Optimization of the Coal Reserve Utilization at Grootegeluk Mine, Waterberg Coalfield, with regards to the Phosphorus Content in Coal

MSc (50/50) RESEARCH REPORT

Prepared by:

C.W. van Heerden (331858)

Submitted to:

School of Mining Engineering, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, South Africa

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Declaration

I declare that this research report is my own unaided work. It is being submitted in fulfilment of the degree of Master of Science in Engineering (Mining) to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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C.W. VAN HEERDEN

Student Number: 331858

Signed on the ________ day of __________________________ Year ___________

Abstract

Most coal seams in the Waterberg Coalfield contain medium to high levels of phosphorus in coal. Thermal coal, which has a lower value than metallurgical coal, is produced from these coal seams. Metallurgical coal used as feed for char production has especially stringent phosphorous content specifications.

Phosphorous levels vary both laterally and vertically through the coal succession of the Vryheid Formation. If the coal horizons with elevated phosphorus could be identified and selectively removed, significant amounts coal could be saved and utilized as metallurgical coal through the life of the mine. Different mining horizons with regards to their phosphorus content have to be determined to increase the amount of char plant feed coal. Bench definitions and their techno-economic applications are therefore the main purpose of the current investigation.

Bench 11 is currently the only source utilized for char plant feed coal. The char plant is therefore entirely dependent on coal supply from Bench 11. This poses a risk on the continual production of char at Grootegeluk Mine. It was determined that this bench is not suitable for char plant feed coal in certain areas of the resource. A high phosphorus coal horizon was identified in the upper portion of the bench. If this coal is removed separately, the phosphorus content of the coal in the remaining portion of the bench would be suitable for char plant feed coal. This alternative step is dependent on the phosphorus distribution in the resource and may therefore not always be effective. No changes to the other bench definitions could be established that would increase the amount of potential char plant feed coal.

Three further aspects were investigated: The potential to reduce phosphorus in coal by means of coal beneficiation was determined. Results showed that phosphorus levels in coal cannot be lowered sufficiently by means of coal beneficiation. Secondly, the suitability of using different coal analyses to improve the estimation of phosphorus in coal was investigated. Results showed that phosphorus prediction and analyses cannot be enhanced nor replaced by other coal analyses. Lastly, the importance of Zone 1 as a source of low phosphorous coal was investigated.

Zone 1 is currently not part of the mine plan, but if mined, it could be used as a source for blending; thereby increasing the amount of char plant feed coal from the reserves. In certain portions of the resource, utilizing Zone 1 may be the only feasible way of securing the continual supply of low phosphorus content coal.

Analytical exploration borehole data of phosphorus in coal is limited in certain areas of the resource. Due to the variability of phosphorus in the coal horizons, more borehole data is required to increase the estimation accuracy of phosphorus in the coal. Based on such data, mining horizons might be changed in future to secure more char plant feed coal.

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Nomenclature

Borehole grid	A systematic layout of spatial positions at which exploration boreholes are planned to be drilled, in order to obtain the desired borehole coverage of a certain area.
Calorific Value	A measure of the amount of heat energy that is released when coal is combusted, measured in mega joule per kilogram (MJ/kg).
Coal ash	Material that remains after coal has been completely combusted (mineral matter of coal).
Coal beneficiation	A process where rock particles with higher relative density are separated and removed from the coal material in order to improve the carbon content of the remaining coal product. Coal beneficiation is also generally referred to as coal washing.
Coal product	Coal material that was beneficiated at a certain relative density to obtain a desired coal quality.
Coal quality	Coal properties and constituents that are inherently present in coal. Certain coal qualities can generally be improved to a certain extent by means of coal beneficiation.
Coal reserve	The economic, minable *in-situ* coal contained in a mine plan that is scheduled to be extracted during the mine's operating life span and sold to the market.
Coal resource	The *in-situ* coal material that is estimated with reasonable geological reliability and that has reasonable prospects of eventual economic extraction.
Coal yield	The percentage by mass of coal product obtained from an amount of coal material after beneficiation has taken place.
Coal zone	A distinct coal-bearing horizon that can be correlated across the coal deposit in the Waterberg Coalfield.
Char	A carbon-enriched product produced from metallurgical coal by means of a high temperature heating process which drives off the volatile matter of the coal. This process is conducted in the absence of oxygen to avoid combustion of the coal.
Char plant feed coal	A metallurgical coal product with specific coal qualities suitable for the production of char.

Drill chips	The fragments of sample material obtained from a percussion borehole.
Drill core	The solid, cylindrical rock sample obtained from a diamond drilled borehole.
Extrapolation	The estimation of coal quality variables at spatial positions other than the positions of the known data from which the estimation is made, but at locations outside the area in which the known values are present.
Free Swelling Index	A coal property that is required in the process of coke production which describes the degree of swelling that takes place when the coal is heated.
Geological model	A computerized spatial representation of a specific coal quality variable or coal seam parameter in the resource. The variable is presented in the form of a continuous grid across an area of interest. Each grid node in the model carries information of the node's spatial position as well as the value of the representing variable.
Inherent moisture	The moisture remaining in coal after it has been air dried. The inherent moisture of coal can only be driven off by applying heat.
In-situ coal	Coal material as it occurs in its natural state in the earth.
Interburden	Non coal (waste) material that separates different coal seams from each other. The interburden normally needs to be removed separately in order to expose the coal seams.
Interpolation	An estimation of coal quality variables at spatial positions other than the positions of the known values from which the estimation is made, but at locations within the area in which the known values are present.
Inverse distance	An estimation algorithm that uses the inverse of the distance from known data positions as the weighting factor to estimate the values of variables at spatial positions other than the data positions.
Lithological units	Discrete coal and/or rock assemblages that can be correlated across the coal deposit.
Mining bench	A mining horizon comprising coal and/or non-coal material that is mined separately to other horizons.
Metallurgical coal	Coal with suitable qualities and properties for use in metallurgical processes.

Middling coal	The remaining coal product after waste material, as well as the prime coal product has been separated from the run-of-mine by a two stage coal beneficiation process.
Overburden	Non-coal (waste) material at the surface that needs to be removed separately in order to expose the underlying coal seams.
P_2O_5 content	The phosphorus penta-oxide percentage (by mass) present in coal, as determined from the coal ash.
Phosphorus in coal	The elemental phosphorous percentage (by mass) that is present in coal, which is calculated using the P_2O_5 content of the coal ash and the ash content of the coal.
Power station coal	Thermal coal products that are produced for the purpose of being utilized in a coal-fired power station.
Raw coal	Unbeneficiated coal or coal material in its natural state.
Roga Index	A measure used to describe the mechanical strength of coke.
Run-of-mine	Raw coal material that is extracted from the mine and delivered either to a beneficiation plant for further beneficiation or to a coal stockpile
Sample	A stratigraphic unit comprising coal and/or shale assemblages which can be correlated across the deposit.
Semi-soft coking coal	Coal containing limited coking properties, for instance the ability to swell to a certain degree when heated. The coking properties of semi-soft coking coal are less prominent than that of hard coking coal.
Sub-sample	A smaller stratigraphic unit obtained as a result of the vertical subdivision of a sample.
Stratigraphic unit	A discrete rock unit that can be correlated across a specific depositional environment.
Thermal coal	Coal products that are utilized for heat or power generation.
Volatile matter	Light hydrocarbons that are released as gas from coal when the coal is heated to a certain extent.
Washability analyses	Coal analyses performed on coal or shale samples that are produced at different consecutive float densities.
XRF-analyses	X-ray florescence analyses performed on coal ash samples to determine the relative amounts of the constituents (mineral oxides) present in the coal ash.

List of Units and Symbols

ft	foot
g/cc	grams per cubic centimetre
km	kilometre
m	meter
Ma	million years
MJ/kg	mega joules per kilogram
mm	millimetre
R^2	coefficient of determination
tpa	tonnes per annum
°	degrees (of angle)
°C	degrees Celsius
%	percentage (by weight)
~	approximately

1 Introduction

1.1 Phosphorous and how it impacts on operations at Grootegeluk Mine

Phosphorus is a non-metallic chemical element with symbol P and atomic number 15. Phosphorus in its mineral form is almost always present in its maximally oxidised state, as inorganic phosphatic rocks. Elemental phosphorus exists in two major forms, white phosphorus and red phosphorus, but due to its high reactivity, phosphorus is never found as a free element on earth. Phosphorus is essential for life. As phosphate, it is a component of DNA, RNA, ATP, and also the phospholipids that form all cell membranes. Demonstrating the link between phosphorus and life, elemental phosphorus was historically first isolated from human urine, and bone ash was an important early phosphate source. Low phosphate levels are an important limit to growth in some aquatic systems. The chief commercial use of phosphorus compounds is for the production of fertilisers due to the need to replace the phosphorus that plants remove from the soil. (Internet: https://en.wikipedia.org/wiki/Phosphorus, 2014).

From the aforementioned facts, it is evident that plants need phosphorous to grow, suggesting they require or store phosphorous in their cell structures. Since coal originates from plant material, it is understandable that coal also contains varying concentrations of phosphorous. These concentrations of phosphorous in coals may vary according to various factors that had an influence on the plants from which the coal originated, as well as external factors controlling the environment in which the plants grew and in which the coal formation took place.

Coal is used extensively in the steel and ferro-alloy industry as a reductant in the smelting processes and as a source of energy during the combustion processes. These processes have to meet certain specifications with regards to the phosphorus content of the feed coal. Excessive phosphorus in the feed coal has major detrimental effects on a product's usage. During the smelting process of metals, phosphorus in the coal reports to the metal, resulting in differential weaknesses in the metal. Detrimental effects of phosphorus in steel include various forms of embrittlement which reduce the toughness and ductility of the steel. (Internet: www.keytometals.com, 2014).

Elevated phosphorus increases the hardness of steel. In cement manufacturing, the presence of phosphorus results in reduced quality and strength of the cement. These detrimental effects associated with the presence of phosphorus in coal has led to phosphorus content becoming one of the most important parameters in terms of coal quality with respect to its use in the metallurgical industry and for other purposes. (Internet: www. keytometals.com, 2014).

Phosphorus is an intrinsic element in coal macerals and therefore cannot be easily removed by coal beneficiation. It is thus important to identify suitably low phosphorous coal seams or low phosphorous coal horizons within coal seams, since these coals are limited in South Africa and in high demand in the metallurgical industry. For this reason, low phosphorous metallurgical coal is of much higher value than ordinary thermal coal. Low phosphorus coal has to contain less than 0.01% phosphorus; medium phosphorus coal has between 0.01% and 0.1% phosphorus and coal exceeding 0.1% phosphorus is generally classified as high phosphorus coal.

Most coal seams of the Waterberg Coalfield cannot be utilized as metallurgical coal due to their high phosphorus content, resulting in the majority of production being thermal coal. Metallurgical coal used as feed coal for the production of char has especially stringent phosphorus content specifications because the phosphorous in the coal remains intact through the charring process. This and the fact that the volatile matter is driven off has an amplified effect on the percentage of phosphorous in the final product.

Exxaro recently endeavoured to enter the reductant market and increase the value-add of its coal reserves at Grootegeluk Mine by expanding its existing suite of coal products through the production of char. Char is a high value downstream product produced from low phosphorous metallurgical coal and is used as a reductant in the ferro-alloy industry.

Bench 11 is currently the only mining bench that is utilised for char plant feed coal at Grootegeluk Mine due to its relatively low phosphorus content. All other coal benches that are extracted contain phosphorous which is too high for the production of char plant feed coal. The char plant at Grootegeluk Mine is therefore entirely dependent on coal supply from Bench 11. It is known that Bench 11 will not supply coal suitable for char plant feed throughout the life of the mine. This poses a risk in terms of the continual production of char. It is therefore important to establish a sound knowledge about the phosphorous distribution through Bench 11, as well as that of the other metallurgical coal seams at Grootegeluk Mine in order to find alternative measures to mitigate the risk of relying on Bench 11 for char plant feed coal.

A thorough study of the lateral and vertical phosphorous distribution of all the Vryheid Formation coal seams is therefore required. This approach will be based on findings by Ryan and Greave (1996) that it is difficult to remove phosphorous from coal by conventional washing techniques. “It is therefore important, in metallurgical coal mines, to understand the distribution of phosphorus in the coal seams, because blending of the run-of-mine coal, rather than washing, may be the best way of controlling the amount in clean coals.” (Ryan and Grieve, 1996, p 277).

The results from this study might determine the appropriateness of introducing different mining horizons (mining bench definitions) at Grootegeluk Mine in order to increase the amount of low phosphorous coal and subsequently improving the resource utilization and the economic value-add of the mine. Before any changes in existing bench definitions can be considered, a good knowledge of the phosphorus distribution in the different coal seams is required. This is currently the limiting factor. Bench definitions and their techno-economic applications are therefore a requirement of the current investigative research.

1.2 Research Objectives

The purpose of this research is to investigate the potential to produce more low phosphorus metallurgical coal from the coal reserves at Grootegeluk Mine. This may optimize the reserves utilization and ultimately increase the value-add of the mine.

This investigative research has two main objectives. Firstly, to evaluate the suitability of the current mining benches with regards to their phosphorous content, in order to supply coal of suitably low phosphorous content to the char plant. To achieve this, the phosphorous content of the different coal seams of the Vryheid Formation needs to be investigated.

The second objective is to establish the lateral and vertical distribution of phosphorous in the coal seams of the Vryheid Formation. The results obtained from this work may determine the appropriateness to establish practical selective mining horizons from the different coal seams which could be utilized to produce low phosphorous coal that is suitable for current and future char production.

In addition to the main objectives, three further aspects will be investigated to enhance this research. Firstly, the possibility of reducing phosphorus in coal by means of coal beneficiation will be reviewed. According to Ryan and Grieve (1996), it is difficult to remove phosphorous from coal by means of conventional washing techniques (coal beneficiation). Secondly, the occurrence of phosphorous in coal in relation to other coal quality parameters will be investigated. These findings could lead to an improvement of the estimation accuracy of phosphorous in coal, especially in those areas of the resource where phosphorous data is limited. The third aspect to enhance this research is to determine the potential of Zone 1 as a source of low phosphorous blend coal. Zone 1 could possibly be used to lower the phosphorus of the run-of-mine mix to the required level.

1.3 Hypothesis

The hypotheses that will be tested through this investigative research are the following:

- Geological models based on sample units across Grootegeluk Mine's resource area will provide the means for selecting mining benches that are of suitably low phosphorus content to provide feed coal for the char plant.
- The coal reserves at Grootegeluk Mine can be optimized by means of selective mining to produce coal of suitably low phosphorous content for the production of char plant feed coal.
- The phosphorus content in the coal at Grootegeluk Mine cannot be sufficiently reduced by means of coal beneficiation for use as char plant feed coal.
- The phosphorus content in coal cannot be associated with other coal quality parameters and therefore these coal qualities cannot be used to compensate for proper phosphorous analyses nor enhance the existing phosphorous analyses.
- The amount of low phosphorous metallurgical coal at Grootegeluk Mine can be increased by blending coal of the existing mining benches with coal from Zone 1.

1.4 Key questions to be addressed

The key questions to be addressed by this investigative research are the following:

- What is the phosphorus content of the different mining benches of the Vryheid Formation at Grootegeluk Mine?
- How does the phosphorous content vary laterally in the mining benches across the resource area pertaining to Grootegeluk Mine?
- What is the phosphorus content of the individual sample units pertaining to the Vryheid Formation mining benches at Grootegeluk Mine?
- How is the phosphorous content distributed vertically through Bench 11?
- Is it possible to selectively remove the high phosphorous coal horizon from Bench 11, therefore lowering the phosphorous in the coal of the remaining portion of the bench to levels suitable for char plant feed coal?
- Can geological models provide the information needed to determine selective mining horizons with regards to the phosphorus content?
- Is it possible to suitably lower the phosphorous content of the run-of-mine coal by means of coal beneficiation?
- To what extent is coal beneficiation required to produce coal that is within the phosphorous specification for char production?
- Do any relationships exist between the occurrence of phosphorous in coal and other coal quality parameters?
- Can other coal quality parameters be used to supplement the estimation of phosphorous in coal?
- Is it possible to lower the phosphorous concentrations in the Vryheid Formation coal benches to suitable levels required for char plant feed coal, by blending it with coal from Zone 1?
- At what ratios should the Vryheid Formation coal benches be blended with coal from Zone 1 to produce a run-of-mine blend that contains suitably low phosphorous levels for the production of char plant feed coal?

1.5 Background of the operation at Grootegeluk Mine

1.5.1 Location

Grootegeluk Mine, a wholly owned subsidiary of Exxaro Resources Ltd, is situated in the Waterberg Coalfield, in the north-western part of the Limpopo Province of the Republic of South Africa. It is located within the Lephalale magisterial district. The Botswana border is 40 km north of the Mine, delineated by the Limpopo River (Figure 1).

1.5.2 Description of the operation

Grootegeluk Mine is a surface coal mining operation on a shallow, open-cast portion of the Waterberg Coalfield. A series of parallel mining benches are advancing progressively across the deposit by a process of drilling, blasting, loading and hauling with truck and shovel fleets. Overburden and interburden waste is being backfilled within the mined-out excavation of the open pit.

Since the commissioning of Grootegeluk Mine in 1980, it has remained the only operating coal mine in the Waterberg Coalfield. The mine was originally developed to produce low-ash semi-soft coking coal from the upper vitrinite-rich Volksrust Formation which was utilized as a reductant in Iscor's steel production process. The Eskom-owned Matimba power station was later built in close proximity to the mine to utilize the "middling coal" or medium quality coal for power generation.

As the mine continued to operate, the lower coal seams of the Vryheid Formation became progressively exposed. Metallurgical coal products and power station coal are produced from these coal seams. Char is also produced on site at a char processing plant consisting of four retorts. These use low phosphorus metallurgical coal at 15% ash, produced at Grootegeluk as the feedstock material. The current char plant has a production capacity of 140 000 tpa of char. The char produced at Grootegeluk is sold as a reductant which is used in the ferro-manganese, titanium and platinum industries. Plans are in place to expand the char plant from the current four retorts to twelve retorts. This will triple the char plant's production capacity, indicating that it will also require three times as much low phosphorus metallurgical coal as feed coal in order to maintain full production.

