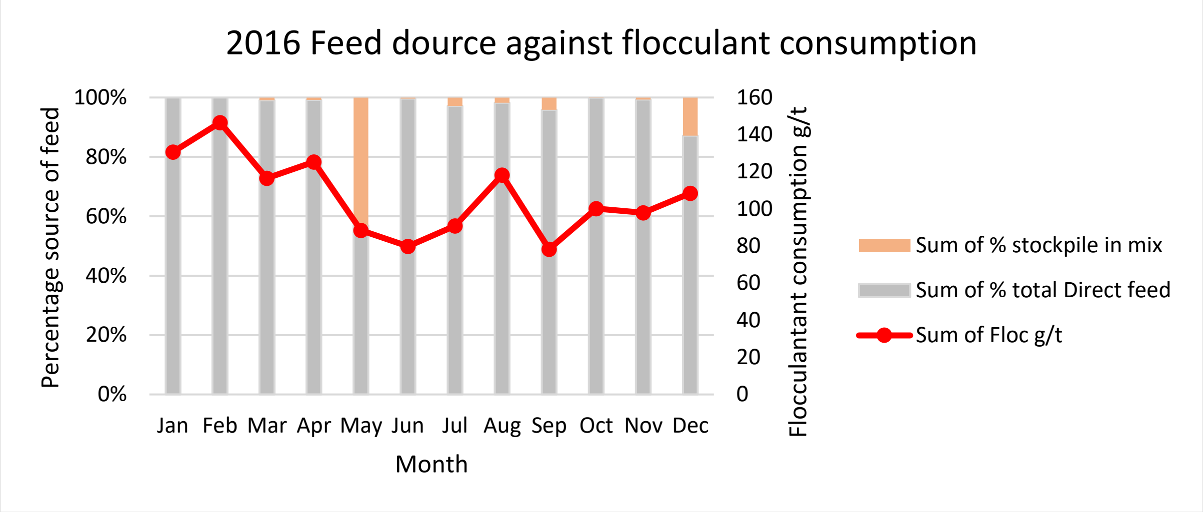
7.4 : Box-and-whisker plot of Serpentine percentage per lithology



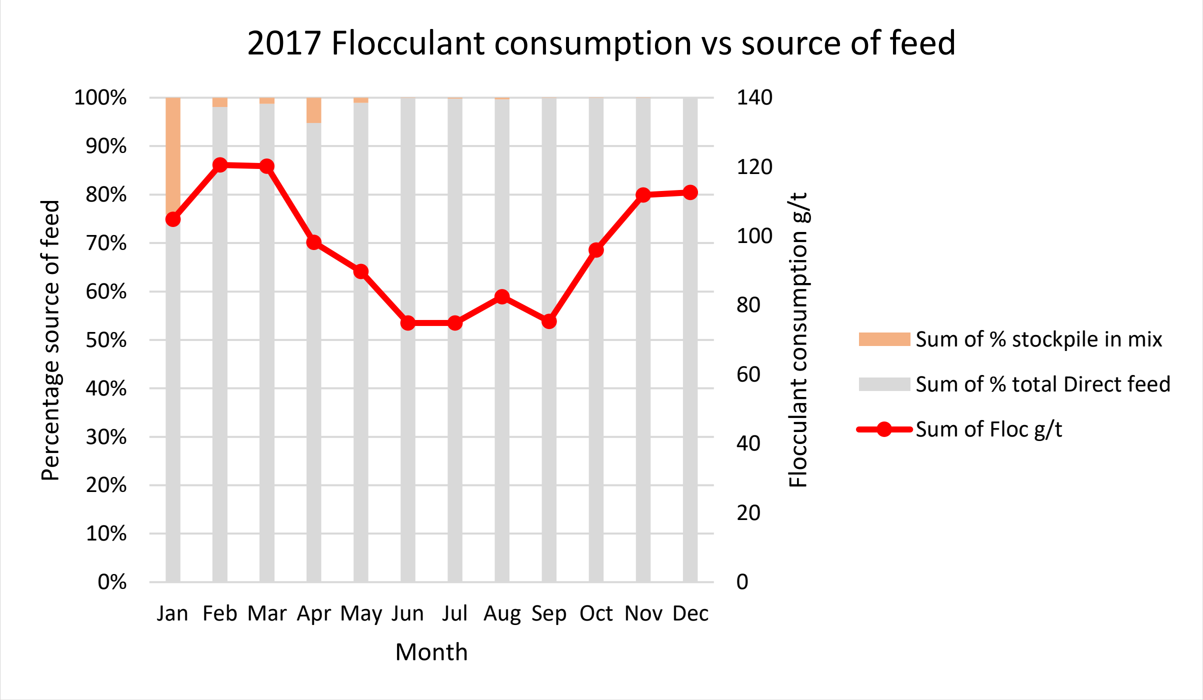
7.5 : 2015 feed source against flocculant consumption



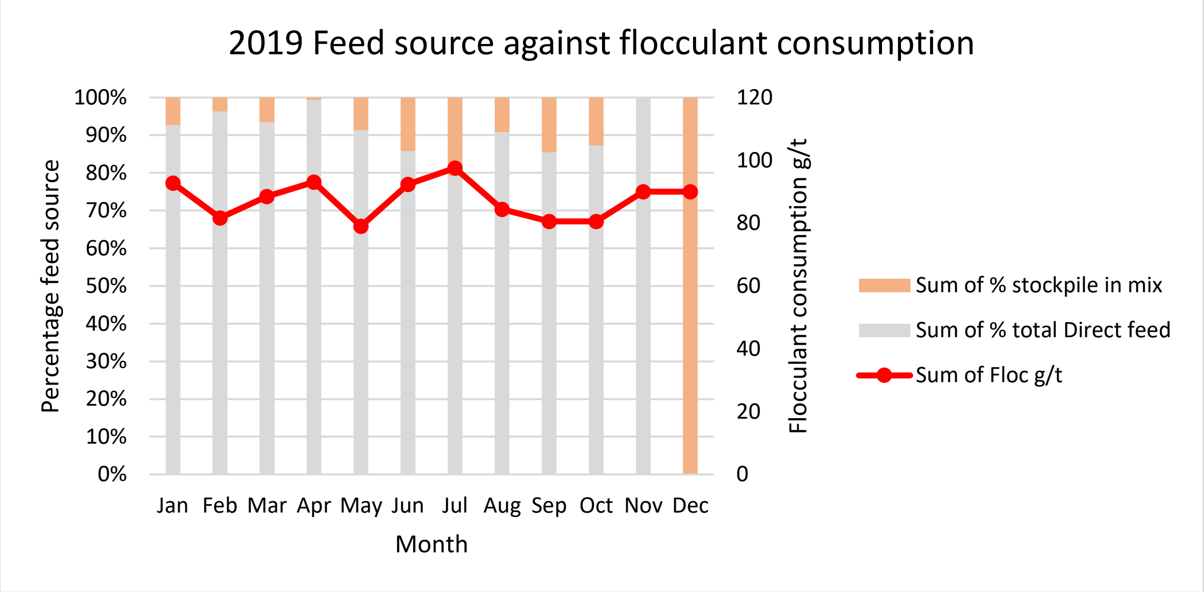
7.6 : 2016 feed source against flocculant consumption



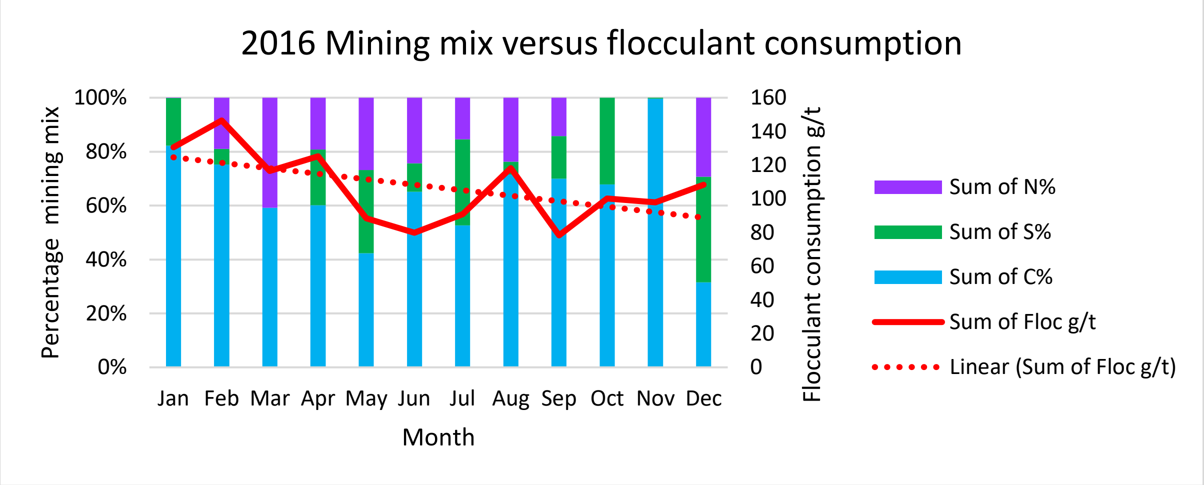
7.7 : 2017 feed source against flocculant consumption



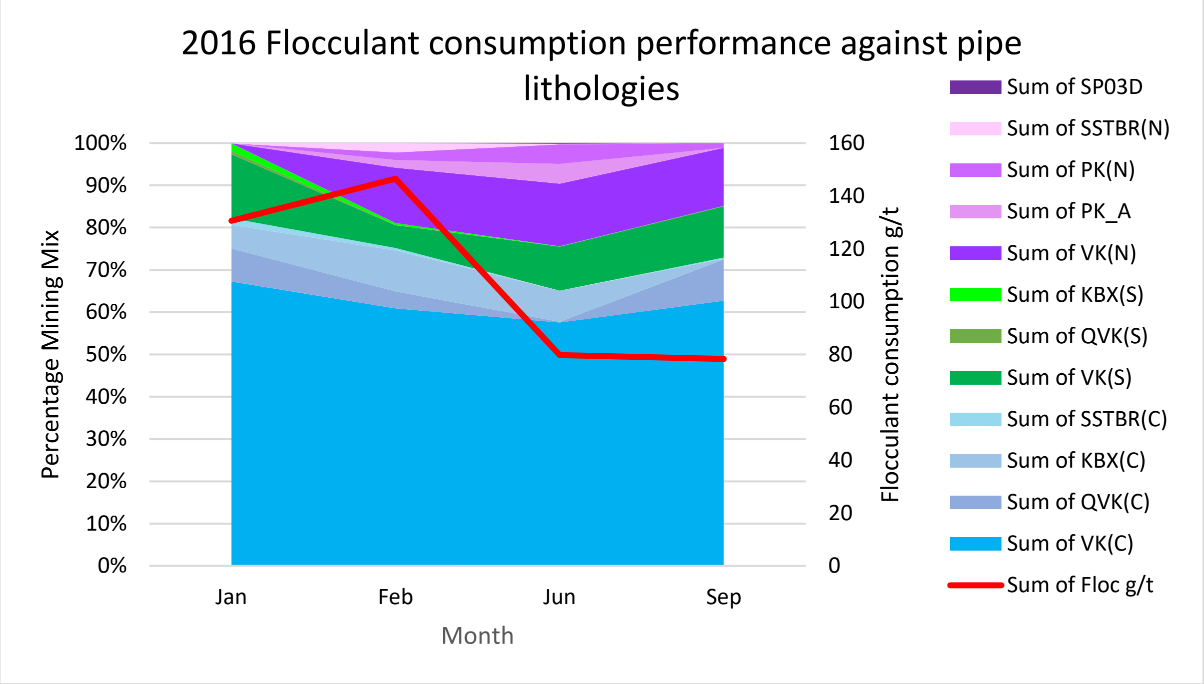
7.8 : 2018 feed source against flocculant consumption