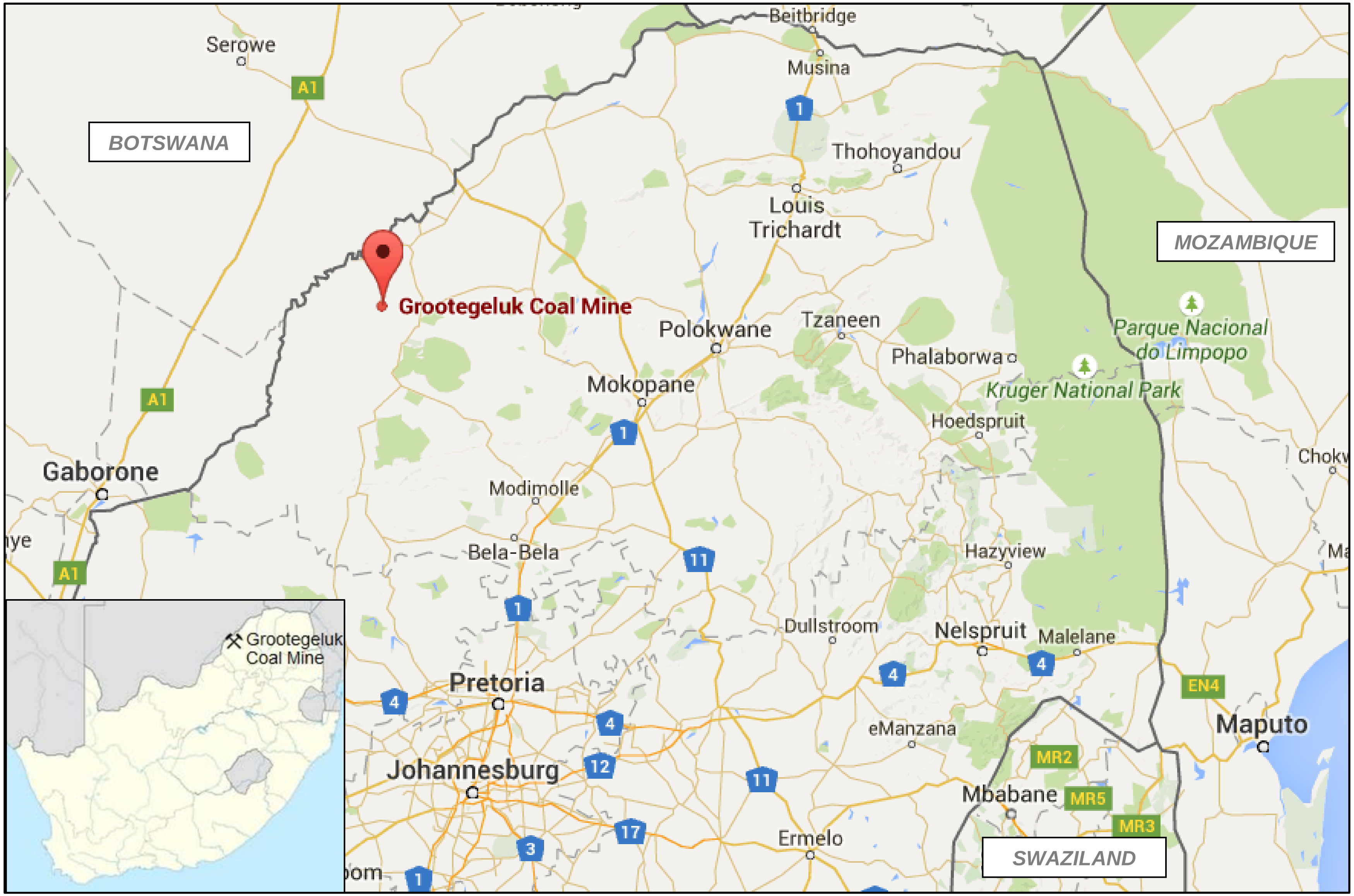

Figure 1 **Locality map of Grootegeluk Mine** **(Adopted from internet: https://www.google.co.za/maps/place/Grootegeluk+Coal+Mine)**

1.5.3 Local geology

Numerous coal seams occur over a stratigraphic thickness of at least 115 m. These coal seams are subdivided into 11 coal zones which are further divided into separate coal and non-coal samples for analyses. A total of 75 samples are correlated and analysed per full succession exploration borehole, consisting of 29 coal samples and 29 non-coal samples for the Volksrust Formation and 13 coal samples and 4 non-coal samples for the Vryheid Formation. Specific sample combinations, based on each unit's physical and chemical properties and/or coal product specifications, form the 14 mining benches for both saleable products and waste that are currently in use at Grootegeluk Mine. In this way the run-of-mine for each bench is reserved for specific beneficiation destinations in order to produce coal products with specific characteristics and of specific coal qualities. The association between the coal zones, samples and mining benches at Grootegeluk Mine is provided in Table 1.

Table 1 Relationship between coal zones, sample units and mining benches

FORMATION	COAL ZONE	SAMPLE	BENCH
VOLKSRUST	Topsoil and Shale*	Not sampled	Bench 1A (Overburden)
	Zone 11	1A, 1B (upper shale)	Bench 1B (Overburden)
		1B (bottom), 1C, 1D	Bench 2
	Zone 10	2, 3, 4, 5, 6	
	Zone 9	7, 8, 9	Bench 3
	Zone 8	10, 11, 12, 13, 14	
	Zone 7	15A, 15B, 16, 17, 18	Bench 4
	Zone 6	19, 20, 21	
	Zone 5	22A, 22B, 22C, 22D, 22E	Bench 5
	Shale Interburden*	22FS	
VRYHEID	Zone 4	23A, 23B, 23C	Bench 6
	Shale Interburden*	23AS, 23BS	Bench 7A (Interburden)
	Zone 4A	24	Bench 7B
	Shale and Siltstone Interburden*	24S	Bench 8 (Interburden)
	Zone 3	25, 25S, 26	Bench 9A
		27, 28, 29	Bench 9B
	Sandstone Interburden*	Not sampled	Bench 10 (Interburden)
	Zone 2	30A, 30B, 31	Bench 11
	Sandstone Interburden*	Not sampled	Not mined presently
	Zone 1	32	Not mined presently

* Not part of coal zones (Interburden waste)

1.5.4 Regional geology

1.5.4.1 Stratigraphy

The Waterberg Coalfield is part of the late Palaeozoic to early Mesozoic (~ 290 Ma - 180 Ma) Karoo Sequence which was formed in the Great Gondwana Basin which covered parts of Southern Africa, India, Antarctica, Australia and South America. Subdivision of the Karoo Sequence as encountered in the Waterberg Coalfield is based mainly on lithological boundaries. All the “classical” units of the Karoo Sequence are present in the Waterberg Coalfield. The exception is the Volksrust Formation where the lithological units comprise intercalated bright coal and carbonaceous mudstone. This Formation represents the seams that contain the majority of the coal resources and reserves at Grootegeluk Mine. The subdivisions of the Karoo Sequence encountered at Grootegeluk Mine are presented in Table 2.

1.5.4.2 Structural setting

The Zoetfontein fault forms the northern boundary of the Waterberg Coalfield, and the Eenzaamheid fault forms the southern boundary. The Daarby fault, with a throw of approximately 350 m, divides the Waterberg Coalfield into a deep north-eastern portion and a shallow south-western portion. The first fresh coal in the shallow south-western portion is on average approximately 20 m below surface. The lowermost coal seam (Zone 1) occurs at a depth of about 130 m below surface in the shallow portion of the coalfield, but this may vary depending on the local structure. The predominantly horizontal coal bearing formations have a very gentle dip towards the south-east in the vicinity of Grootegeluk Mine. Only a few dolerite dykes outcrop in the south-eastern portion of the Waterberg Coalfield and no sills have been encountered in any of the exploration boreholes drilled within the mine lease area to date. A geological map of a portion of the Waterberg Coalfield in the vicinity of Grootegeluk Mine is presented in Figure 2.

Table 2 Stratigraphy of the Karoo Sequence

GROUP	FORMATION (SACS, 1980)	FORMATION (Cilliers, 1951)	Representative Rock Type	Average Thickness
STORMBERG	Drakensberg Basalt	Drakensberg	Lava, purplish to red, amygdaloidal	95 m
	Clarens Sandstone	Cave Sandstone	Sandstone, fine grained, white to yellow-brown to reddish	80 m
	Elliot	Red Beds	Mudstone, red to chocolate brown, clayey	90 m
	Molteno	Molteno	Sandstone, white, medium to coarse grained, scattered pebbles	15 m
BEAUFORT	Beaufort	Beaufort	Mudstone, purple and greenish grey, alternating at top, light grey at base	90 m
ECCA	Volksrust Shale	Upper Ecca	Intercalated shale and bright coal	60 m
	Vryheid	Middle Ecca	Sandstone and grit, intercalated carbonaceous shale, siltstone, few thick coal seams, mainly dull	55 m
	Pietermaritzburg Shale	Lower Ecca	Shale and sandstone, grit in lower portions	150 m
DWYKA	Dwyka	Dwyka	Tillite	3 m

(Adopted from Dreyer, 1994)

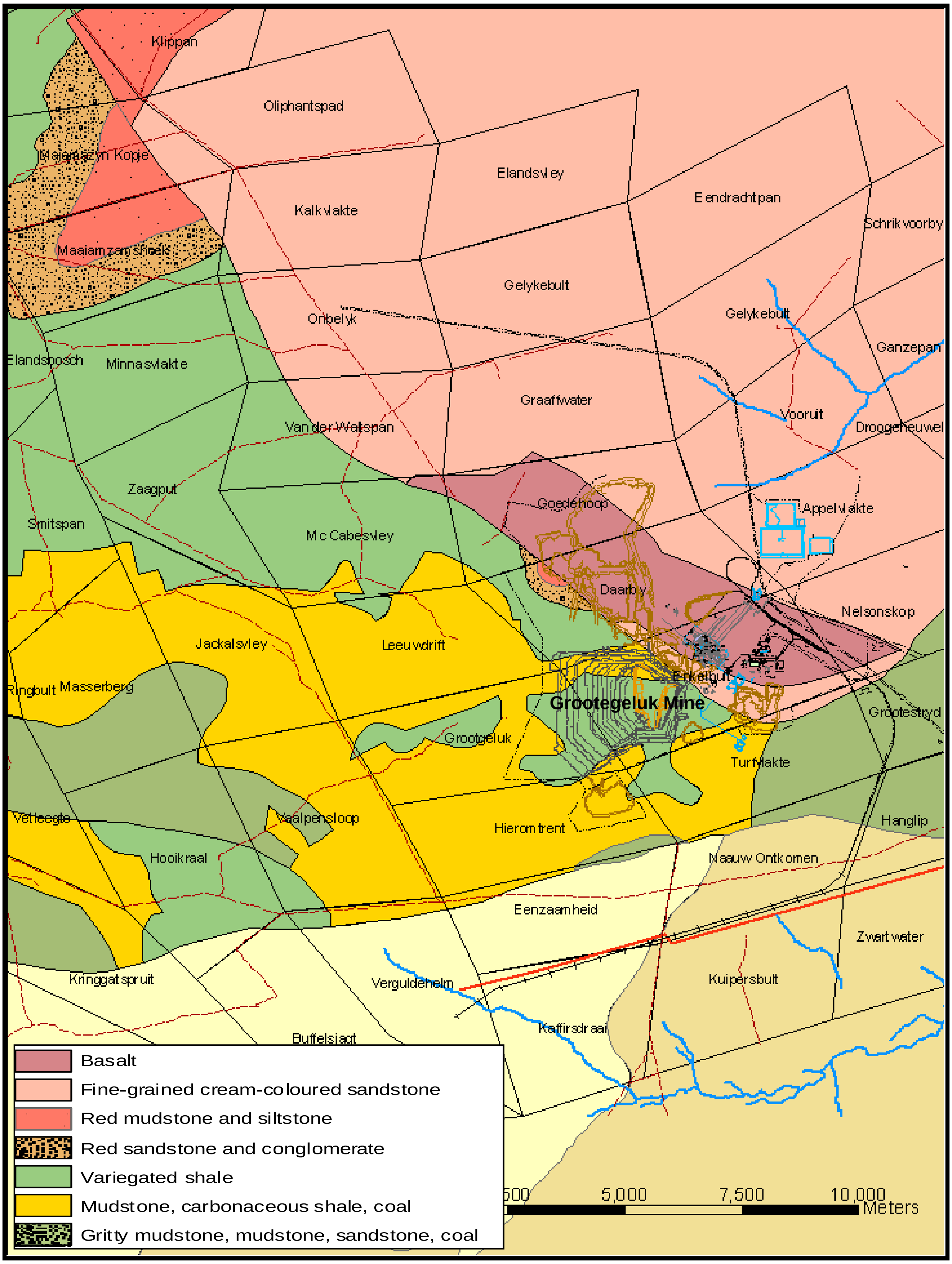

Figure 2 Geological map of a portion of the Waterberg Coalfield

(Adopted from the Geological Survey Map, 1:250 000 Geological Series, 2326 Ellisras, Printed and published by the Government Printer, Pretoria, 1993)

1.5.5 Coal types and occurrence

1.5.5.1 Volksrust Formation

The top portion of the coal bearing stratigraphy, the Volksrust Formation of the Ecca Group in the Karoo Sequence (Table 2), is classified as a Thick Interbedded Seam Deposit Type according to the South African guide to the systematic evaluation of coal resources and coal reserves (SANS 10320, 2004). This succession is approximately 60 m thick and comprises intercalated shale or carbonaceous mudstone and bright coal layers. It displays such a well-developed repetition of coal-shale assemblages that it can be divided into 7 discrete sedimentary cycles or zones which are grouped into 4 mining benches (Table 1). It is the intercalated nature of the shale and coal within the Volksrust Formation which has resulted in the establishment of the massive beneficiation capacity at Grootegeluk Mine, to convert run-of-mine into saleable products. Power station coal and semi-soft coking coal is produced from the Volksrust Formation.

Although the thickness and coal quality of the Volksrust Formation are reasonably constant across the Waterberg Coalfield, significant variations in the yield of semi-soft coking coal as well as the total sulphur content occur vertically in the coal succession.

1.5.5.2 Vryheid Formation

The bottom portion of the coal bearing stratigraphy, the Vryheid Formation of the Ecca Group in the Karoo Sequence (Table 2), is classified as a Multiple Seam Deposit Type according to the South African guide to the systematic evaluation of coal resources and coal reserves (SANS 10320, 2004). This succession is approximately 55 m thick and comprises carbonaceous shale and sandstone with interbedded coal seams varying in thickness from 1.5 m to 9 m (Zone 1 to Zone 4). The Vryheid Formation coal seams consist predominantly of dull coal, with some bright coal developed at the base of Zones 2, 3 and 4. Thermal coal and metallurgical coal are produced from the run-of-mine of the Vryheid Formation.

Due to lateral facies changes and variations in the depositional environment, the coal seams of the Vryheid Formation are characterised by a large variation in thickness and quality. It is noted in the mine lease area that the coal seams of the Vryheid Formation diminish in a westward direction due to sedimentological facies changes.

1.5.6 Mining operations

When Grootegeluk Mine was commissioned in 1980, mining horizons (benches) with fixed elevations were used to mine the coal of the Volksrust Formation. These mining benches resulted in an uncontrolled mix from different lithological units (samples) since the stratigraphy is not entirely horizontally, but dips on average at an angle of 3° in a south-easterly direction across the open pit area. The samples are also not of a constant thickness throughout the deposit. The result was a run-of-mine mix that was of inconsistent quality, making it very difficult for the beneficiation process to be controlled and executed efficiently in order to deliver the planned product yields and the desired coal quality expectations.

The fixed mining elevation method was changed in 1987 to bench elevations that coincide with geological contacts (sample boundaries) (Dreyer, 1994). Adjacent samples with more or less similar coal properties and qualities are selected and combined to form mining benches that are of a practical mining height that can be handled more efficiently by the mining equipment employed at the mine. The new mining benches ensure that the floors of the mining benches of the Volksrust Formation coincide with a prominent shale layer for the mining equipment to drive on. This preserves the underlying coal as much as possible by limiting the generation of fines due to mechanical breakdown when mining equipment drives over the surface of the mining benches. The coal itself is also kept unexposed to the atmosphere for as long as possible to prevent oxidation and consequently the changing of the inherent coal properties. At the same time, the mining benches following the gently dipping strata, ensures that rain water will run off to a point at the bottom of the pit and accumulates in the pit sump, from where it can be retrieved for use in the beneficiation plants.

Except for Zone 3, which was later subdivided into two coal benches namely Bench 9A and Bench 9B, the coal seams of the Vryheid Formation are mined according to their full seam height (Table 1). Zone 1, the basal Vryheid Formation coal seam, contains good quality metallurgical coal but is not included in the mine plan due to the high stripping ratio as a result of a 12 to 14 m thick overlying sandstone layer. Besides the occasional construction of a storm water sump at the open pits' bottom, the coal of Zone 1 is left untouched in the ground. Since beneficiation plant waste and interburden waste is backfilled in the mined out void of the open pit, Zone 1 is currently sterilized for future mining.

2 Literature Survey

Phosphorus occurs in all coals to some extent because it is essential to plant life. (Van Den Bussche and Grieve, 1990). Phosphorus in coal is recognized globally as a problem when evaluating coal for the metallurgical coal market, and to some extent the thermal coal market. Knowledge of the phosphorus content and its associations in coking coal is important from an economic point of view, as phosphorus in steel has a detrimental embrittling effect and its presence in coking coals is therefore limited to as little as 0.01% by weight. (Van Den Bussche and Grieve, 1990).

Most literature that could be found on the distribution of phosphorus in the coal seams of the Waterberg Coalfield is in the form of short unpublished internal memorandums and reports by personnel previously employed at the geology department at Grootegeluk Mine. These reports were mainly prepared to inform mine management about ad-hoc investigations of the phosphorus content of certain coal seams at Grootegeluk Mine. The published literature found on this topic is mostly about the phosphorus distribution in other coal deposits, and using methods of extraction other than those employed at Grootegeluk Mine, but this information can be used to substantiate most findings regarding the phosphorus distribution in the coals seams of the Waterberg Coalfield.

Richards (1985), describes in an internal memorandum of Grootegeluk Mine, test work that was done to investigate the phosphorus content of the coal seams of the Volksrust Formation. The test work involved the drilling of twelve percussion boreholes, each 15 m deep, through the four coal benches of the Volksrust Formation (Benches 2, 3, 4 and 5). The drill chips from the twelve boreholes were collected per bench and combined together to form bench composite samples. The sampled material was sent to a laboratory for analyses in order to determine single phosphorus content values per bench. This procedure was followed for Benches 2, 3 and 4 but in the case of Bench 5, three separate composites representing the upper, middle and lower portion of the bench were compiled. This was done to verify drill core analyses that indicated that the phosphorus content of Bench 5 is generally higher than that of Benches 2, 3, and 4, and that the phosphorus tends to be concentrated near the bottom of Bench 5.

In his recommendations, Richards (1985) suggested that an association may exist between high phosphorus values and higher concentrations of potassium, barium and strontium. The significance of the work done by Richards is that it confirmed that the phosphorus content varies between the different benches and that the phosphorus concentration varies vertically within Bench 5.