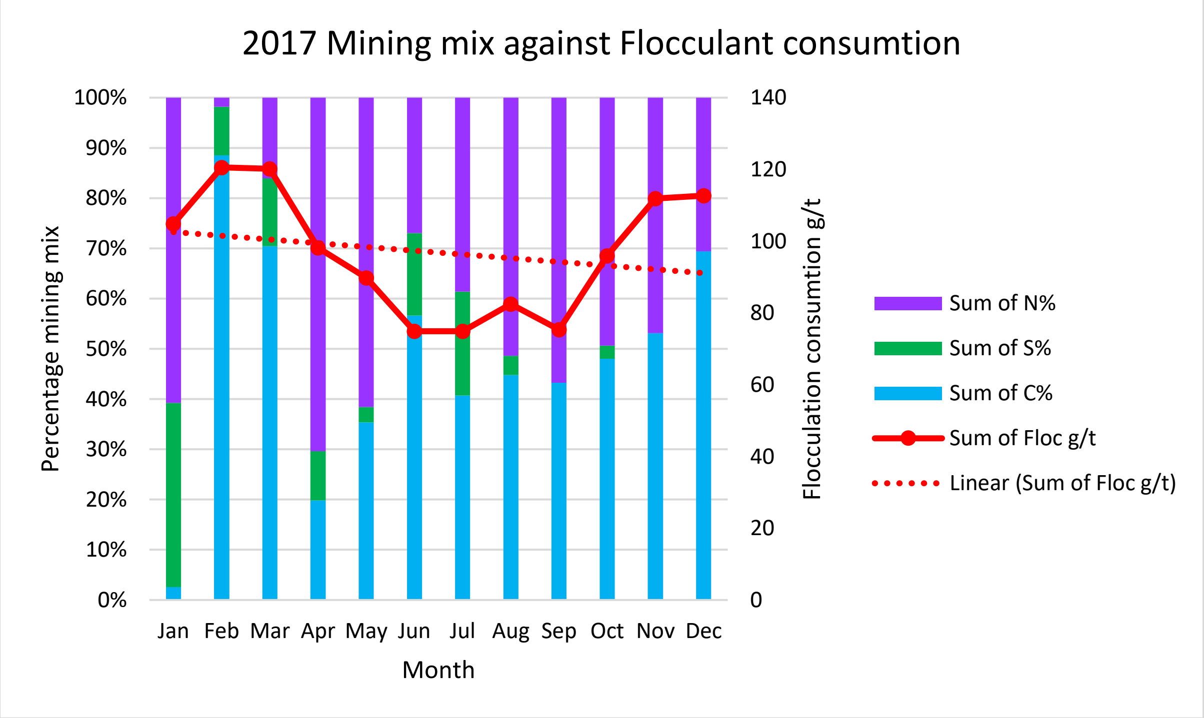
7.9 : 2016 mining mix against flocculant consumption



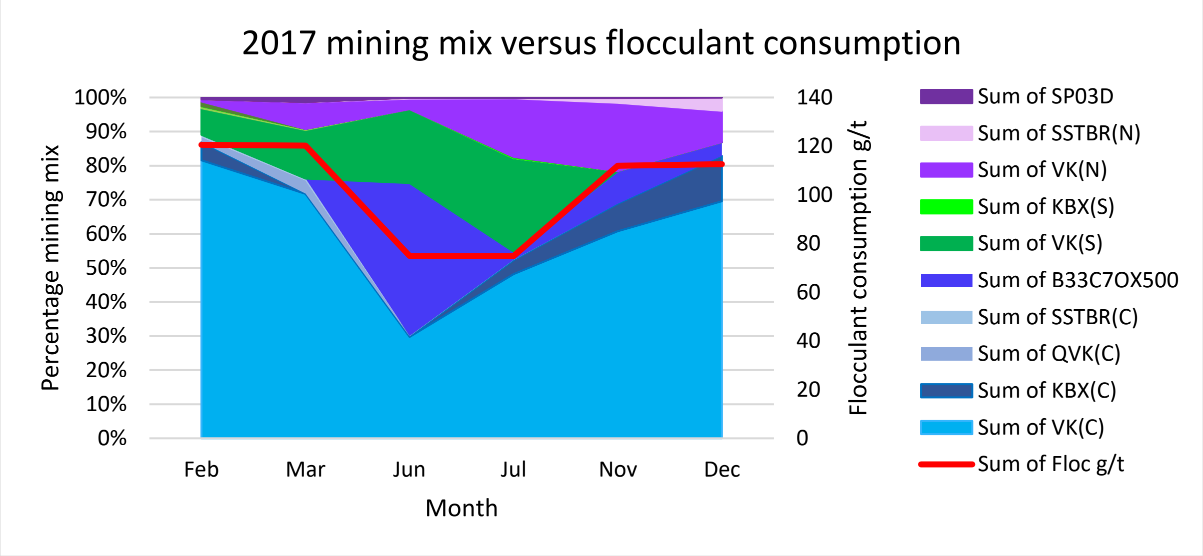
7.10 : 2016 mining mix against flocculant consumption



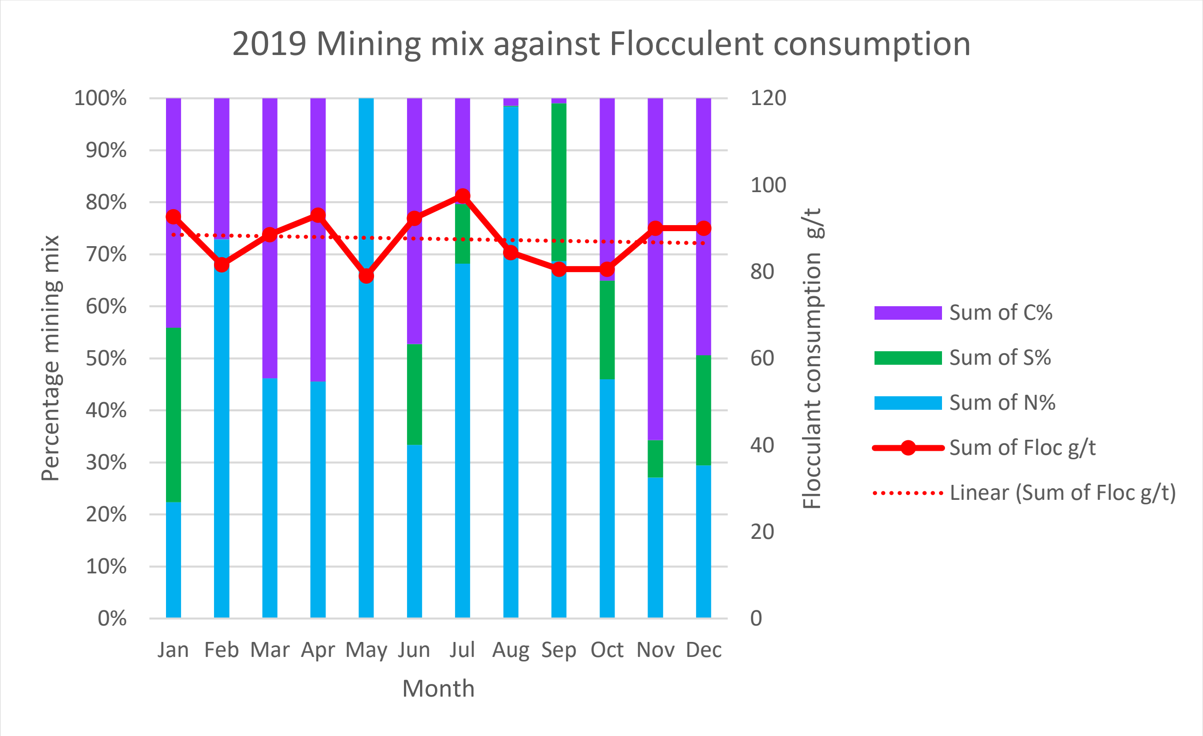
7.11 : 2017 mining mix against flocculant consumption



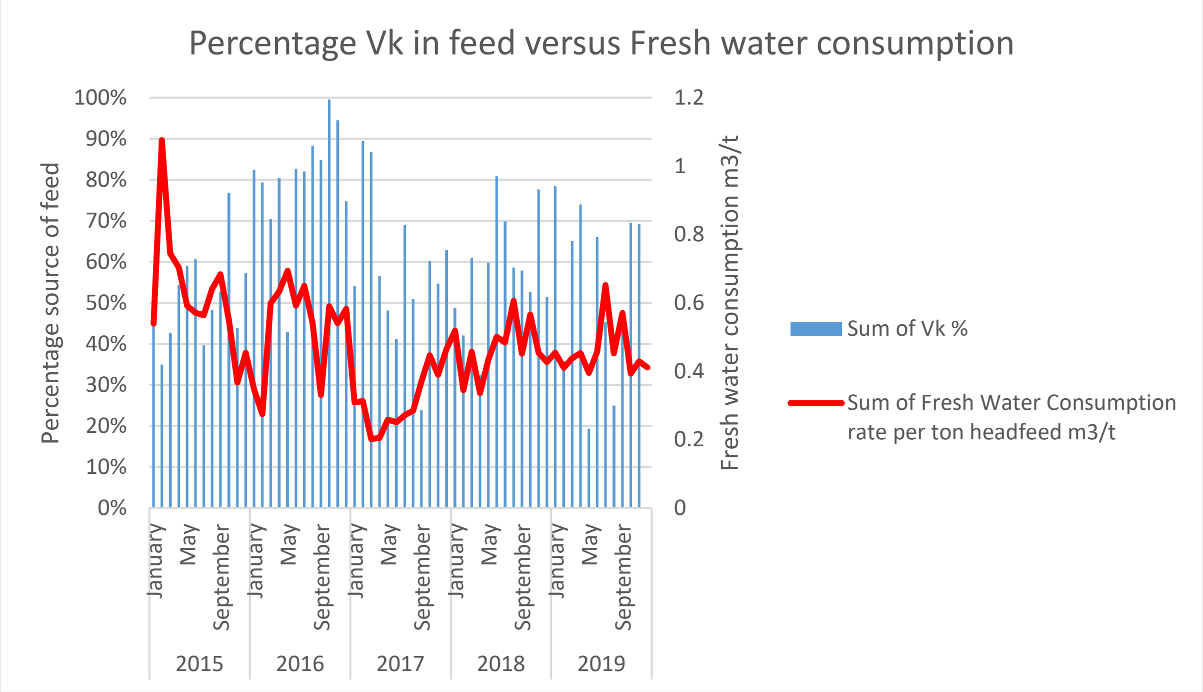
7.12 : 2017 mining mix against flocculant consumption