In an internal memorandum of Grootegeluk Mine, Dreyer (2007) describes test work that was undertaken to determine if the phosphorus is more concentrated in the upper portion of Bench 11. The test work involved the drilling of four cored boreholes from the roof of the exposed Bench 10 in the pit to ensure that the entire Bench 11 was intersected. In three of the boreholes, Sample 30 (the upper of the two samples comprising Bench 11 at the time) was subdivided into three arbitrary sub-samples, and in one borehole it was subdivided into four arbitrary sub-samples, from top to bottom through the sample. The cored sub-samples each ranged between 500 mm and 600 mm in length. The samples were sent to a laboratory to be individually analysed at a total float density of 1.50 g/cc. From the results obtained it was evident that the overall majority of the phosphorus was concentrated in the upper portion of Sample 30.

Dreyer (2007) took the test work a step further to determine if percussion borehole drill chip analyses of the raw coal (unwashed coal) would be similar to that of raw coal phosphorus analyses from cored boreholes, and whether it would be possible to use the percussion borehole data to predict the phosphorus content of a washed coal product. This time three sets of cored and percussion holes were drilled through Sample 30 from the roof of Bench 11. The drilling took place after Bench 10 was removed and the subsequent cleaning and preparation for blast hole drilling on Bench 11 had already been completed. The focus was therefore not on the entire sample as such but rather on the portion of the sample that should under normal circumstances be sent to the beneficiation plant. The boreholes were each sampled in three vertical sub-sections. Sample material analyses from each sub-section comprised of the raw coal of the core samples, the raw coal of the percussion samples and a washed product at 1.50 g/cc derived from the cored samples in order to simulate the beneficiated run-of-mine. The phosphorus content in the different sample sets was compared and the following conclusions were made:

- The high phosphorus content in Bench 11 occurs at the top of the bench (Sample 30).

- No discrete lithological contact could be distinguished in the drill core that was used to guide the selective removal of the high phosphorus coal.
- Due to the thickness of the high phosphorus coal (± 0.5 m to 0.6 m), it will be impractical to selectively remove this material with the current mining equipment.
- Part of the high phosphorus coal is removed through the mining of Bench 10 as well as with the cleaning and preparation for blast holes on Bench 11.
- The phosphorus is not removed from the coal by crushing and beneficiation. The phosphorus of the raw coal can be used as an indicator of the phosphorus content in the washed product.
- Drill chips from percussion boreholes can be used to determine the phosphorus content of the coal remaining in Bench 11 as well as the phosphorus content of the washed coal, and as such can be used for short term planning purposes.

An updated internal report by Dreyer (2010) describes additional work that was done to further understand the distribution of the phosphorus content at the top of Bench 11. The work comprised the drilling of two cored boreholes through the entire Bench 11. The upper part of Bench 11 (Sample 30) was this time divided into 9 sub-samples in one borehole and 8 sub-samples in the other borehole. The bottom portion of Bench 11 (Sample 31) was sampled as one unit in each borehole. The samples taken from the boreholes were analysed at float density 1.50 g/cc. From this work it was proved that the highest phosphorus content occurs at the top of Bench 11, and that it coincides with Sample 30A, a new subdivision of Sample 30 that was introduced in 2005. This work implies that the phosphorus content of Bench 11 can be lowered by the selective removal of Sample 30A.

Many international authors who have studied the distribution of phosphorus in coal deposits recognize that phosphorus may occur unevenly distributed in the seams of the vertical coal succession. As an example, Ward et al. (1996) indicated that in ply-by-ply studies of selected seams in Australian coals, the phosphorus is typically abundant in only a few sub-sections or plies; the remaining parts of the coal seams, even in high-phosphorus coals, commonly have significantly lower phosphorus levels.

Rao and Walsh (1999) investigated the lateral extent of phosphorus rich zones in bituminous coal from northern Alaska. The authors obtained three drill cores up to three kilometres apart from the same coal seam. A detailed investigation of the cores was undertaken to determine the nature and mode of occurrence of phosphorus minerals. Certain sub-sections of 150 mm of the coal seam have shown higher phosphorus concentrations. In order to investigate the lateral extent of such high phosphorus bands in the coal, the maceral composition allowed for interpretation of the different environments in which coal deposition took place. Acid-extractable phosphorus analysis of the sub-sections was used to identify the high phosphorus horizons. Electron microscope analyses identified the phosphorus mineral as crandallite. Correlation of high phosphorus intervals with corresponding environments of deposition suggests that phosphorus precipitation was promoted by an oxidizing environment with a lowered water table during the peat stage. A study of thin sections from the high phosphorus samples showed that crandallite is associated with structured vitrinite as cell fillings in fusinite. The study confirms the potential for using high phosphorus horizons for the correlation of coal seams. A high phosphorus horizon was found at 450 mm above the bottom of the seam in all of the boreholes, indicating a uniformity of the coal forming environment and the availability of crandallite constituent elements over the entire 3 km area. The uniformity of high phosphorus concentrations through the top 2 m of the three boreholes also showed a distinct correlation.

In terms of international methods to remove phosphorus in coal, Ryan and Grieve (1996) reported that limited data indicated that phosphorus is difficult to remove from coal by conventional washing techniques. It is therefore important to understand the distribution of phosphorus in coal seams, because blending of the run-of-mine coal, rather than washing may be the best way of controlling the amount of “clean coal”. This would require integrating sound advanced knowledge of phosphorus concentrations in coal seams into long range mine plans.

Mahony et al. (1980) found that the determined values of the phosphorus content of cokes and their feed coals indicated that the phosphorus present in the coal is completely retained in the cokes when carbonized to temperatures between 900°C and 1050°C. On the basis of these experimental results, Mahony et al (1980) suggested that the phosphorus content of coke can generally be calculated from knowledge of the phosphorus content of the feed coal and the coke yield, with an accuracy which is sufficient for normal requirements.

According to Geer et al. (1944), some investigators found that phosphorus in Washington coals was removed in the coal-washing process, but others observed that the beneficiated coal contained as much or even more phosphorus than the raw coal. If the phosphorus is associated with the heavy impurities in a coal, it can be eliminated in the washing operation to the same extent that these impurities are eliminated; if on the other hand, it is distributed throughout the light, low-ash coal, it cannot be removed by washing.

Geer et al. (1944) had washability analyses done on representative samples of the most important coking coal seams of Washington, and the phosphorus content of the different density fractions was determined. The samples were taken in such a way as to include all the impurities that would have to be removed in a commercial coal beneficiation operation, and the coal was tested at about the size at which it would be crushed in a coal beneficiation plant.

Geer et al. (1944) also analysed channel samples taken from specific benches over as large an area as possible, to examine the possibility of selective mining. The benches were sampled in a manner so that each parting or band of impurity was sampled separately, to supply information on how the phosphorus content of the bench would be affected by coal beneficiation. The fractional analyses, in terms of their specific gravity phosphorus content, of the Wilkenson West 3 and 5 Beds, Wilkenson East 2 and 4 Beds, the Roslyn No. 3 and 6 Coal Beds as well as Roslyn Coal Bed washed products were discussed.

Geer et al. (1944) concluded that the elimination of phosphorus by coal washing methods depends entirely upon its mode of occurrence; therefore each coal bed presents a different challenge in terms of phosphorus removal. The phosphorus content of two coal seams studied (the East No. 2 Bed and the West No. 3 Bed at Wilkenson, Pierce County) is reduced greatly by the washing procedure required to produce coal of satisfactory ash content. In the other five seams examined, the phosphorus is associated with the clean coal rather than with the impurities and therefore could not be eliminated by ordinary coal washing methods. The lowest phosphorus content obtained with the coals studied was 0.043%. Lower values might be obtained in different seams from different areas that were not part of the investigation.

Chapman and Mott (1928) described the work that Cowley (1924) performed on Cumberland and South Wales coals. According to Cowley, normal flotation washing is no more successful than jig-washing in removing phosphorus from coal. Under the most favourable conditions the percentage removal of phosphorus is small.

Chapman and Mott (1928) also described work performed by Fulton (1905) on the Pittsburg coal seam in Pennsylvania in the Connellsville region. In this study the coal seam was divided into two portions, each with three subdivisions or benches. The highest concentration of phosphorus (0.062%) appears in the upper bench (1 ft) of the upper portion of the coal seam and the lowest concentration pf phosphorus (0.009%) in the lower bench (3 ft) of the bottom portion of the coal seam. It is therefore suggested that mining the seam selectively, if possible, would reduce the phosphorus content of the coal.

Chapman and Mott (1928) also described work performed by Davies (1926) on the distribution of phosphorus in coals from South Wales. Davies divided a number of coals into different sizes, but did not find any regular variation in the phosphorus content of the different sized fractions. By separating the fractions in liquids of different densities, a progressive increase was found in the phosphorus content in coals floating in higher density liquids. Davies calculated that, to produce coal at 0.025% phosphorus content, the ash content of these coals would need to be at 3.75% or less. To produce washed coals at such a low ash percentage (at which the phosphorus content will be satisfactory) was considered to be justifiable only when it was possible to dispose of a separate middlings fraction.

In order to establish the extent of the phosphorus distribution laterally and vertically throughout the Vryheid Formation coal seams at Grootegeluk Mine, and to be able to propose mining benches that are either suitable for char plant feed coal, or that can be utilized after blending with low phosphorous material from other seams, phosphorus data needs to be studied and geological models constructed. This approach will be based upon Ryan and Greave’s theories that (1) phosphorus is difficult to remove from coal by conventional coal beneficiation techniques and (2) “it is important to understand the distribution of phosphorus in the coal seams, because blending of the run-of-mine coal, rather than washing, may be the best way of controlling the amount of phosphorus in clean coals.” (Ryan and Grieve, 1996).

3 Methodology

3.1 Data preparation

3.1.1 Sampling and analyses

Analytical data from historically drilled exploration boreholes as well as the results from the five specially drilled boreholes through Bench 11 were used and treated similarly for this project. The historic borehole analyses were obtained from the exploration borehole database of Grootegeluk Mine. This database contains cored exploration borehole data that were drilled across the resource area of the mine over a period of several decades. The same procedure to determine sample boundaries in borehole core had been followed in all exploration boreholes, by correlating the coal succession obtained from the drilled core with other randomly selected previously drilled and correlated boreholes. A few new sample intervals were introduced over the years to enable higher resolution of coal analyses along the vertical succession in certain benches. These sample subdivisions include the split of Sample 23 into Samples 23A, 23B and 23C as well as Sample 30 into Samples 30A and 30B respectively. Original lithological boundaries were never changed, i.e. by compositing the sample analyses of Samples 30A and 30B in a specific borehole, the sample analyses for Sample 30 is obtained for that borehole. Bench composition analyses per borehole are therefore obtained when the specific samples pertaining to the different benches are composited. The relationship between sample units and mining benches at Grootegeluk Mine is illustrated in Table 1.

Coal washability analyses (fractional float and sink analyses) are performed on the coal and/or shale material obtained from the drill core within each sample unit of each exploration borehole. The suite of washability analyses includes proximate analyses as well as ash composition analyses at a set range of float densities and the sink fraction (the material that doesn’t float at the maximum float density). Proximate analyses are performed on each float and sink fraction of a sample in order to determine the yield (the percentage by weight of material that floats), the ash content, the moisture content and the volatile matter content.

After proximate analyses were conducted, the coal material that floated at each density fraction, as well as the material that reported in the sink fraction, is separately combusted to produce the coal ash which is further prepared and analysed for the ash composition. XRF-analyses are conducted on this material to determine the relative percentages of elemental oxides that are present in the ashes (mineral content) of each sample. A full range of washability analyses are therefore obtained for the ash composition data of each sample unit. P_2O_5 forms part of the suite of elemental oxides that is analysed for in the coal ash. This entails that the fractional ash composition washability analyses include the percentage P_2O_5 present in the coal ash of each sample unit of an exploration borehole. The percentage ash content and the P_2O_5 content in the coal ash are used to calculate the phosphorous content of the coal sample.

3.1.2 Method used to calculate the phosphorous content in coal

The amount of P_2O_5 in the coal ash has to be converted to the percentage phosphorus in coal. Phosphorus in coal is calculated from the P_2O_5 percentage by using the molecular mass of the phosphorus in relation to the total molecular mass of P_2O_5. This is represented by the following formula:

$$\% \, P \; in \; P_2O_5 \; = \; \frac{(P_{mm} \; x \; 2)}{(P_{mm} \; x \; 2) + (O_{mm} \; x \; 5)} \; x \; \frac{100}{1} \qquad [1]$$

$$= \; 43.64207 \; \%$$

where:

% P	=	*percentage phosphorus*
P_2O_5	=	*% phosphorus penta oxide in the ash*
P_{mm}	=	*molecular mass of phosphorus*
O_{mm}	=	*molecular mass of oxygen*

Since the percentage P_2O_5 values are determined from the coal ash only, which does not take the combustible portion of the coal into account, the percentage phosphorus therefore needs to be adjusted to be representative of the full coal sample. This is obtained from the percentage ash in the coal as well as the percentage P_2O_5 in the coal ash. An example of this calculation is shown in Formula 2. In this example the coal has an ash content of 15%. The percentage phosphorus in the coal is therefore adjusted for a coal product containing 15% ash.

$$\% \, P \, in \, coal \, containing \, 15\% \, ash \; = \; \frac{\% \, P_2O_5 \;\; x \;\; 43.64207}{100} \;\; x \;\; \frac{15}{100} \qquad [2]$$

3.1.3 Method used to composite and cumulate analytical data

Fractional sample washability analyses (sample wash tables) are composited and cumulated to form wash tables per mining bench in order to determine the coal qualities of each bench. The composited phosphorus analyses for the different mining benches are therefore calculated from the different sample wash tables pertaining to each mining bench. The raw relative density, thickness and the yield of each respective sample are used as the weighting factors. The composited analysis per bench is calculated from the sample data as follows:

$$Composited\_Thickness_{ut} = \sum_i Thickness_i \qquad [3]$$

$$Composited\_Raw\_RD_{ut} = \frac{\sum_i (Raw\_RD_i \times Thickness_i)}{Composited\_Thickness_{ut}} \qquad [4]$$

$$Composited\_Yield_{ut,i,j} = \frac{\sum_i (Raw\_RD_i \times Thickness_i \times Yield_j)}{\sum_i (Raw\_RD_i \times Thickness_i)} \qquad [5]$$

$$Composited\_Analysis_{ut,i,j,k} = \frac{\sum_i (Raw\_RD_i \times Thickness_i \times Yield_j \times Analysis_k)}{\sum_i (Raw\_RD_i \times Thickness_i \times Yield_j)} \qquad [6]$$

Composited wash table coal analyses are cumulated for the purpose of deriving single line coal analyses (coal product assays) at any given float density or ash percentage. The formula used to cumulate the coal analyses in a wash table at each consecutive float density is as follows:

$$Cumulated\_Analysis_{ut,i,j,k} = \frac{\sum_i (Frac.Comp.Yield_j \times Frac.Comp.Analysis_k)}{\sum_i (FractionalCompositedYield_j)} \qquad [7]$$

Table 3 and Table 4 shows a worked example of the calculations required to composite coal analyses for a coal bench consisting of three samples named Sample A, Sample B and Sample C in this example. Table 5 shows the calculations required to cumulate the composited bench analyses derived for the same example.

Table 3 Practical example of the calculations required to derive composited analyses

Fractional Sample Analysis with Calculations								
Sample Name	Sample data					Calculations		
	Float RD Fractions (g/cc)	Sample Raw RD (g/cc)	Sample Thickness (m)	Fractional Yield (%)	Fractional Analyses (units)	Raw RD x Thickness	Raw RD x Thickness x Yield	Raw RD x Thickness x Yield x Analyses
Washability Table Sample A	1.35	1.56	0.81	10.54	5.15	1.26	13.31	68.56
	1.40	1.56	0.81	3.34	11.21	1.26	4.22	47.31
	1.50	1.56	0.81	29.93	15.51	1.26	37.82	586.56
	1.60	1.56	0.81	25.43	22.41	1.26	32.13	720.05
	1.70	1.56	0.81	11.03	30.50	1.26	13.93	425.02
	1.80	1.56	0.81	4.78	39.14	1.26	6.03	236.21
	1.90	1.56	0.81	4.29	46.66	1.26	5.42	253.05
	2.00	1.56	0.81	3.72	52.74	1.26	4.70	247.84
	2.10	1.56	0.81	2.44	59.60	1.26	3.08	183.46
	2.20	1.56	0.81	1.90	65.50	1.26	2.41	157.59
	(Sink)	1.56	0.81	2.61	72.50	1.26	3.30	239.47
Washability Table Sample B	1.35	1.46	1.21	16.30	4.96	1.77	28.80	142.84
	1.40	1.46	1.21	20.87	8.30	1.77	36.86	305.94
	1.50	1.46	1.21	34.68	12.12	1.77	61.27	742.58
	1.60	1.46	1.21	12.43	22.61	1.77	21.96	496.41
	1.70	1.46	1.21	7.59	28.99	1.77	13.42	388.92
	1.80	1.46	1.21	3.45	33.73	1.77	6.09	205.58
	1.90	1.46	1.21	0.88	35.23	1.77	1.56	54.89
	2.00	1.46	1.21	0.36	38.67	1.77	0.63	24.46
	2.10	1.46	1.21	0.14	44.15	1.77	0.25	11.15
	2.20	1.46	1.21	0.17	46.06	1.77	0.29	13.43
	(Sink)	1.46	1.21	3.13	53.66	1.77	5.53	296.71
Washability Table Sample C	1.35	1.49	1.77	15.34	4.68	2.64	40.46	189.36
	1.40	1.49	1.77	15.84	9.06	2.64	41.77	378.46
	1.50	1.49	1.77	37.00	13.31	2.64	97.57	1298.62
	1.60	1.49	1.77	11.62	20.48	2.64	30.63	627.40
	1.70	1.49	1.77	5.42	29.43	2.64	14.30	420.91
	1.80	1.49	1.77	3.83	34.41	2.64	10.10	347.57
	1.90	1.49	1.77	2.01	38.62	2.64	5.31	205.03
	2.00	1.49	1.77	1.37	42.74	2.64	3.61	154.31
	2.10	1.49	1.77	1.08	50.47	2.64	2.85	144.02
	2.20	1.49	1.77	1.23	64.54	2.64	3.24	209.19
	(Sink)	1.49	1.77	5.26	57.80	2.64	13.88	802.12

Table 4 Practical example of the calculations required to derive composited analyses

Fractional Composited Analysis					
Sample Name	Float RD Fractions (g/cc)	Calculations			
		Composited Thickness (m) [3]	Composited Raw RD (g/cc) [4]	Composited Yield (%) [5]	Composited Analyses (%) [6]
Washability Table Sample A, B & C combined	1.35	3.79	1.50	14.57	4.85
	1.40	3.79	1.50	14.62	8.83
	1.50	3.79	1.50	34.70	13.36
	1.60	3.79	1.50	14.95	21.76
	1.70	3.79	1.50	7.35	29.65
	1.80	3.79	1.50	3.92	35.51
	1.90	3.79	1.50	2.17	41.74
	2.00	3.79	1.50	1.58	47.71
	2.10	3.79	1.50	1.09	54.76
	2.20	3.79	1.50	1.05	64.02
	(Sink)	3.79	1.50	4.01	58.93

Table 5 Practical example of the calculations required to derive cumulated bench analyses

Cumulative Composited Analysis							
Sample Name	Float RD Fractions (g/cc)	Calculations					
		Composited Yield (%) [5]	Cumulative Yield (%)	Composited Analyses (%) [6]	Composited Yield x Composited Analyses	Cumulated (Comp. Yld. x Comp. Anal.)	Cumulative Analyses (%) [7]
Washability Table Sample A, B & C combined	1.35	14.57	14.57	4.85	70.71	70.71	4.85
	1.40	14.62	29.19	8.83	129.11	199.82	6.85
	1.50	34.70	63.89	13.36	463.65	663.47	10.39
	1.60	14.95	78.84	21.76	325.34	988.81	12.54
	1.70	7.35	86.19	29.65	217.88	1206.69	14.00
	1.80	3.92	90.11	35.51	139.28	1345.97	14.94
	1.90	2.17	92.28	41.74	90.51	1436.48	15.57
	2.00	1.58	93.85	47.71	75.27	1511.76	16.11
	2.10	1.09	94.95	54.76	59.75	1571.51	16.55
	2.20	1.05	95.99	64.02	67.08	1638.59	17.07
	(Sink)	4.01	100.00	58.93	236.14	1874.73	18.75

A cumulative coal washability table, like the example shown in Table 5, is used to plot the various cumulative coal analyses against the float densities in graph format. In this worked example, the coal quality variable used is the percentage by weight ash content of the coal. Figure 3 shows the cumulative washability table in graph format. From this graph it is easy to note that a coal product which is washed at a relative density of ~1.80 g/cc will result in ~15% ash content and will deliver ~90% yield.