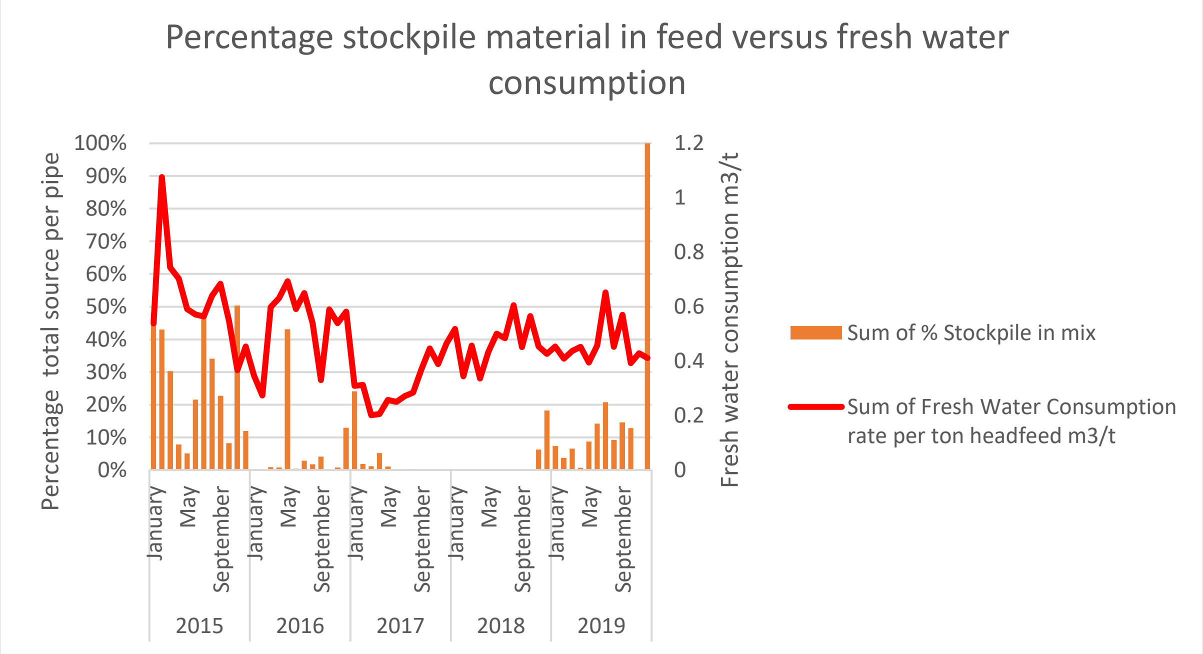
7.13 : 2019 mining mix against flocculant consumption



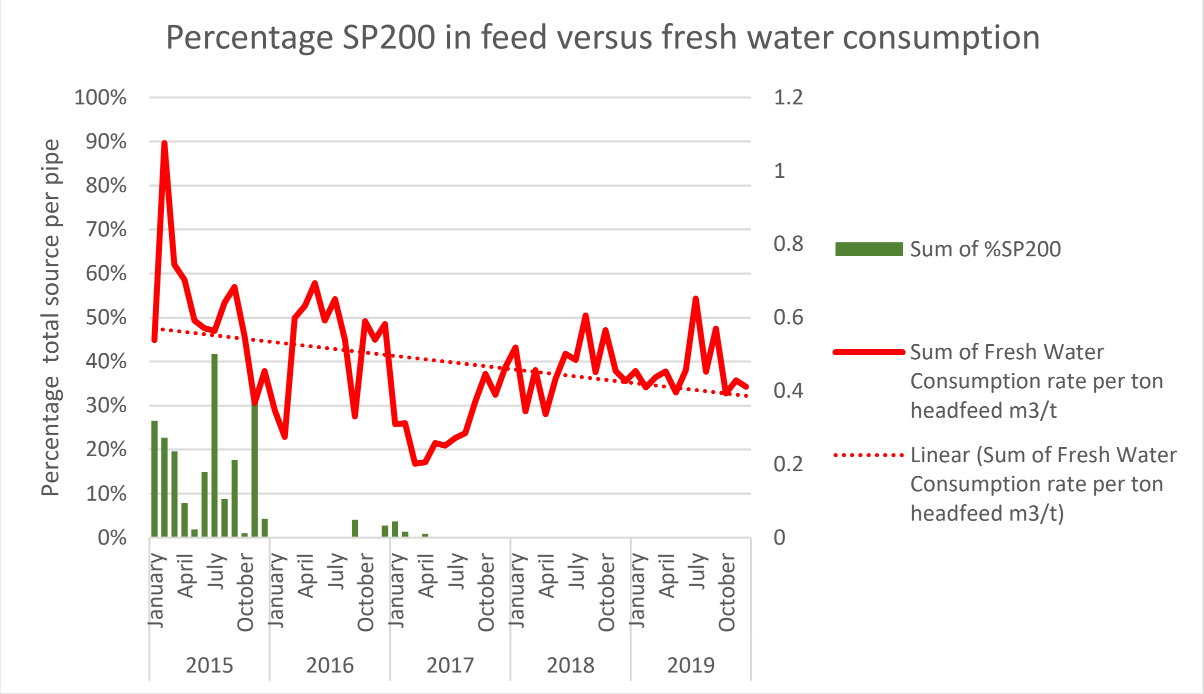
7.14 : Percentage VK in feed versus fresh water consumption



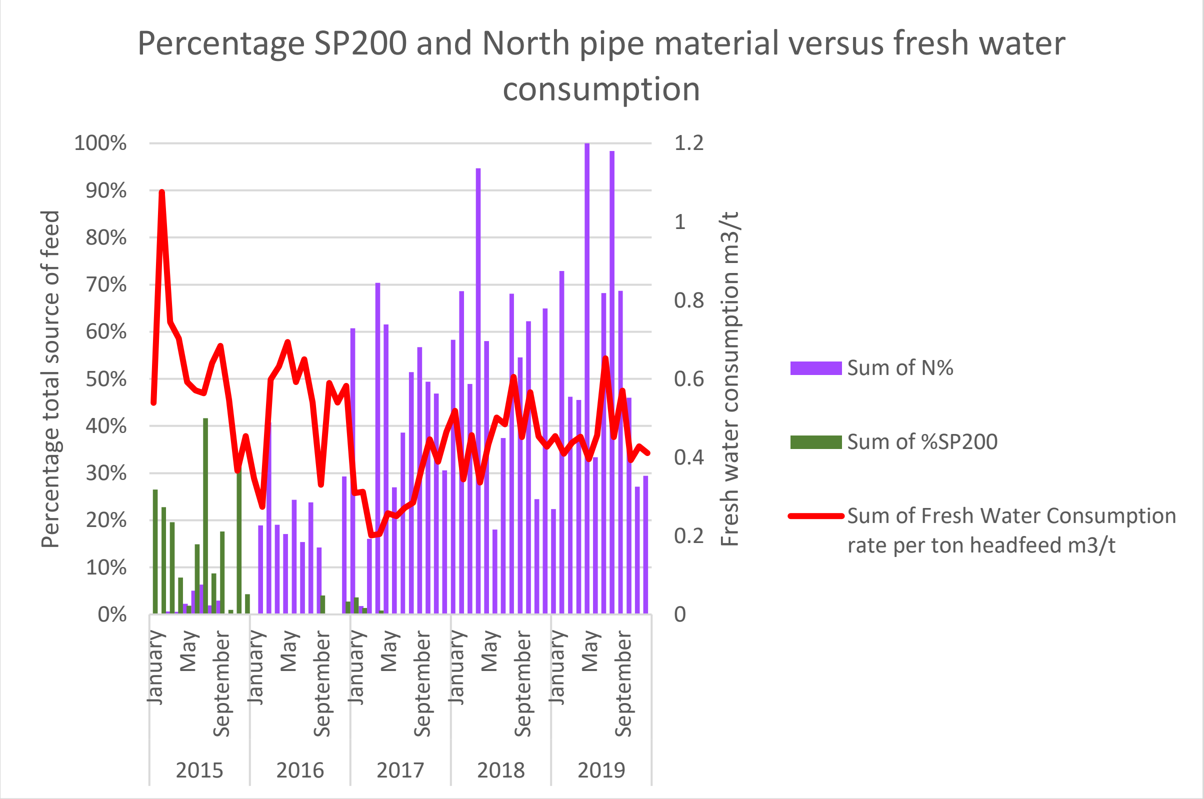
7.15 : Percentage stockpile in feed versus fresh water consumption