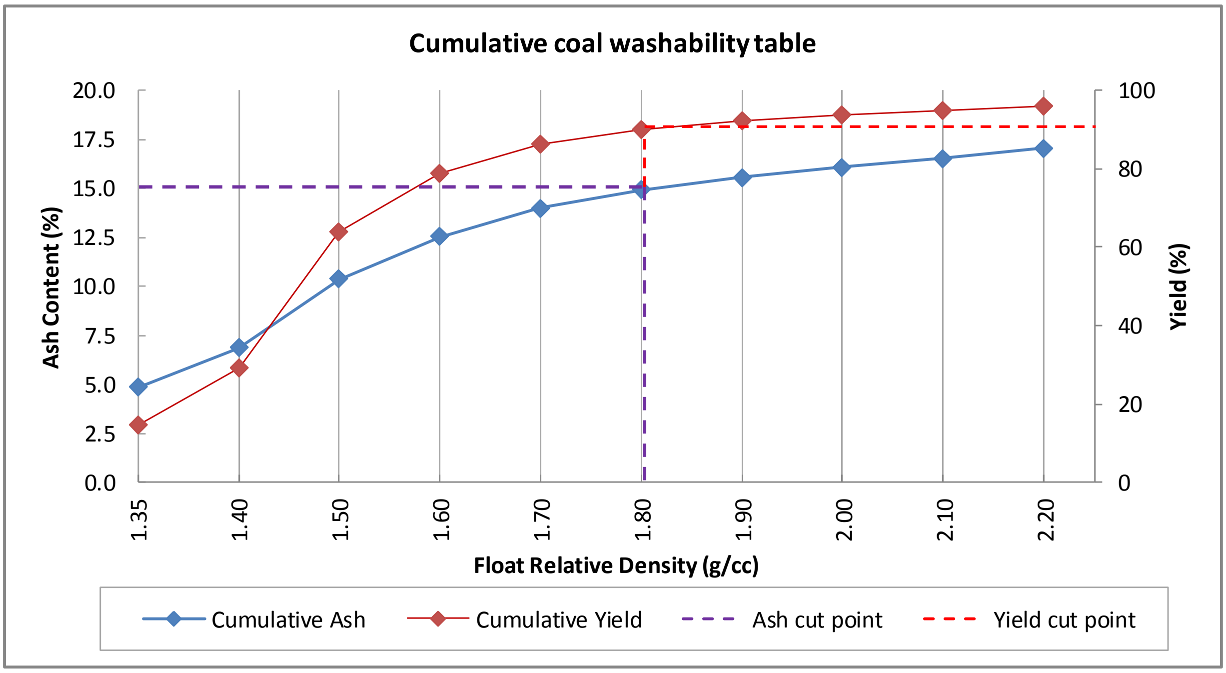

Figure 3 Example of a cumulative coal washability table in graph format

Much more accurate coal quality readings are obtainable when fitting a curve through the data points on the graph, and using that specific curve's mathematical formula to calculate the required quality values at a specific cut point (e.g. the ash content set at 15%). Once the relative density value at the desired ash content cut point is established, it is used as the cut-point and applied to the other coal qualities, to determine each coal quality's product value at the required ash content. In this example, a relative density cut point of ~1.80 g/cc will yield coal qualities for a 15% ash product.

The Coal Analyses and Beneficiation module (CAB module) of Sable Data Warehouse geological database software was used to calculate the coal qualities of the different lithological units from the exploration borehole data that were used in this study. These calculations are based on the principles and formulas described in the preceding paragraphs.

3.2 Statistical analyses

Statistical analyses were conducted on the phosphorous content in the mining benches of the Vryheid Formation at Grootegeluk Mine to determine their general phosphorous content and the distribution in each bench. All available sample analyses from the exploration borehole database comprising the different coal benches were used. ‘Full-seam’ bench washability tables were created from the relevant sample washability tables which were used in this investigation.

Coal qualities for coal containing an ash content of 15% were extracted per bench, in order to produce single-line coal product qualities for the different benches as intersected in each exploration borehole. This was done in order to simulate the final coal product, after beneficiation would have taken place, to identify the suitability of each bench for the production of char plant feed coal with regards to their phosphorous content. The borehole population used is represented by the number of exploration boreholes containing phosphorus data for each bench under consideration.

Statistical analyses were also used to examine the phosphorus content of the individual sample units. In general, the results from these statistical analyses are envisaged to give an indication of the vertical phosphorus distribution through the different Vryheid Formation coal benches.

Finally, statistical analyses of the phosphorus content of the Sample 30A sub-samples were also used to determine the general phosphorus distribution of these smaller lithological units. The results from this work will give an indication of how the phosphorus is distributed vertically through Sample 30A (the upper portion of Bench 11).

3.3 Geological modelling

This portion of the investigation requires the use of geological models that are generated from the spatially distributed exploration borehole data. The shortfall of using only statistical analyses is the fact that it does not take the spatial distribution of the data into consideration. The positions of the exploration boreholes are important and are taken into consideration when using geological models of the phosphorous distribution throughout the entire extent of the resource. Geological models may therefore be used to recognize areas of low phosphorous coal that might be suitable for the char plant feed coal. Geological models produce fairly accurate estimates of the data at positions other than the actual data from which the estimates are made, forming continuous grids of data across the area of interest. This is especially important in order to be able to recognize the possibility of trends in the phosphorous content of the different lithological units across the resource area. The significance of high and low values in a dataset can also be assessed by making use of geological models.

Since the different samples pertaining to each mining bench are combined to form mining benches (Section 3.1.1), the qualities of individual samples were overlooked for many years. In order to establish the vertical and lateral phosphorus distribution throughout the resource area and to be able to propose different mining horizons that might be suitable for char plant feed coal, geological models of individual samples also need to be compiled. It is envisaged that geological models of individual samples rather than mining benches are more likely to provide the means to evaluate the coal qualities of different sample combinations which may ultimately develop new mining benches with acceptable phosphorus concentrations.

For the purpose of this study, geological models refer to modelled continuous grids covering the resource area of Grootegeluk Mine. These geological models contain geological information at the centres of each grid node, derived from the spatially distributed exploration boreholes containing the base information. The geological models were generated for the phosphorus content of the different lithological units in the coal product containing 15% ash. This is the same data that is evaluated in the statistical evaluation, i.e. the coal product that might be used for char plant feed coal.

Minex geological modelling software was used to perform the geological modelling for this study. The ESC Growth Technique interpolation method, which is generally used in Minex, was applied to create the geological models. This interpolation method is based on the principle of the inverse distance, but also takes trends in the source data into consideration. The exact algorithm describing the ESC Growth Technique is the intellectual property of the software owner company, Dassault Systèmes Geovia, and is not available in the public domain.

A maximum extrapolation distance of 1000 m was used in the geological modelling. This ensures that the estimation of data is terminated at a distance of 1000 m away from actual observations in order to deliver more accurate models. The size of the grid nodes of the models was selected to be 50 m by 50 m each; this node size was found to be of an appropriate size compared to the distribution of the data (borehole locations). The geological models were furthermore terminated against the Daarby and Eenzaamheid faults as well as the perimeter of the resource area of Grootegeluk Mine in order to honour tenure regulations.

The geological models of the phosphorus content of the different lithological units are illustrated by means of colour shaded contour maps, i.e. each colour on the different maps represents a different phosphorus range. The colour scale on each map describes the values used for the different phosphorus ranges used.

The exploration borehole positions, from which the relative phosphorus data were retrieved, are also indicated on the colour shaded contour maps in order to indicate the spatial distribution of the data from which the models were created. Due to the fact that Grootegeluk Mine is continuously narrowing its exploration borehole grid in advance of the current pit position, the resultant exploration borehole population is higher in the eastern portion of the resource than in the western portion. The distribution of boreholes containing the historical Sample 30 (before it was subdivided into Samples 30A and 30B) for example, is much more concentrated in the eastern portion of the resource, while boreholes containing Samples 30A and 30B are more concentrated in the western portion of the resource. This is the result of the subdivision of Sample 30 that was introduced at a later stage, after a portion of the borehole grid had already been covered by exploration drilling.

3.4 Subdivision and selective mining of Bench 11

Previous work performed at Grootegeluk Mine highlighted the existence of changing phosphorus content through the vertical sequence within certain coal benches, such as Bench 5 and more recently also Bench 11 (Dreyer, pers. comm., 2013). It is therefore believed that at least a portion of Sample 30A (upper portion of Bench 11) may comprise of low phosphorous coal. This aspect initiated the current investigation, i.e. to determine the vertical boundaries of the low phosphorus coal horizon within Bench 11 and to establish a practical mining horizon in order to minimize the loss of low phosphorous metallurgical coal when removing the high phosphorus coal selectively.

The sub-sampling of Bench 11 is therefore the most important component of this investigation. The information obtained from the statistical analyses as well as the geological modelling of the phosphorous content of the different Bench 11 horizons will be used to determine the vertical portion of which needs to be removed separately in order to have suitably low phosphorous coal that can be used for char plant feed coal in the remaining portion of Bench 11.

Initially during the pre-mine exploration drilling phase and for an extensive period of time after the mine was commissioned, Bench 11 consisted of two vertical subdivisions or samples for coal analyses, namely Sample 30 (upper portion of Bench 11) and Sample 31 (lower portion of Bench11). These two samples were based on the thickness of the coal seam, i.e. Bench 11 has an overall average thickness of 4 m and therefore these two samples were on average 2 m thick each. Several years later it became apparent that the phosphorus concentration of Sample 30 is generally higher than that of Sample 31. If Bench 11 was subdivided on this basis (between Samples 30 and 31), approximately 50% of the coal from Bench 11 would have been lost for the production of char plant feed coal. As a consequence, it was decided in 2005 to subdivide Sample 30 in more or less equal proportions, resulting in Samples 30A and 30B. These two samples, on average 1 m in thickness each, supported enough drill core material to maintain the standard suite of coal analyses performed on Grootegeluk Mine's exploration borehole samples. The intention for the subdivision of Sample 30 at the time was to have usable analytical data for Bench 11, should the upper portion (Sample 30A) have to be removed separately to reduce the phosphorus content of the bench.

The removal of Sample 30A from Bench 11 will result in an average loss of 25% of the run-of mine from Bench 11. This will have a negative impact on the resource utilization of the Mine for the remainder of the Mine's operational life. To date the subdivision of Bench 11 had not been introduced due to the current relatively low phosphorus levels present in the coal mined from the bench. The current investigation is performed to determine whether the high concentrations of phosphorus of Bench 11 may be present in an even smaller vertical portion of the bench, in order to optimize the remaining low phosphorus content portion. This component of the investigation is similar to work that was previously performed by Dreyer (2007) which proved that the high phosphorus content of Bench 11 is situated in Sample 30A.

This investigation included the drilling of five cored boreholes through the entire thickness of Bench 11 in the pit. The boreholes were drilled in the current open pit through Bench 11. The borehole positions were carefully selected to obtain the best possible borehole distribution over the length of the pit in order to obtain drill core samples as representative as possible of Bench 11. The boreholes were drilled from the top of Bench 10 to ensure that no vertical portion of Bench 11 was already removed by the possible over mining of Bench 10 or by the preparation and cleaning of Bench 11 that is carried out prior to the drilling of blast holes. Core samples of the entire seam thickness of Bench 11 were therefore intersected in each of these five boreholes.

The borehole core of each of the specially drilled boreholes was geologically logged, correlated and divided into the standard sample units of Bench 11, namely Sample 30A, Sample 30B and Sample 31. Sample 30A was then further subdivided into three smaller lithological units or sub-samples. No discrete lithological contacts could be distinguished in the drill core that could be used to guide the position of the sub-sample boundaries geologically. Subdivisions of more or less equal lengths, based on the intersected thickness of Sample 30A in each borehole, were therefore used. This resulted in the Sample 30A sub-samples from all five boreholes having more or less equal thicknesses. The average thickness of these three sub-samples was 350 mm each. The sub-samples derived from Sample 30A were called Sample 30A-1, Sample 30A-2 and Sample 30A-3 from top to bottom in each borehole. Table 6 illustrates lithological units of the core retrieved and the vertical subdivision of Sample 30A in these boreholes.

Table 6 Lithological units intersected by the specially drilled boreholes

Bench	Sample	Sub-sample (subdivisions of Sample 30A)
Bench 10 (Sandstone interburden) (~ 4 m thick)		
Bench 11 (Zone 2) (~ 4 m thick)	Sample 30A (~ 1 m thick)	Sub-sample 30A-1
		Sub-sample 30A-2
		Sub-sample 30A-3
	Sample 30B (~ 1 m thick)	
	Sample 31 (~ 2 m thick)	

Coal washability analyses were performed on the Sample 30A sub-samples, as well as on Sample 30B and Sample 31 as obtained from each of the specially drilled boreholes. Proximate analyses and ash composition analyses were performed on the different float and sink fractions of each individual sample taken. Single-line coal qualities, including phosphorus content, for a coal product containing 15% ash were derived from the washability tables for further investigation. The investigation involves statistical analyses and geological modelling of the different sub-samples intersected in the five specially drilled boreholes through Bench 11. The analytical results obtained from these boreholes will be used to determine the vertical position of high phosphorus horizons in Bench 11. This work was done according to the methods described in the preceding sections (Sections 3.1 to 3.3).

3.5 Coal beneficiation

It is generally accepted that it is difficult to remove phosphorus from coal by means of beneficiation. This principle needs to be investigated for coal from the Waterberg Coalfield to complete the current investigation. If the phosphorus in Waterberg coals can be removed by means of beneficiation by lowering the ash content of the run-of-mine, it might be possible to produce low phosphorus char plant feed coal from medium and/or high phosphorus coal seams. This method of producing low phosphorus coal may also encompass a certain amount of yield loss. This amount of associated yield loss may determine to what extent it is economically viable to produce coal at lower ash content in order to reduce the phosphorus in the coal.

A pragmatic approach was followed to simulate the coal beneficiation process in order to determine the phosphorus content of different coal products produced from the same lithological units. The coal washability data of exploration boreholes were used to determine the phosphorus content of different coal products. The coal products used range from a 10% ash product to a 15% ash product in 1% coal ash content increments. The coal thickness, product yield and product relative density of the different lithological units were used as the weighting factors to determine the weighted average phosphorus content of each coal product per lithological unit. The resultant phosphorus concentrations were compared for each coal product.

This part of the investigation was conducted in three stages. Initially the weighted average coal product phosphorus content in the different coal benches was used. Secondly, phosphorus in the sample units comprising Bench 11 was examined and finally the phosphorus of the Sample 30-A sub-samples was examined. The different stages of this study are important to provide information for all the lithological units, ruling out the possibility of a masking effect when dealing with coal seams comprising more than one lithological unit.

3.6 Comparison of phosphorus data with other coal quality data

Phosphorus data is relatively limited in certain portions of the resource at Grootegeluk Mine. This part of the investigation was done to determine whether different coal quality analyses can be used to indicate the phosphorus content of the coal. If a relationship between the phosphorus content and other analytical coal parameters could be established, then such other coal qualities could be used to increase the estimation accuracy of the phosphorus content of the coal.

The coal analytical data obtained from the five specially drilled boreholes through Bench 11 in the pit area was used. The different sub-samples pertaining to Sample 30A as well as Sample 30B and Sample 31 were examined in order to cater for all the vertical sub-divisions of Bench 11. The analytical data from each lithological unit was compared with the phosphorus content of the coal. The coal analyses used in this study were determined from each borehole's washability data for a coal product at total float density of 1.50 g/cc. By using this coal product rather than a product containing 15% ash, it was also possible to evaluate the coal ash content as one of the coal quality variables in relation to the phosphorus content of the coal.

The coal qualities used in this study include the inherent moisture content, ash content and volatile matter content; free swelling index, Roga index, total sulphur content and calorific value. The weighted average coal product qualities per lithological unit were derived by using the thicknesses of the lithological units from each borehole and the coal yield as obtained at a total float density of 1.50 g/cc as the weighting factors.