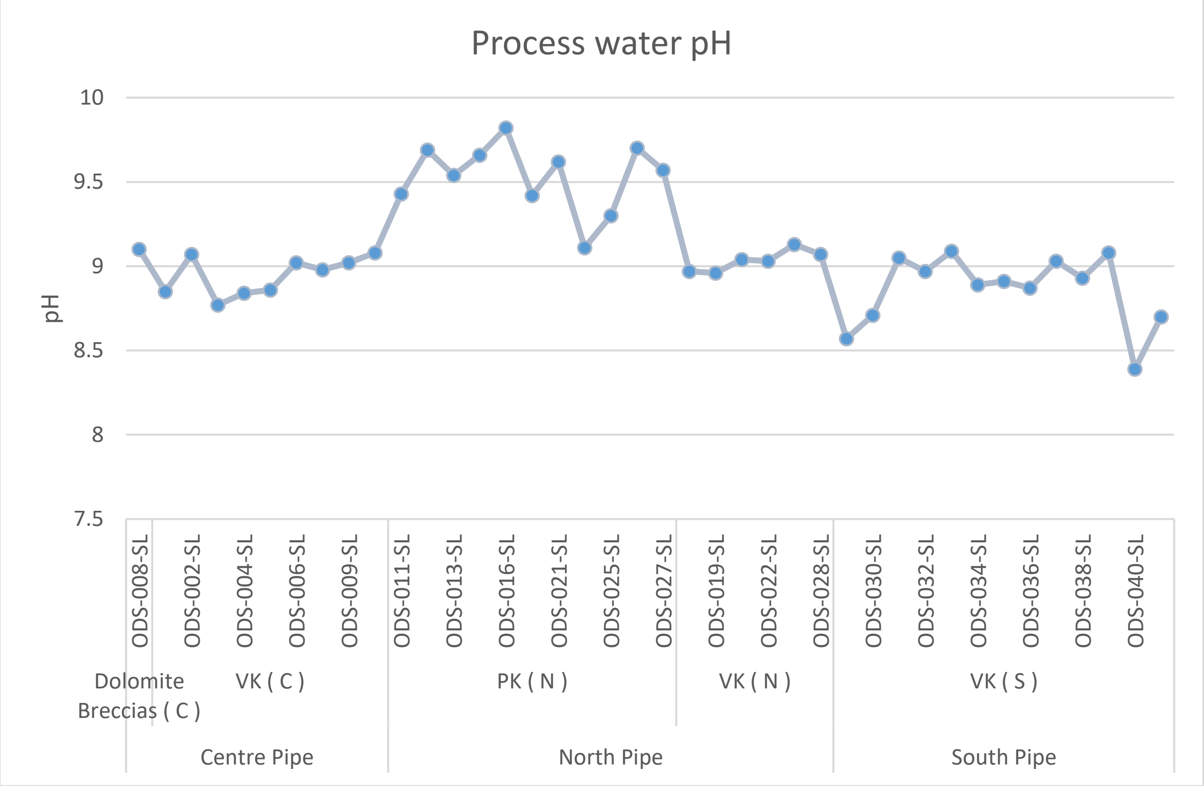
7.16 Percentage SP200 in feed versus fresh water consumption



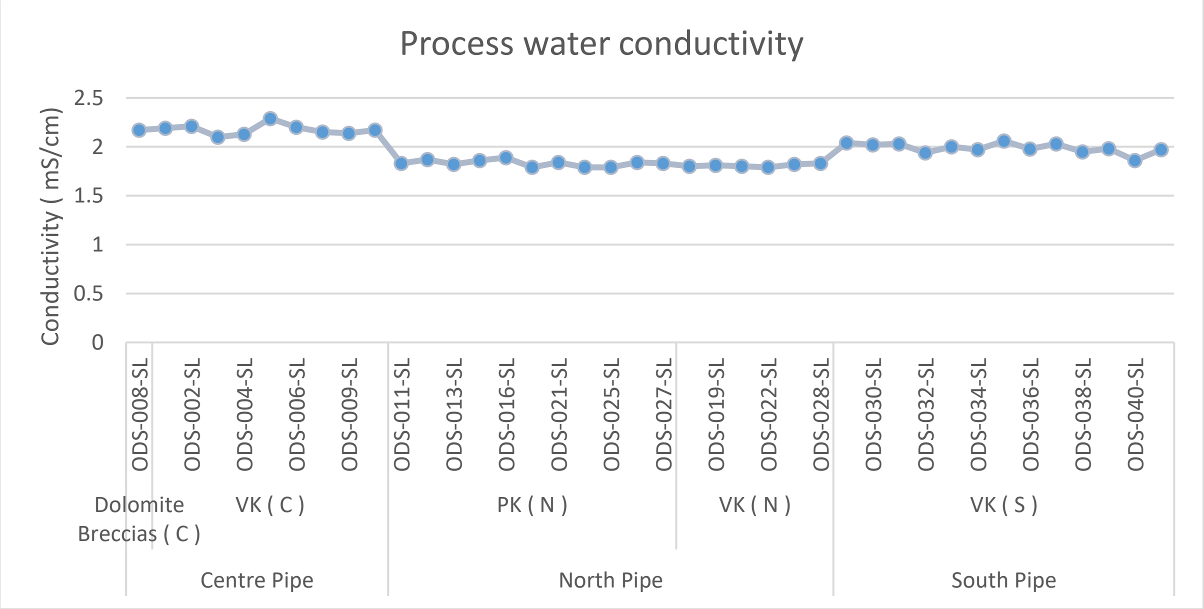
7.17 Percentage SP200 and North pipe in feed versus fresh water consumption