3.7 Blending potential of Zone 1

Zone 1 is the lowermost coal seam in the Waterberg Coalfield. Zone 1 does not currently form part of the mine plan at Grootegeluk Mine due to the high stripping ratio and associated high mining cost to extract this rather thin coal seam. Consequently Zone 1 is left in the ground and is sterilized for future mining due to the backfilling of the pit with interburden waste and beneficiation plant waste that is dumped inside the mined-out void of the pit. It is known that Zone 1 consists of low phosphorus coal. To date no work has been undertaken to determine whether this coal seam could be utilized as a source of low phosphorus blending coal to lower the phosphorus content in the run-of-mine feed. It is therefore also not known how much of this coal would be required to suitably lower the phosphorus of the current mining benches at Grootegeluk Mine. Blending the run-of-mine coal with coal from Zone 1 may provide an alternative way to increase the amount of low phosphorus char plant feed coal at the mine, optimizing the resource by producing more high value coal from the same resource.

In order to establish blending ratios from the different benches with coal from Zone 1, the respective weighted average phosphorus and product yields for a coal product containing 15% ash were used. This data was derived for the different mining benches by using exploration borehole data that were drilled across the resource area at Grootegeluk Mine. The expected average product yield and phosphorus content of the different benches for a coal product containing 15% ash were used in these calculations. The different mining benches differ in coal properties and yield, and each bench will therefore react differently to the blending process. The method of calculation applied was based on average coal properties per mining bench. Since coal qualities vary laterally in the resource these calculations cannot be exact but merely aims to give an indication of the required coal blending ratios.

If the results of this study indicate that practical blending ratios are possible, the extraction of Zone 1 at Grootegeluk Mine should be reconsidered to mitigate the risk of interrupted char production due to a lack of suitable low phosphorus coal in the current mining benches.

4 Results

4.1 Statistical analyses

4.1.1 Mining benches

Table 7 summarises the results obtained from the statistical analyses of the phosphorus content of the mining benches. Although Zone 1 is not currently being extracted at Grootegeluk Mine, it is included in the study for completeness and future reference. Part of this investigative research is to determine the intrinsic value of Zone 1 being a source of low phosphorus content coal. The outcome of this study may lead to the future extraction of Zone 1, and therefore it is important that it be included in this investigation.

Table 7 Statistical analyses results of the phosphorus content of the mining benches

Stratigraphic Unit (Mining Bench)	Number of exploration boreholes containing phosphorus data	Percentage phosphorus in coal containing 15% ash				
		Minimum	Maximum	Range	Average	Standard deviation
Bench 6	138	0.0517	0.4432	0.3915	0.2205	0.0803
Bench 7B	123	0.0079	0.3967	0.3889	0.1589	0.0594
Bench 9A	114	0.0092	0.6121	0.6029	0.2889	0.1276
Bench 9B	144	0.0046	0.2527	0.2481	0.0655	0.0553
Bench 11	148	0.0033	0.0890	0.0858	0.0135	0.0100
Zone 1*	131	0.0007	0.0295	0.0288	0.0085	0.0041

Rounding-off of figures may cause computational discrepancies.
* Zone 1 is currently not extracted at Grootegeluk Mine.

The data depicted in Table 7 shows that the average phosphorus content in the mining benches strongly increases upwards from Zone 1 (the bottom coal seam) to where it reaches its highest level in Bench 9A. In the benches above Bench 9A, the phosphorus levels fluctuate but remain very high. The current maximum allowable phosphorus concentration for char plant feed coal is 0.012%.

Bench 6 is the only bench that has no values below 0.012% phosphorus throughout the data population. Its average phosphorus content is very high at 0.2205%. The phosphorus content in the coal of Bench 6 is well dispersed, hence the relatively high range and standard deviation. From these results, it is possible to conclude that Bench 6 as a solitary unit cannot be utilized for char plant feed coal due to its high phosphorus content.

The average phosphorus content of Bench 7B is also very high, but is lower than that of Bench 6. The average phosphorus content of Bench 7B is too high to be considered for char plant feed coal, but the minimum is below 0.012% phosphorus. This indicates that at least a certain area of the resource of Bench 7B does comply with the phosphorus specification of char plant feed coal. Further investigation is required to determine the significance of this low minimum phosphorus content in Bench 7B.

Bench 9A contains the highest average phosphorus content of all the Vryheid Formation mining benches, which is far too high for use as char plant feed coal. The phosphorus content of this bench is highly dispersed, hence the extremely high maximum and the relatively low minimum value as well as the high standard deviation. As in the case of Bench 7B, the minimum phosphorus value of Bench 9A is also below 0.012% which therefore requires further investigation.

The average phosphorus content of Bench 9B is much lower than that of Bench 9A, but still much higher than the maximum allowable amount required for char plant feed coal. The phosphorus distribution in Bench 9B is well dispersed, indicated by the high range and standard deviation. The minimum value of 0.0046% phosphorus is well below the maximum allowable amount of char plant feed coal. This means that a certain area of the resource comprising Bench 9B does comply with the phosphorus specification of char plant feed coal and requires further investigation.

The average phosphorus content of Bench 11 is 0.0135% which is higher than what is required for the char plant. Since Bench 11 is currently the only bench utilized for the production of char plant feed coal due to its relatively low phosphorus content, this poses a risk on the availability of suitably low phosphorus coal in the resource throughout the life of the mine. The range and standard deviation indicates that the phosphorus distribution of Bench 11 is much less dispersed than that of Bench 9B. The significance of the relatively high maximum value requires further investigation.

Zone 1 is the only coal horizon at Grootegeluk Mine that has an average phosphorus content of less than 0.012%. The phosphorus content of Zone 1 is also the least dispersed, hence the relatively small range and standard deviation. This indicates that the phosphorus values throughout the population remain relatively close to the average value. The maximum phosphorus value demonstrates that even Zone 1 also has areas in the resource that are not suitable for char plant feed coal.

From the data depicted in Table 7 it is evident that the average phosphorus content in Bench 11 is approximately 1.6 times higher than that of Zone 1, while Bench 9B has average phosphorus of approximately 4.9 times higher than that of Bench 11. The average phosphorus content in the mining benches relative to that of Zone 1 and Bench 11 is summarized in Table 8. The increase in phosphorus towards the upper coal benches can be clearly observed from Table 8.

Table 8 Phosphorus content of the mining benches compared to Bench 11 and Zone 1

Stratigraphic Unit (Mining Bench)	Percentage phosphorus in coal containing 15% ash		
	Average phosphorus in coal	Phosphorus content relative to Bench 11	Phosphorus content relative to Zone 1
Bench 6	0.2205	16.3	25.9
Bench 7B	0.1589	11.8	18.7
Bench 9A	0.2889	21.4	34.0
Bench 9B	0.0655	4.9	7.7
Bench 11	0.0135	1.0	1.6
Zone 1*	0.0085	0.6	1.0

Rounding-off of figures may cause computational discrepancies.
* Zone 1 is currently not extracted at Grootegeluk Mine.

The statistical study of the phosphorus content in the different mining benches is further assessed by the use of histograms. Histograms help to show how the data in a population is distributed. In order to illustrate the different data distributions properly, bin sizes as well as the horizontal scale of the various histograms could not be kept equally sized. Although not exactly statistically correct, it was decided to use the same amount of bins throughout all the histograms. This was done in order to simplify the comparison between the histograms of the different coal seams. The seam containing the most data was used to determine the amount of bins to be used in all histograms throughout this report.

It was also decided to start histogram ranges as far as practically possible from 0% phosphorus in coal for the purpose of easier comparison between the histograms of the different seams. Figure 4 to Figure 9 illustrate the histograms for the phosphorus content of the different mining benches of the Vryheid Formation for a coal product containing 15% ash, as derived from the exploration borehole data.

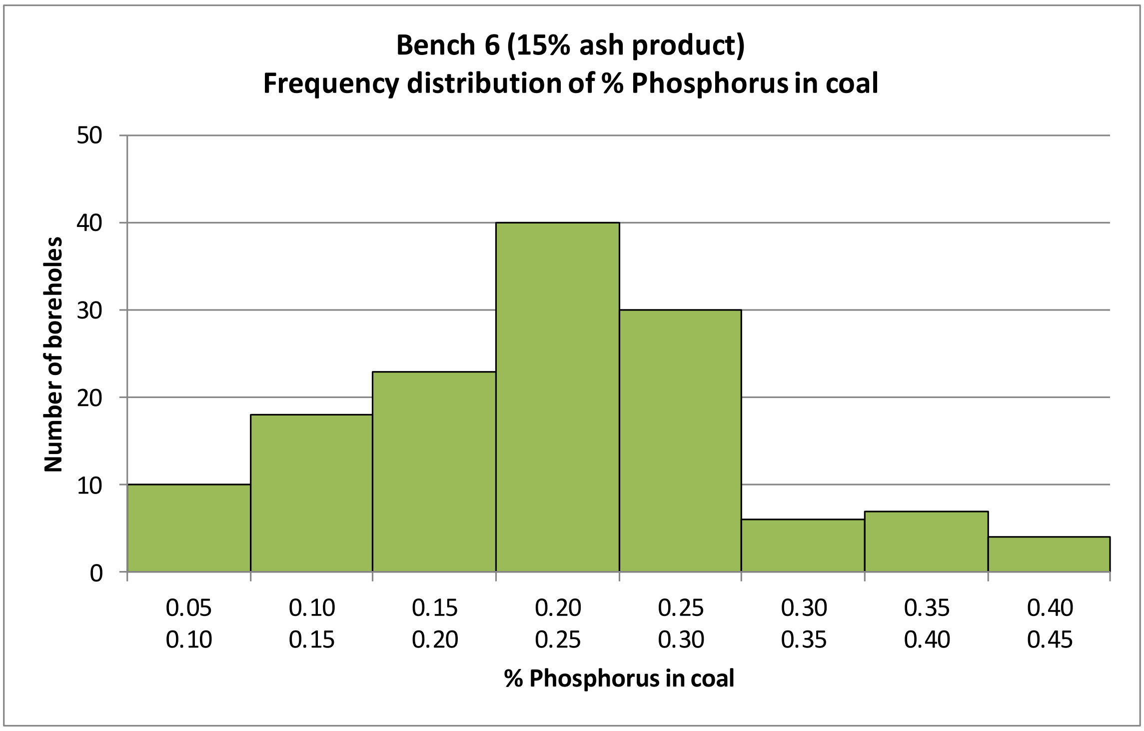

Figure 4 Histogram of the phosphorus content of Bench 6

The histogram of the phosphorus content of Bench 6 (Figure 4) indicates a near normal distribution with the average situated close to the median of the population. The entire population contains phosphorus in coal values that are higher than the allowable maximum of 0.012% used for char plant feed coal. This histogram shows that Bench 6 has very high phosphorus content.

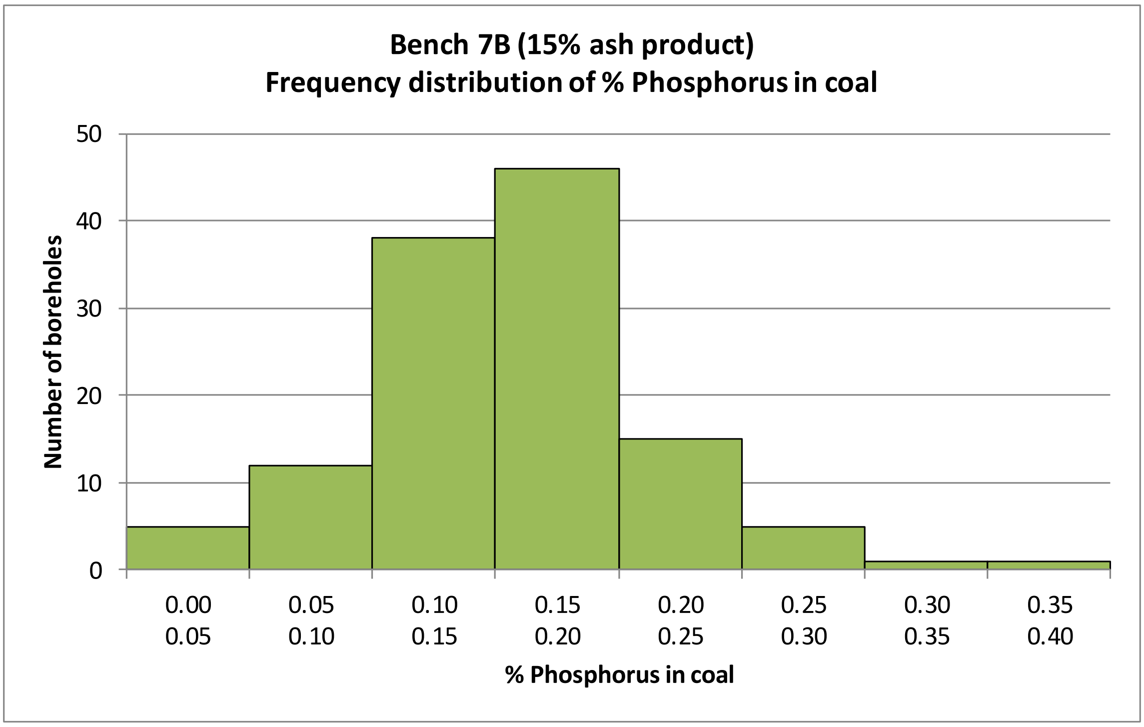

Figure 5 Histogram of the phosphorus content of Bench 7B

Note: The horizontal scale of Bench 7B has a range from 0.00% to 0.40% phosphorus in coal while that of Bench 6, illustrated in Figure 4, has a range of 0.05% to 0.45% phosphorus in coal.

The histogram of the phosphorus content of Bench 7B (Figure 5) indicates a rather normal distribution with the average close to the median of the population. Only five values fall in the lowermost class of this histogram (0.00% to 0.05% phosphorus in coal), meaning that these values might be below the required phosphorus specification for char plant feed coal. In general the histogram shows that Bench 7B has very high phosphorus content.

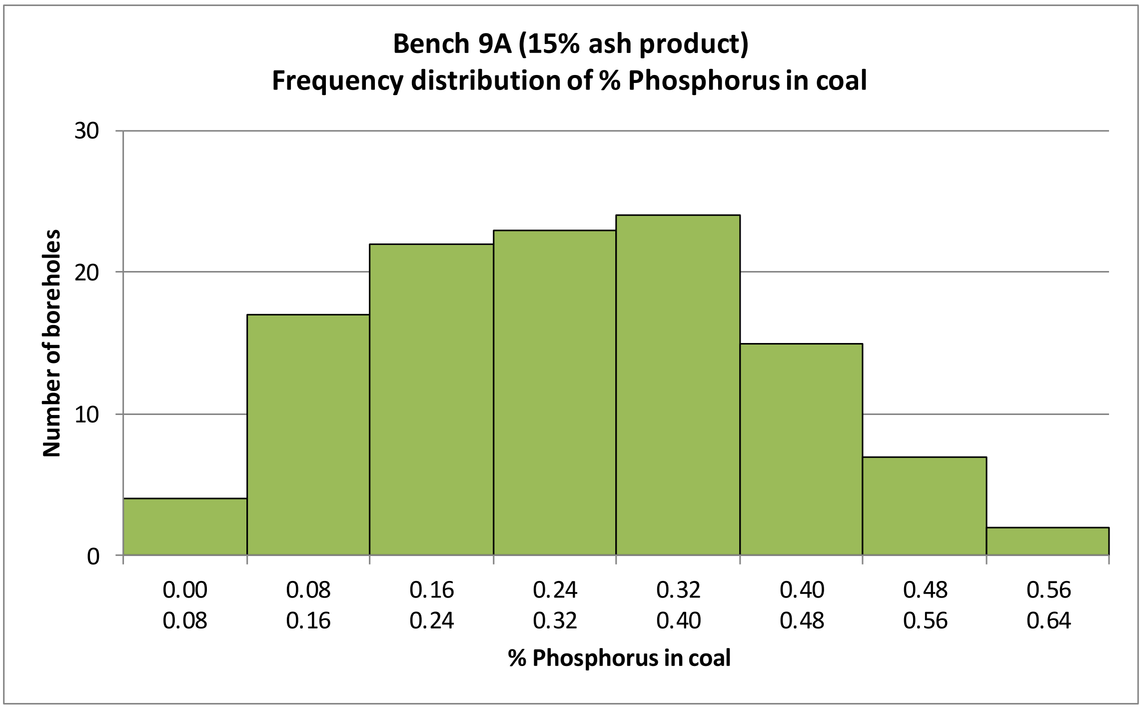

Figure 6 Histogram of the phosphorus content of Bench 9A

Note: The horizontal scale and bin sizes used in the histogram of Bench 9A differ from those of Benches 6 and 7A due to the variation in phosphorus content between the different mining benches. The histogram of Bench 9A has a range from 0.00% to 0.64% phosphorus in coal.

The histogram of the phosphorus content of Bench 9A (Figure 6) illustrates a rather normal distribution, with the average situated close to the median of the population. Similar to Benches 6 and 7B, very high phosphorus concentrations are present in the coal of Bench 9A. Only four values out of a total of 114 fall within the lowermost class of the range. This class, however, contains values of up to 0.08% phosphorus in coal and therefore these values might be too high for char plant feed coal.

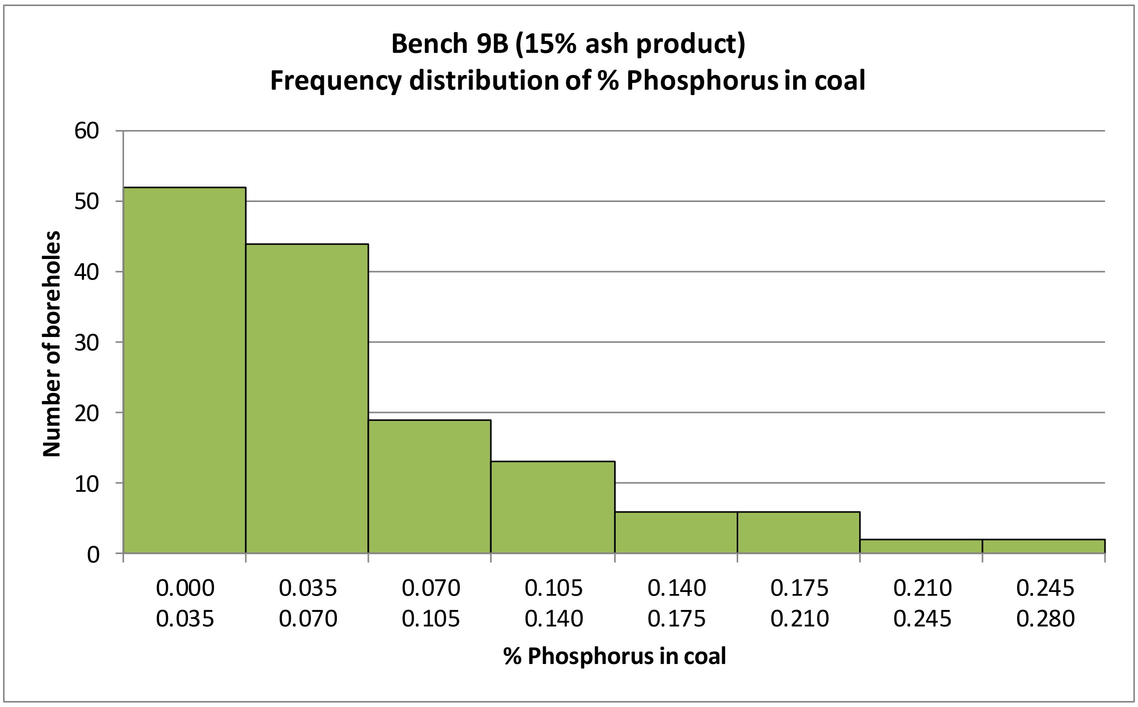

Figure 7 Histogram of the phosphorus content of Bench 9B

Note: The horizontal scale and bin sizes used in the histogram of Bench 9B differ from those of the other mining benches due to the variation in phosphorus content between the different mining benches. The histogram of Bench 9B has a range from 0.00% to 0.28% phosphorus in coal.

The histogram of the phosphorus content of Bench 9B (Figure 7) illustrates a strong positive skewness, with the average situated near the lower end of the population. In this histogram, 36% of the population fall within the lowermost class (0.00% to 0.035% phosphorus in coal). The upper limit of the lowermost class is higher than the allowable maximum of phosphorus required for char plant feed coal. It is therefore not possible to determine the significance of these relatively low values from the statistical analyses alone. Due to the high percentage of values falling in the lowermost class, further investigation of the phosphorus distribution in Bench 9B is required. Further investigation should include the lateral phosphorus distribution of the mining benches by means of geological models. Bench 9B is currently being used at Grootegeluk Mine for the production of metallurgical coal.

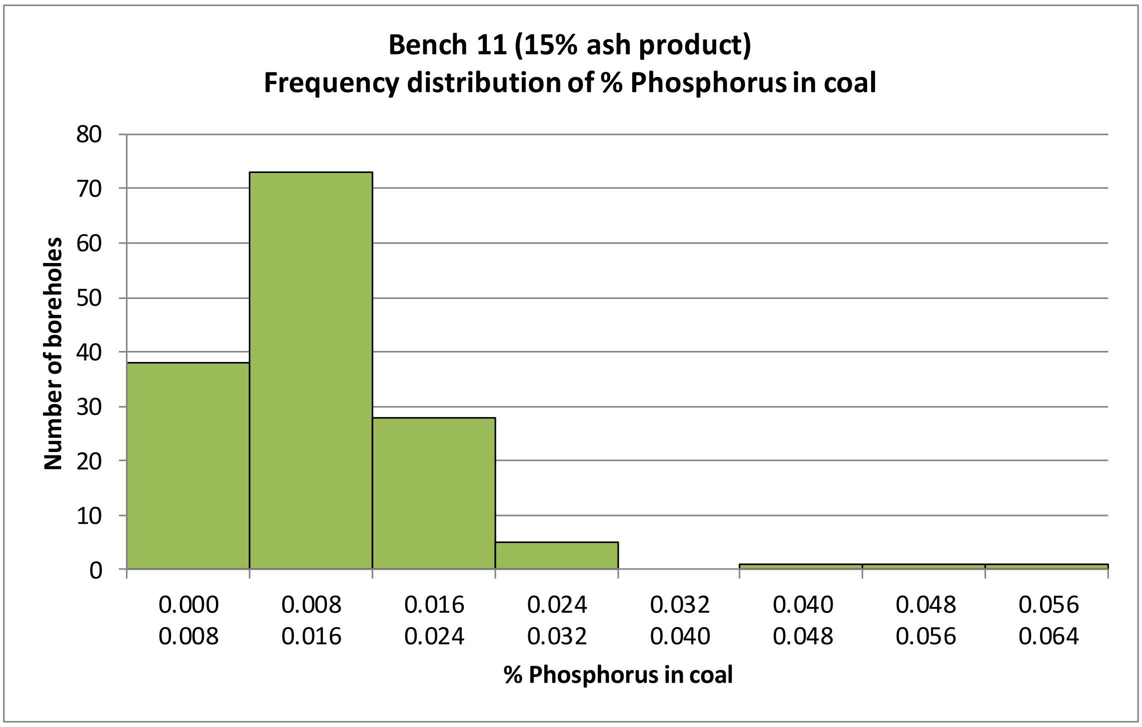

Figure 8 Histogram of the phosphorus content of Bench 11

Note: The horizontal scale and bin sizes used in the histogram of Bench 9B differ from those of the other mining benches due to the variation in phosphorus content between the different mining benches. The histogram of Bench 11 has a range from 0.00% to 0.064% phosphorus in coal.

The histogram of the phosphorus content of Bench 11 (Figure 8) shows a strong positive skewness, with the average value situated near the lower end of the population. One extremely high value of 0.089% phosphorus was regarded as an outlier and removed from the data for the purpose of this part of the investigation. This was done in order to get a better distribution of the remaining data by means of the histogram. The outlier value will be used when assessing the geological modelling of the phosphorus content of Bench 11 to get a better understanding of how this value relates to its neighbouring values and how big its influence may be on the resource.

Almost 26% of the phosphorus values of Bench 11 fall in the lowermost class of the population (0.00% to 0.008% phosphorous). These boreholes all contain phosphorus in the coal which is within specification for the production of char plant feed coal. The values in the second class of the histogram account for almost 50% of the population. It is however not possible to determine from this histogram what amount of these values are below 0.012% phosphorus in coal.

All the remaining classes in the histogram of Bench 11 contain phosphorus in coal values which are above the maximum specification limit for char plant feed coal. These values alone accounts for more than 24% of the population. Bench 11 is currently the only source of coal that is utilized for the production of char plant feed coal. Bench 11 is also utilized to produce metallurgical coal products when the demand for char plant feed coal is fulfilled.

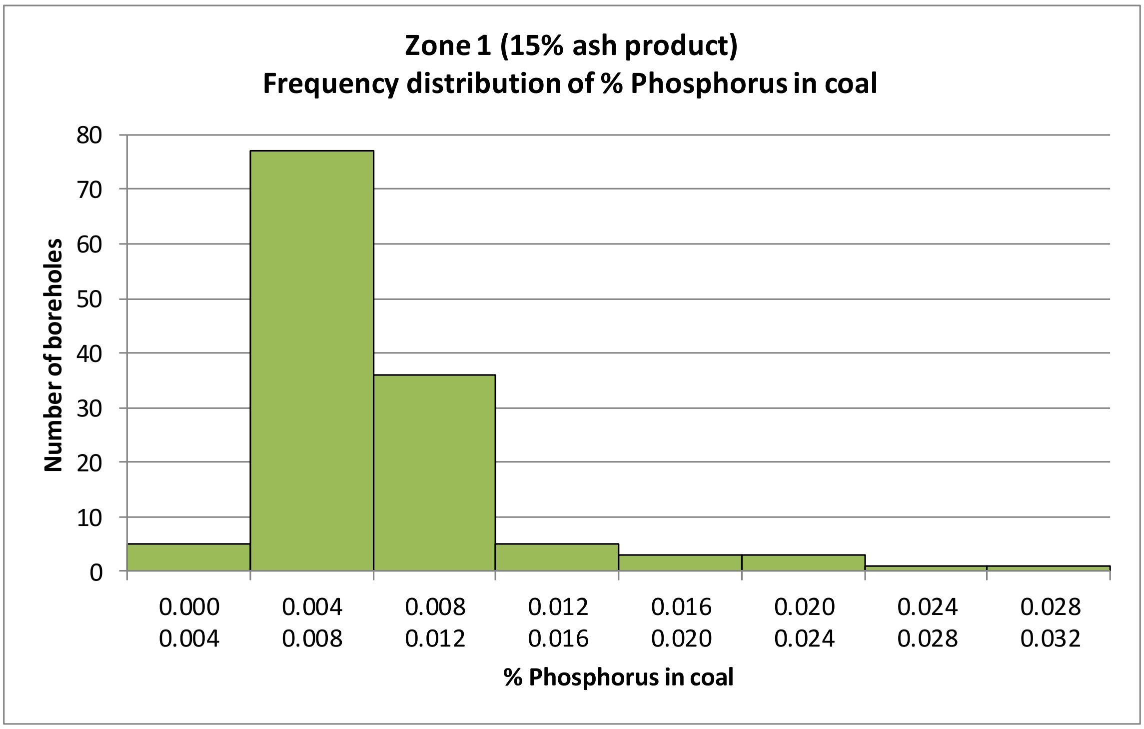

Figure 9 Histogram of the phosphorus content of Zone 1

Note: The horizontal scale and bin sizes used in the histogram of Zone 1 differ from those of the other benches due to the variation in phosphorus content of the different mining benches. The histogram of Zone 1 has a range from 0.00% to 0.032% phosphorus in coal.

The histogram of the phosphorus content of Zone 1 (Figure 9) is positively skewed, with the average situated near the bottom end of the population. The phosphorus content of Zone 1 is generally low. All the values included in the first three classes (90% of the data) fall within the phosphorus specification required for char plant feed coal. It can therefore be concluded that Zone 1 is the best suited to be utilized for char plant feed coal, but certain areas in the resource remain above this limit, illustrated by the classes containing data greater than 0.012% phosphorus in coal. A compilation of the phosphorus in coal histograms of the different mining benches is presented in Figure 10 and Figure 11. These figures provide a comparison of the variation in phosphorus content between the different benches.

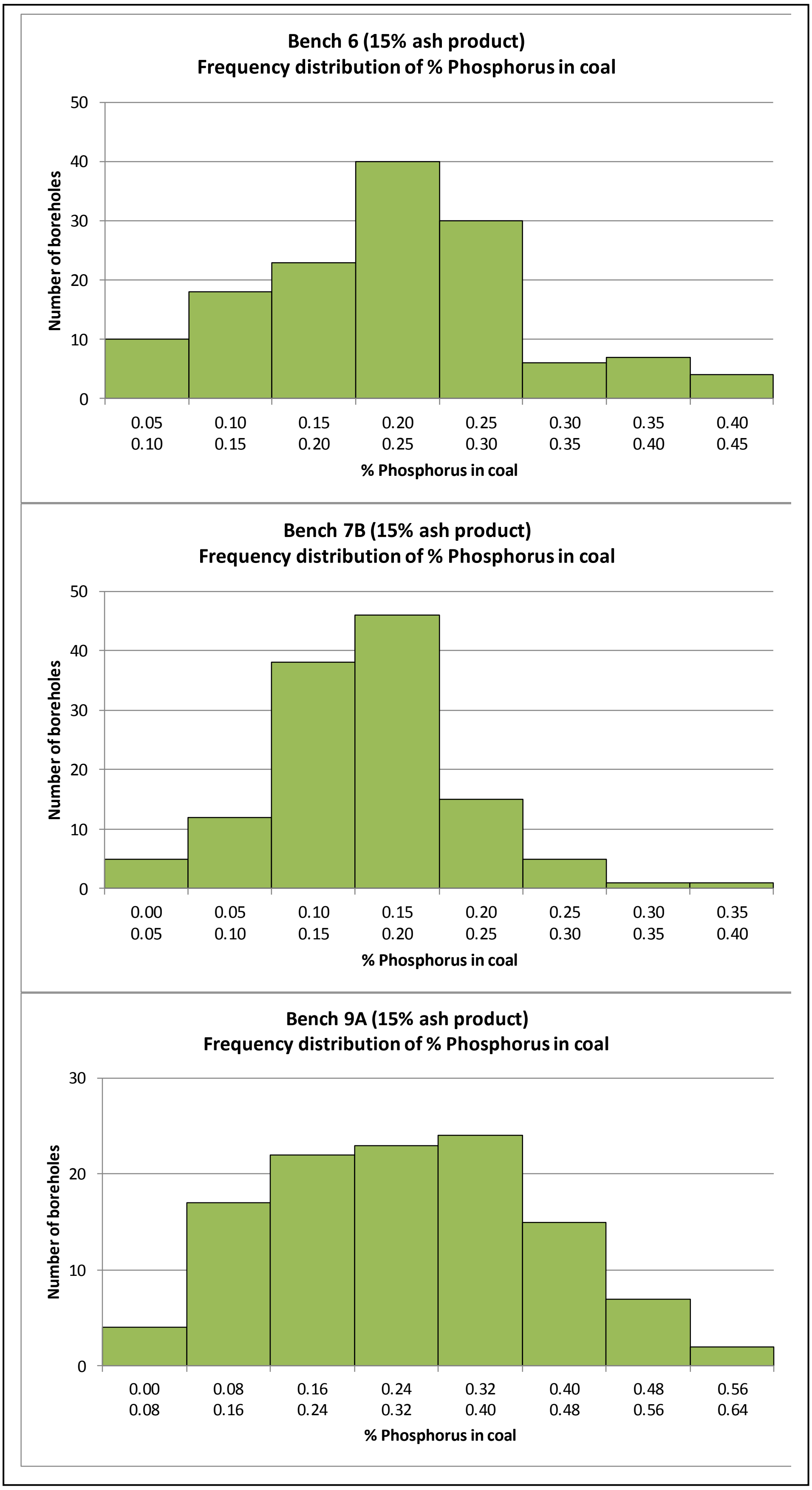

Figure 10 Compilation of the phosphorus in coal histograms of the mining benches

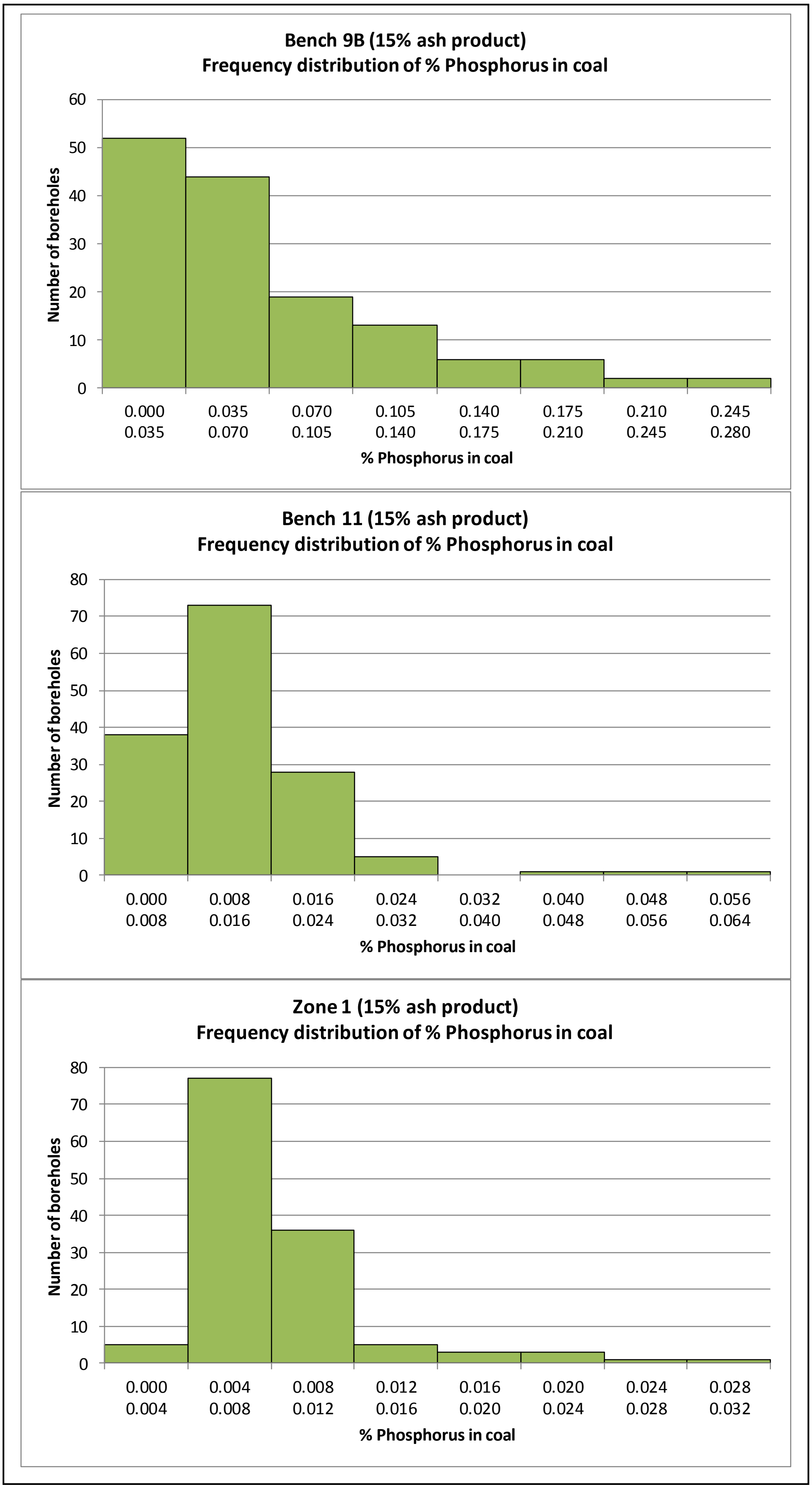

Figure 11 Compilation of the phosphorus in coal histograms of the mining benches

4.1.2 Sample units

The results of the statistical analyses of the phosphorus content of the sample units are summarised in Table 9.

Table 9 Statistical analysis of the phosphorus content of the samples

Stratigraphic Unit		Number of exploration boreholes containing phosphorus data	Percentage phosphorus in coal containing 15% ash				
			Mini-mum	Maxi-mum	Range	Average	Standard deviation
Bench 6	Sample 23A	138	0.0419	0.6160	0.5741	0.2316	0.1110
	Sample 23B	138	0.0380	0.9918	0.9538	0.3989	0.2094
	Sample 23C	138	0.0137	0.3424	0.3286	0.1211	0.0544
Bench 7B	Sample 24	123	0.0079	0.3967	0.3889	0.1589	0.0594
Bench 9A	Sample 25	29	0.0013	0.2023	0.2010	0.0872	0.0663
	Sample 25S*	Insignificant yield*					
	Sample 26	115	0.0092	0.6343	0.6252	0.2931	0.1311
Bench 9B	Sample 27	120	0.0347	0.7090	0.6743	0.1608	0.1496
	Sample 28	120	0.0059	0.2789	0.2730	0.0440	0.0421
	Sample 29	144	0.0046	0.1538	0.1493	0.0296	0.0273
Bench 11	Sample 30A**	62	0.0033	0.1100	0.1067	0.0224	0.0203
	Sample 30B**	63	0.0033	0.0262	0.0229	0.0074	0.0039
	Sample 30***	82	0.0026	0.0484	0.0458	0.0202	0.0101
	Sample 31	147	0.0026	0.1283	0.1257	0.0092	0.0126
Zone 1	Sample 32	131	0.0007	0.0295	0.0288	0.0085	0.0041

Rounding-off of figures may cause computational discrepancies.