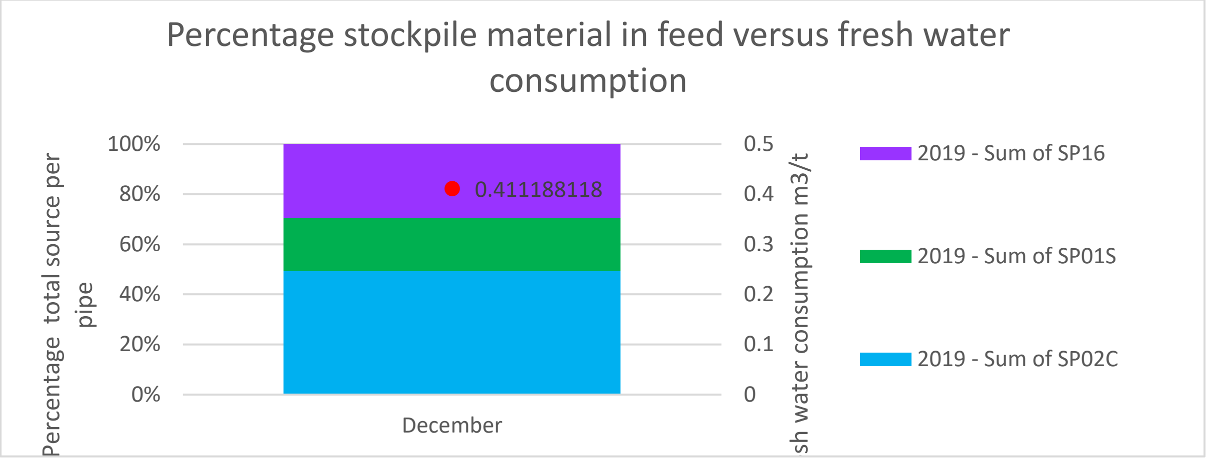
7.18 :ODS process water pH tests



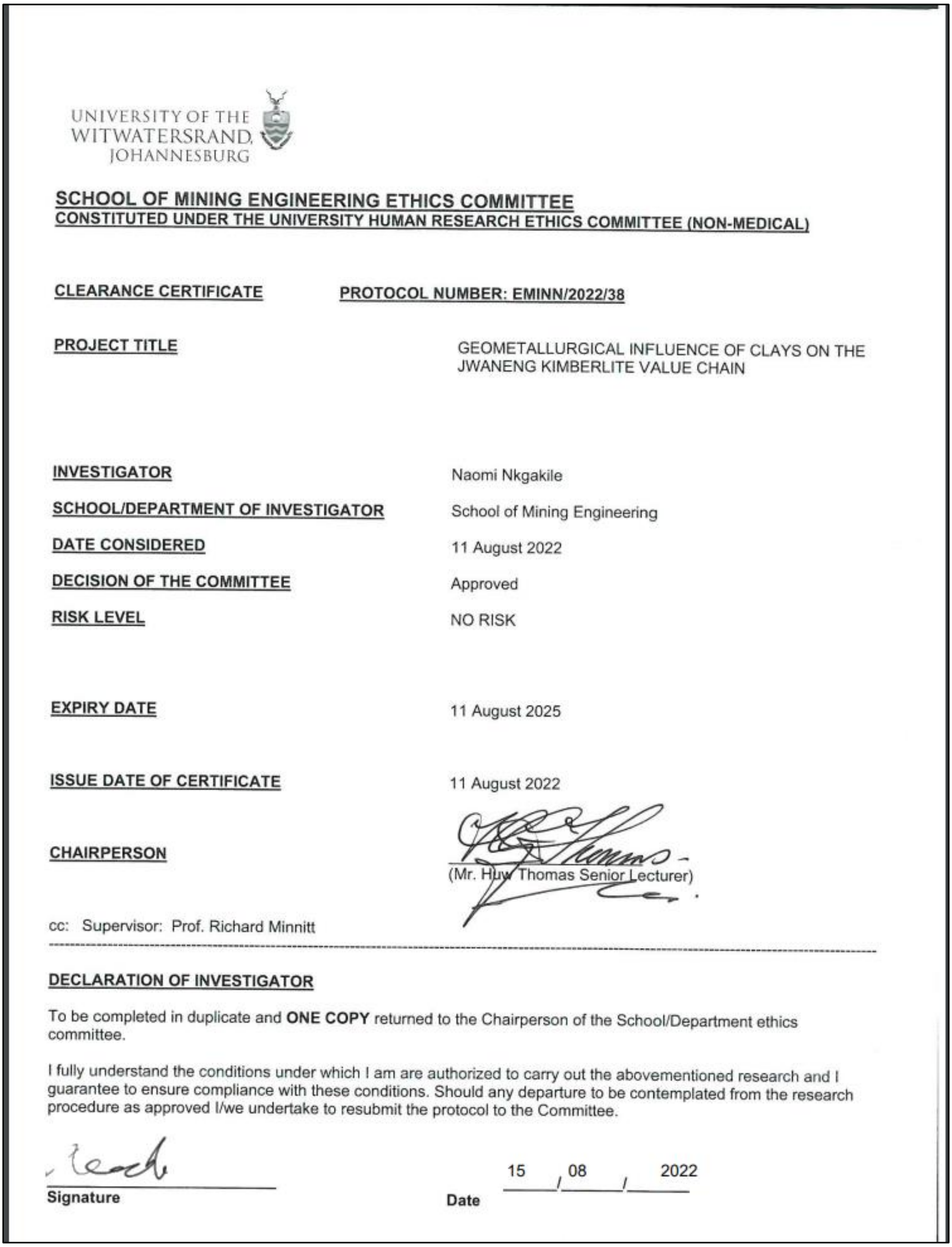
7.19 : ODS process water conductivity tests



7.20 : Percentage stockpile material in feed versus fresh water consumption



7.21 Ethical clearance certificate



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

SCHOOL OF MINING ENGINEERING ETHICS COMMITTEE
CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER: EMINN/2022/38**
PROJECT TITLE	GEOMETALLURGICAL INFLUENCE OF CLAYS ON THE JWANENG KIMBERLITE VALUE CHAIN
INVESTIGATOR	Naomi Nkgakile
SCHOOL/DEPARTMENT OF INVESTIGATOR	School of Mining Engineering
DATE CONSIDERED	11 August 2022
DECISION OF THE COMMITTEE	Approved
RISK LEVEL	NO RISK
EXPIRY DATE	11 August 2025
ISSUE DATE OF CERTIFICATE	11 August 2022
CHAIRPERSON	(Mr. Huw Thomas Senior Lecturer)

cc: Supervisor: Prof. Richard Minnitt

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I fully understand the conditions under which I am are authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

Signature

Date 15 / 08 / 2022