* Sample 25S is a thin shale unit that forms part of Bench 9A. This sample delivers insignificant yield at 15% ash and is therefore not applicable to this evaluation.

** Samples 30A and 30B are new lithological units that were introduced in 2005 by introducing a division of the traditional Sample 30.

*** Sample 30 as a single lithological unit before the division into Sample 30A and Sample 30B was introduced.

The individual sample units were investigated in order to evaluate the vertical phosphorus distribution in the mining benches. The selection of different mining benches or selective mining benches will have to be based on combinations of adjacent sample units. The interrelationship between mining benches and sample units is also shown in Table 9.

4.1.2.1 Bench 6 samples

Bench 6 consists of Samples 23A, 23B and 23C from top to bottom. Table 9 indicates that the average phosphorus concentrations in all three of these samples are very high, but the basal sample (Sample 23C) has much less phosphorus than the upper two samples of the bench. The highest average phosphorus is present in Sample 23B (the middle portion of the bench). The minimum values of all three of the Bench 6 samples are above the maximum allowable percentage phosphorus required for char plant feed coal. It is therefore not worthwhile to investigate the phosphorus distribution of Bench 6 any further. Bench 6 is currently being utilized for power station coal at Grootegeluk Mine and this investigation confirms that this option should remain unchanged for the time being due to the high phosphorus content of the bench.

4.1.2.2 Bench 7B samples

Sample 24 is the only sample comprising Bench 7B. In the statistical analyses of the mining benches (Section 4.1.1), it was already determined that Bench 7B has a very high average phosphorus concentration (0.1589%). Bench 7B is also relatively thin (on average only approximately 1.5 m thick). This makes any subdivision of Bench 7B impractical to adopt due to current mining extract. Due to this and the fact that the vertical phosphorus distribution of Bench 7B cannot be studied at a finer resolution, it is not worthwhile to investigate the phosphorus distribution of Bench 7B any further. Bench 7B is currently being utilized for power station coal at Grootegeluk Mine and this investigation confirms that this option should remain unchanged for the time being due to the high phosphorus content of the bench.

4.1.2.3 Bench 9A samples

Bench 9A consists of Samples 25, 25S and 26 from top to bottom. Sample 25 is a very thin coal unit (approximately 0.5 m thick) and is not developed throughout the resource area. It was mainly intersected in exploration boreholes that were drilled long ago in the area of the current mined-out pit. This is the reason for the relatively small population of Sample 25 data.

Sample 25S is a carbonaceous shale unit situated between Samples 25 and 26, hence the number of this sample ending with the letter "S". Sample 25S is only present where Sample 25 is also developed, and therefore also has a relatively small population. Due to its composition, Sample 25S delivers insignificant yields at 15% ash and is therefore not considered relevant to this evaluation. This and the fact that Samples 25 and 25S have not been intersected in most exploration boreholes drilled in the remaining portion of the resource, makes their contribution towards the purpose of this investigation insignificant. Sample 26 is therefore the only sample of interest comprising Bench 9A for future mining purposes and of relevance to the current investigation.

The average phosphorus content of Sample 26 is very high (0.2931%). The phosphorus of Sample 26 is also highly dispersed hence the large range and standard deviation. The minimum is below the char feed phosphorus limit of 0.012% but the maximum is extremely high and exceeds this limit by far. Figure 12 illustrates the histogram of the phosphorus content of Sample 26.

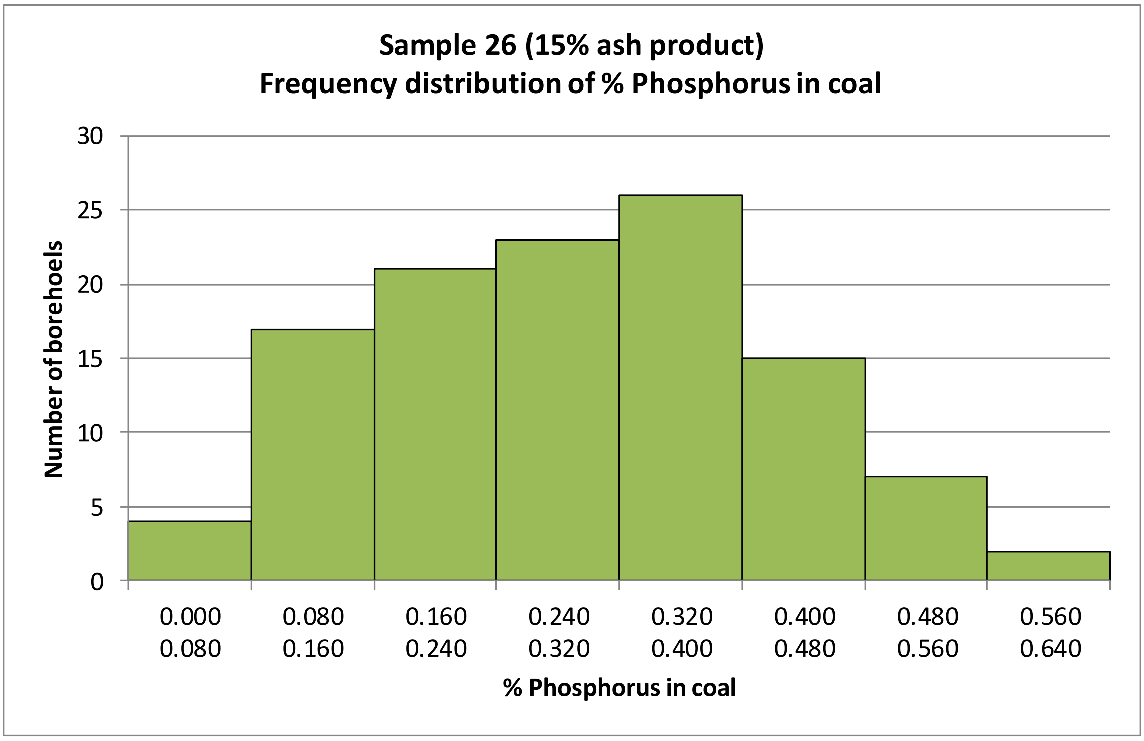

Figure 12 Histogram of the phosphorus content of Sample 26

The histogram of the phosphorus content of Sample 26 (Figure 12) has a normal shape, with the average situated near median of the population. The flat shape emphasizes the variability of the phosphorus distribution in the coal. Only four values are present in the first class. The upper limit of the first class is 0.08% phosphorus in coal which is much higher than the requirement for char plant feed coal. This investigation therefore confirms that Sample 26 contains very high phosphorus concentrations and is not suitable for char plant feed coal with regards to its phosphorus content. Bench 9A is currently being utilized for power station coal at Grootegeluk Mine and this investigation confirms that this option should remain unchanged for the time being due to the high phosphorus content of the bench.

4.1.2.4 Bench 9B samples

Bench 9B consists of Samples 27, 28 and 29 from top to bottom. The statistical analyses of the samples (Table 9) indicate that the average phosphorus content increases from the basal sample upwards. The average phosphorus content in all three of these samples is higher than the maximum allowable amount of 0.012% required for char plant feed coal. However, the minimum phosphorus value in both Samples 28 and 29 are below this limit. It is therefore imperative to investigate the frequency distributions of the Bench 9B samples in order to complete the investigation of the vertical phosphorus distribution in the bench. Figure 13 to Figure 15 illustrate the histograms of the phosphorus content of Samples 27 to 29 respectively.

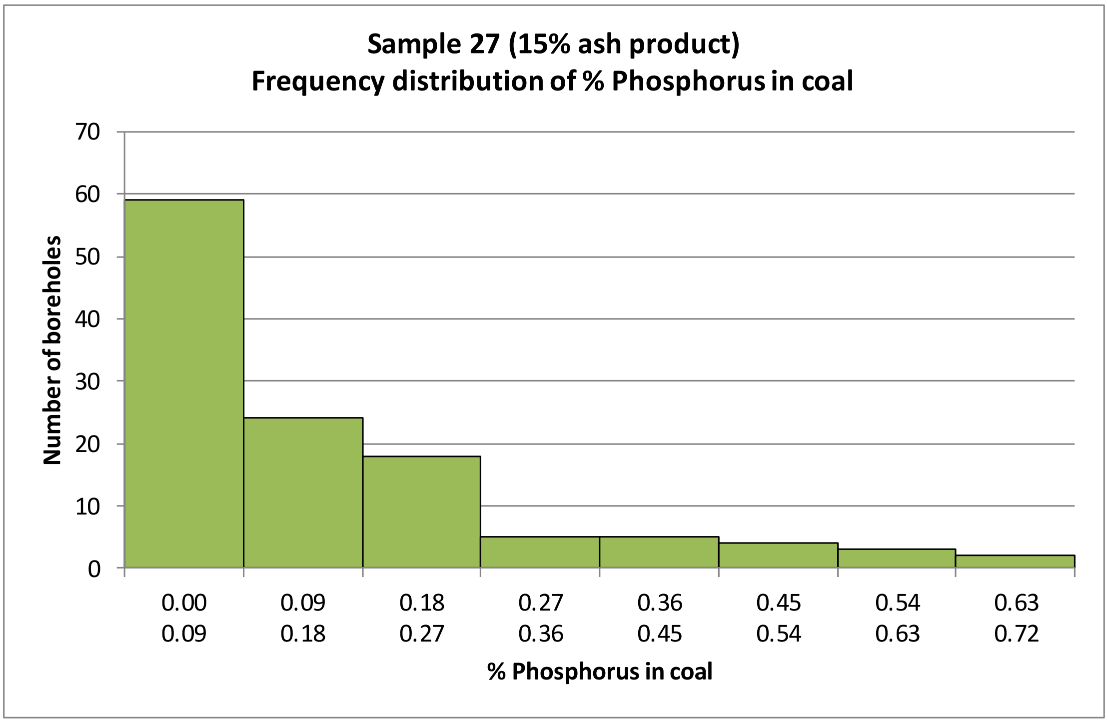

Figure 13 Histogram of the phosphorus content of Sample 27

Note: The horizontal scale and bin sizes used in the histogram of Sample 27 differ from that of Sample 26 due to the variation in phosphorus content between the different sample units. The histogram of Sample 27 has a range from 0.00% to 0.72% phosphorus in coal while that of Sample 26 has a range from 0.00% to 0.64% phosphorus in coal.

The histogram of the phosphorus content of Sample 27 (Figure 13) is positively skewed with the average situated near the bottom end of the population. Although more than 49% of the population fall in the lowermost class (0.00% to 0.09% phosphorus in coal), the upper limit of this class is higher than 0.012% phosphorus in coal. This means that these values might be above the allowable maximum phosphorus limit for char plant feed coal. In general this histogram shows that the phosphorus content of Sample 27 is very high.

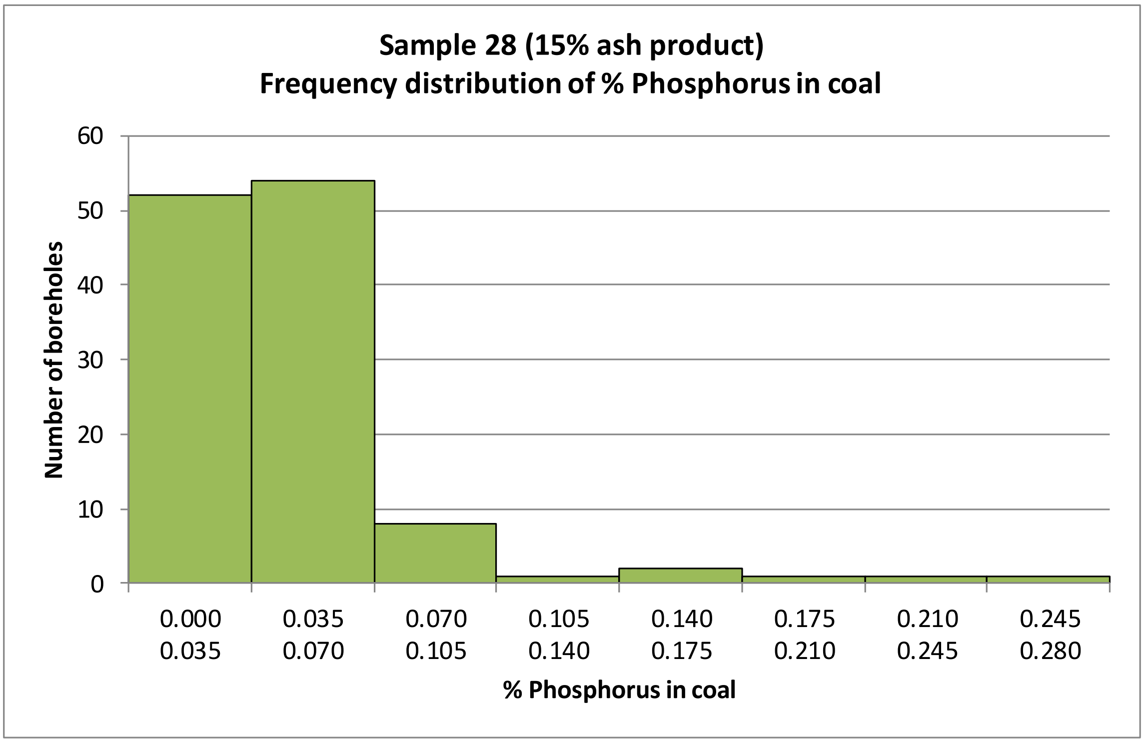

Figure 14 Histogram of the phosphorus content of Sample 28

Note: The horizontal scale and bin sizes used in the histogram of Sample 28 differ from that of Sample 27 due to the variation in phosphorus content between the two samples. The histogram of Sample 28 has a range from 0.00% to 0.28% phosphorus in coal while that of Sample 27 has a range from 0.00% to 0.72% phosphorus in coal.

The histogram of the phosphorus content of Sample 28 (Figure 14) is positively skewed with the average situated near the bottom end of the population. More than 43% of the values fall in the lowermost class of the population (0.00% to 0.035% phosphorus in coal). Since the upper limit of the lower class is higher than 0.012% phosphorous, it is not possible to determine the significance of these low values by means of statistical analyses alone. Additional investigative methods are therefore required to complete the study.

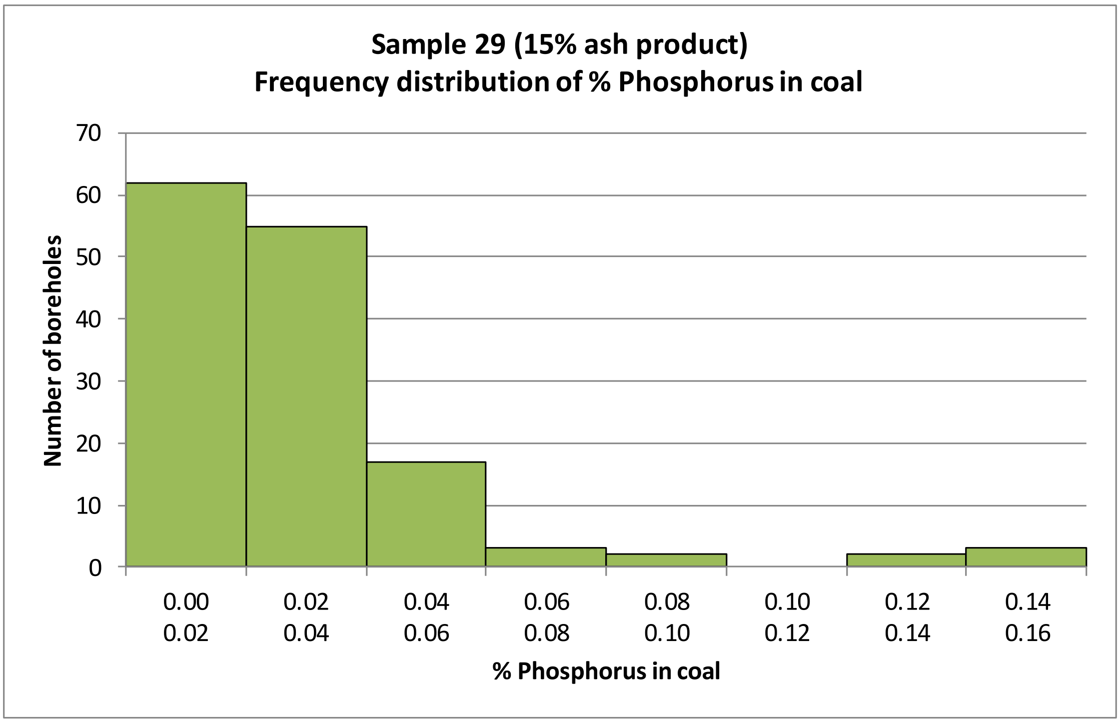

Figure 15 Histogram of the phosphorus content of Sample 29

Note: The horizontal scale and bin sizes used in the histogram of Sample 29 differ from those of the other sample units due to the variation in phosphorus content between the different sample units. The histogram of Sample 29 has a range from 0.00% to 0.16% phosphorus in coal while that of Sample 28 has a range from 0.00% to 0.28% phosphorus in coal.

The histogram of the phosphorus content of Sample 29 (Figure 15) is positively skewed, with the average situated near the bottom end of the population. In this histogram, 43% of the population fall in the lowermost class (0.00% to 0.02% phosphorus in coal). Like in the case of Sample 28, the upper limit of the lowermost class of the histogram of Sample 29 is also above 0.012% phosphorus and therefore not all values in this class can be regarded as suitable for char plant feed coal. Further investigation is required to determine the significance of these low phosphorus values. The values in the upper classes were not regarded as outliers and have not been removed from the data. Bench 9B is currently being utilized to produce medium phosphorus metallurgical coal at Grootegeluk Mine.

A compilation of the phosphorus in coal histograms of the samples comprising Bench 9B is illustrated in Figure 16 (from upper to lower sample). This figure provides for easy comparison of the variation in the phosphorus content between the different samples.

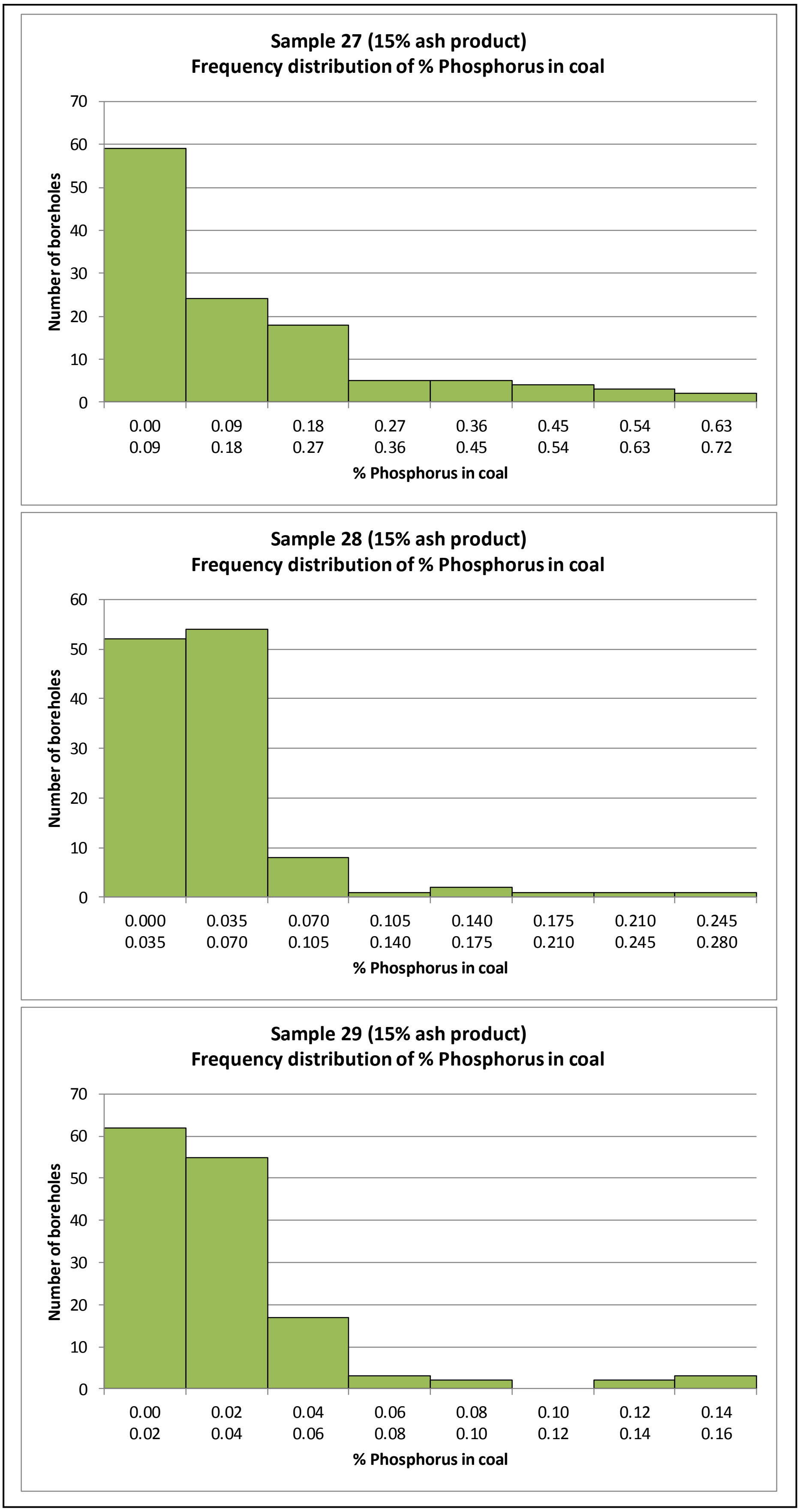

Figure 16 Compilation of the phosphorus in coal histograms of the Benches 9B samples

4.1.2.5 Bench 11 samples

Bench 11 consists of Samples 30A, 30B and 31 from top to bottom (Table 9). In the case of Samples 30A and 30B, the statistical analyses were performed on those boreholes that were drilled since 2005, after the division of Sample 30 had been introduced. Similarly, the statistical analysis of Sample 30 is derived from borehole data that were drilled before the division of Sample 30 was introduced. These statistical analyses are therefore performed on an individual sample basis, i.e. no combining of sample data is involved. Sample 30 is being studied here for completeness only.

Table 9 depicts that the average phosphorus concentrations in all three samples comprising Bench 11 are relatively low, with Sample 30B having the lowest average phosphorus content. The phosphorus content of Sample 30B is slightly lower than that of Sample 31, but roughly three times lower than that of Sample 30A. It is therefore evident that the high phosphorus in Bench 11 occurs in the upper portion of the bench (Sample 30A). This confirms previous work by Dreyer (2007) which indicated that Sample 30A contains the highest proportion of phosphorus in Bench 11. Figure 17 to Figure 19 illustrate the histograms of the phosphorus content of Samples 30A, 30B and 31 respectively.

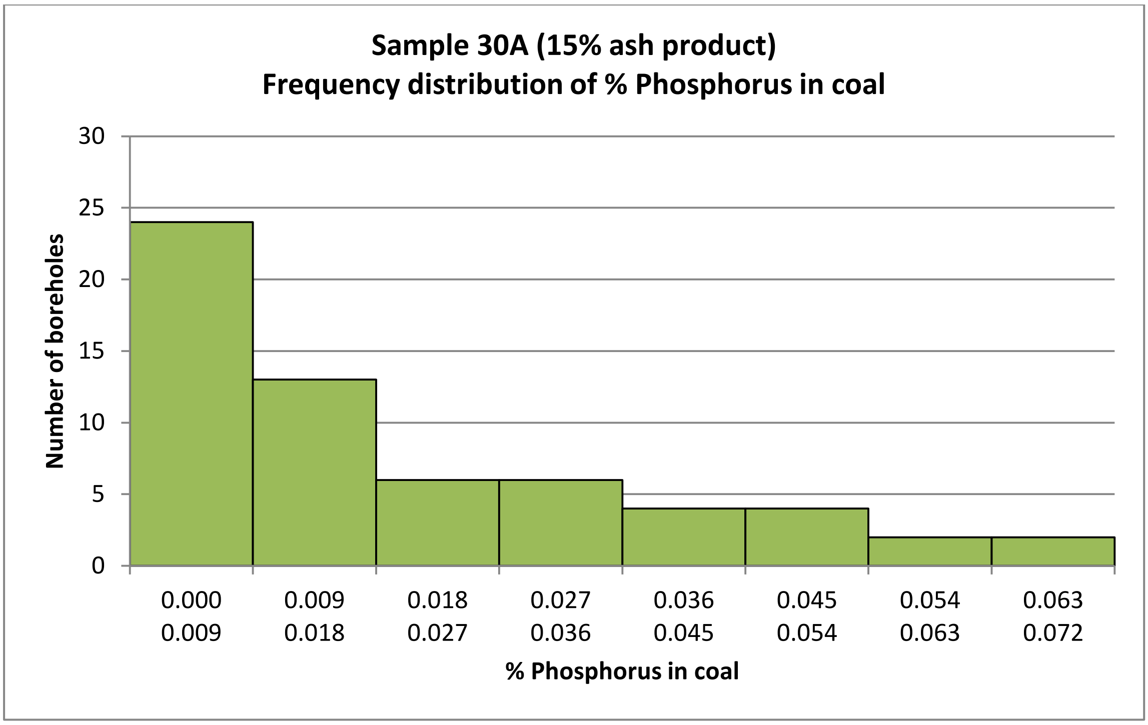

Figure 17 Histogram of the phosphorus content of Sample 30A

Note: The histogram of Sample 30A has a range from 0.00% to 0.072% phosphorus in coal.

The histogram of the phosphorus content of Sample 30A (Figure 17) has a strong positive skewness with the average situated near the bottom end of the population. One very high value which may be an outlier was excluded from the data used in the histogram. This value however will be used in the geological modelling in order to evaluate its influence on the Sample 30A resource. The majority of the data (> 39%) fall in the lowermost class of the population (0.00% to 0.009% phosphorus in coal). The upper limit of this class is lower than the required maximum phosphorus content required for char plant feed coal; this portion of the population would therefore be suitable for the production of char plant feed coal. In general, Sample 30A has phosphorus which is higher than the required level for char plant feed coal, but certain areas in the resource may be of suitably low phosphorus content.

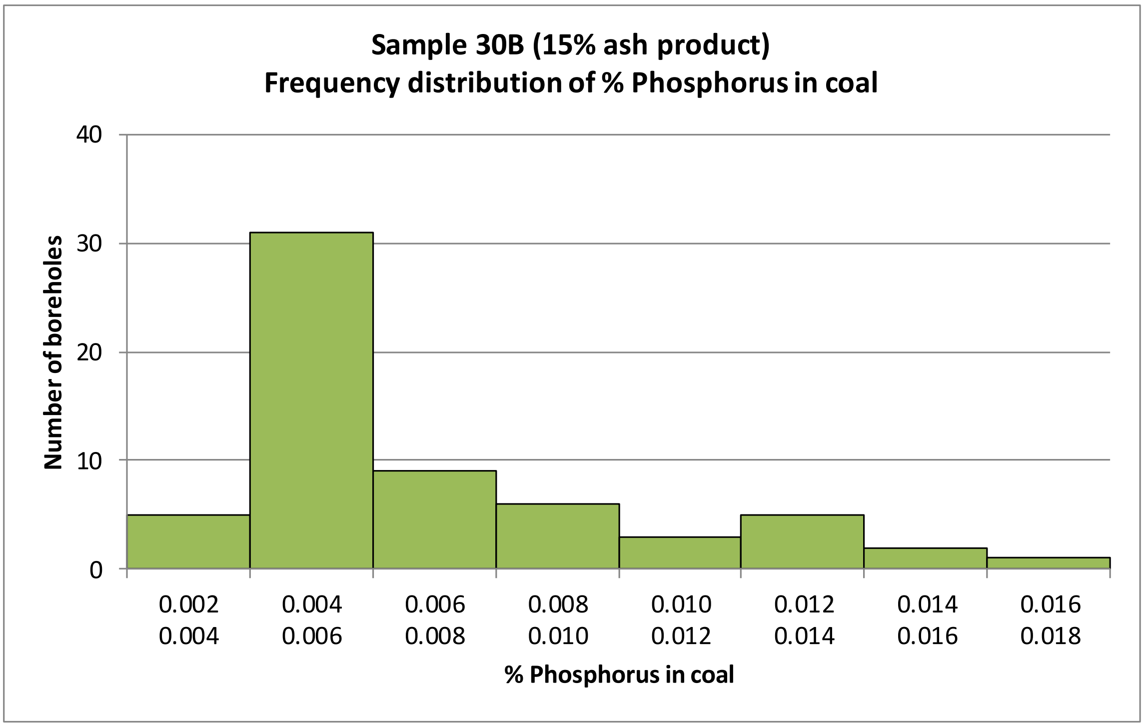

Figure 18 Histogram of the phosphorus content of Sample 30B

Note: The horizontal scale and bin sizes used in the histogram of Sample 30B differ from that of Sample 30A due to the variation in phosphorus content between these two samples. The histogram of Sample 30B has a range from 0.002% to 0.018% phosphorus in coal while that of Sample 30A has a range from 0.00% to 0.072% phosphorus in coal.

The histogram of the phosphorus content of Sample 30B (Figure 18) has a strong positive skewness with the average situated near the bottom end of the population. As was the case with Sample 30A, one very high value, which may be an outlier, was excluded from the data used in the histogram. This value will also be used in the geological modelling in order to evaluate its influence on the phosphorus content over the Sample 30B resource. All data falling in the bottom five classes of the histogram is within the required phosphorus specification for char plant feed coal. In general the phosphorus content of Sample 30B is within the specification limit of char plant feed coal, but a few higher values mean that this sample does not always comply.

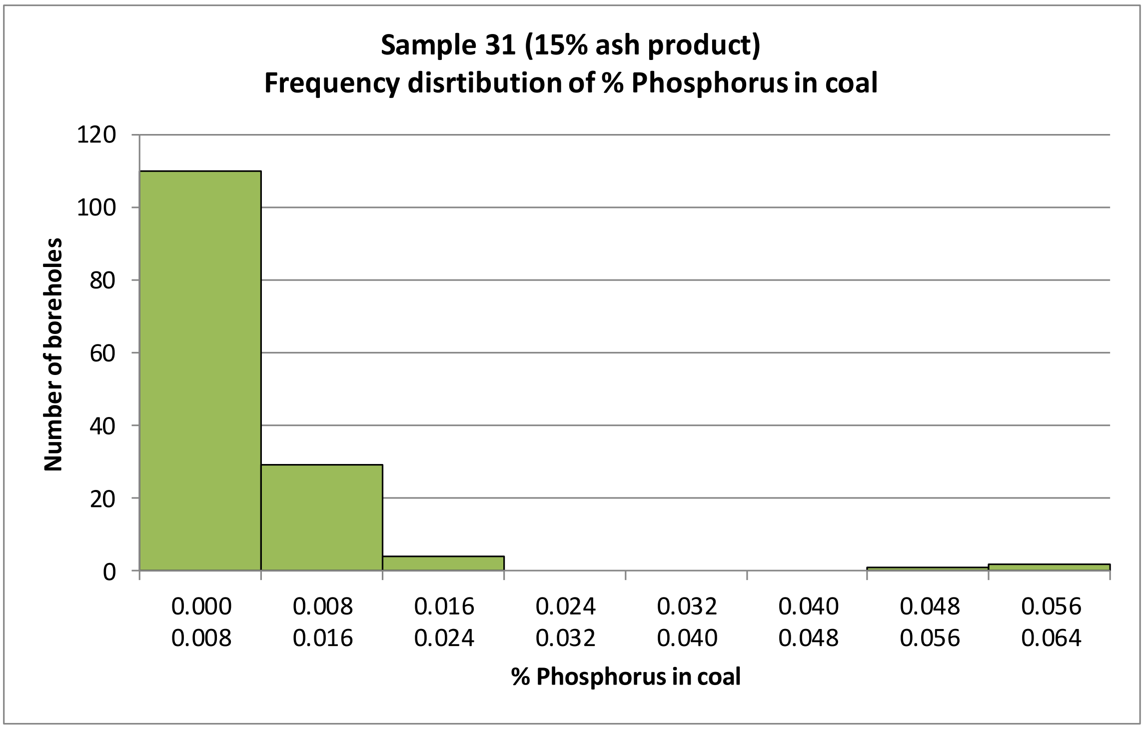

Figure 19 Histogram of the phosphorus content of Sample 31

Note: The horizontal scale and bin sizes used in the histogram of Sample 31 differ from those of Sample 30A and Sample 30B due to the variation in phosphorus content between the sample units. The histogram of Sample 31 has a range from 0.00% to 0.064% phosphorus in coal.

The histogram of the phosphorus content of Sample 31 (Figure 19) has a very strong positive skewness, with the average situated close to the bottom end of the population. A few very high values contribute to the strongly positive skew shape of the histogram. One extremely high value, which may be an outlier, was excluded for from the data used in the histogram. This value will be used in the geological modelling in order to evaluate its influence on the Sample 31 resource. More than 75% of the data falls in the lowermost class of the population (0.00% to 0.008% phosphorus in coal). All values falling in this class are within the required phosphorus specification for char plant feed coal. In general the phosphorus content of Sample 31 is rather low, but a few higher values have a negative effect on the average phosphorus content of the sample.

The frequency distribution of the phosphorus content of Sample 30, as obtained from boreholes which were drilled before the subdivision of this lithological, was also examined. Figure 20 illustrates the histogram of the phosphorus content of Sample 30.

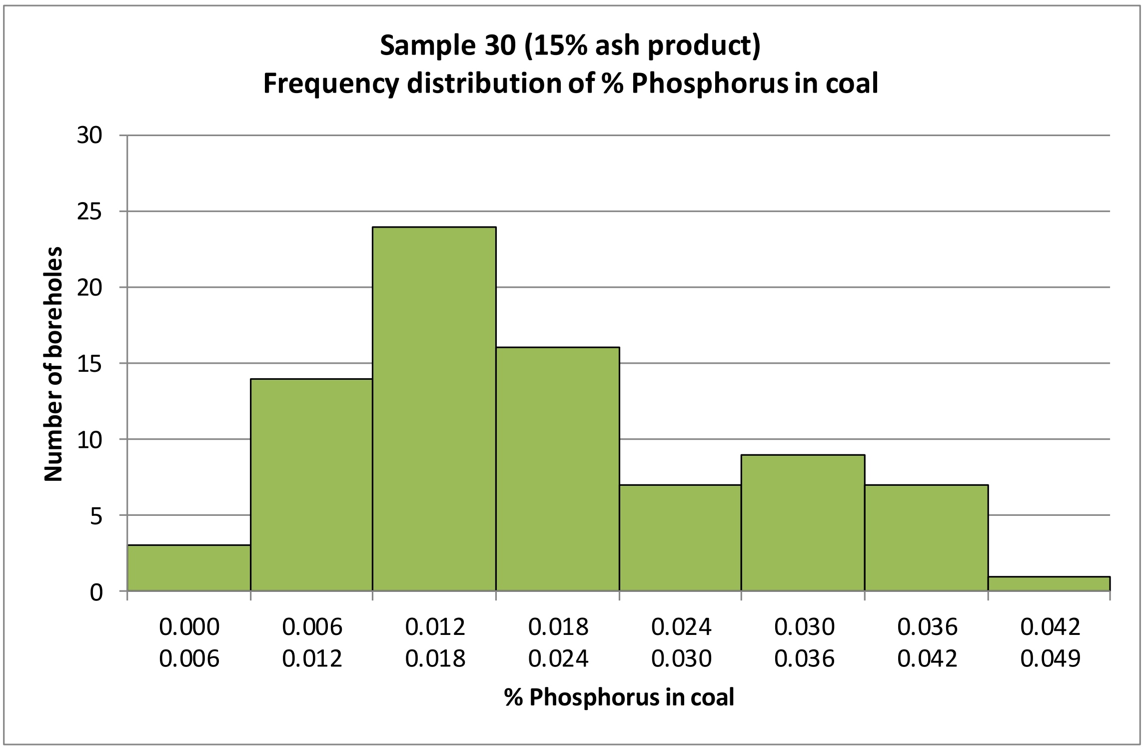

Figure 20 Histogram of the phosphorus content of Sample 30

Note: The horizontal scale and bin sizes used in the histogram of Sample 30 differ from those of Sample 30A and Sample 30B due to the variation in phosphorus content between the sample units. The histogram of Sample 30 has a range from 0.00% to 0.049% phosphorus in coal.

The histogram of the phosphorus content of Sample 30 (Figure 20) shows a moderate positive skewness and exhibits both extremely low values as well as some fairly high values. It is interesting to note that the phosphorus distribution of Sample 30 represents neither that of Sample 30A nor Sample 30B. Both these samples have strong positively skewed histograms while the histogram of Sample 30 is much flatter and well dispersed across its range. A compilation of the phosphorus in coal histograms of the samples comprising Bench 11 is illustrated in Figure 21. This figure provides for easy comparison of the variation in the phosphorus distribution of the different Bench 11 samples. Sample 30 was left out here in order to focus on the current sample composition of Bench 11 rather than on the historical sample composition of the bench.

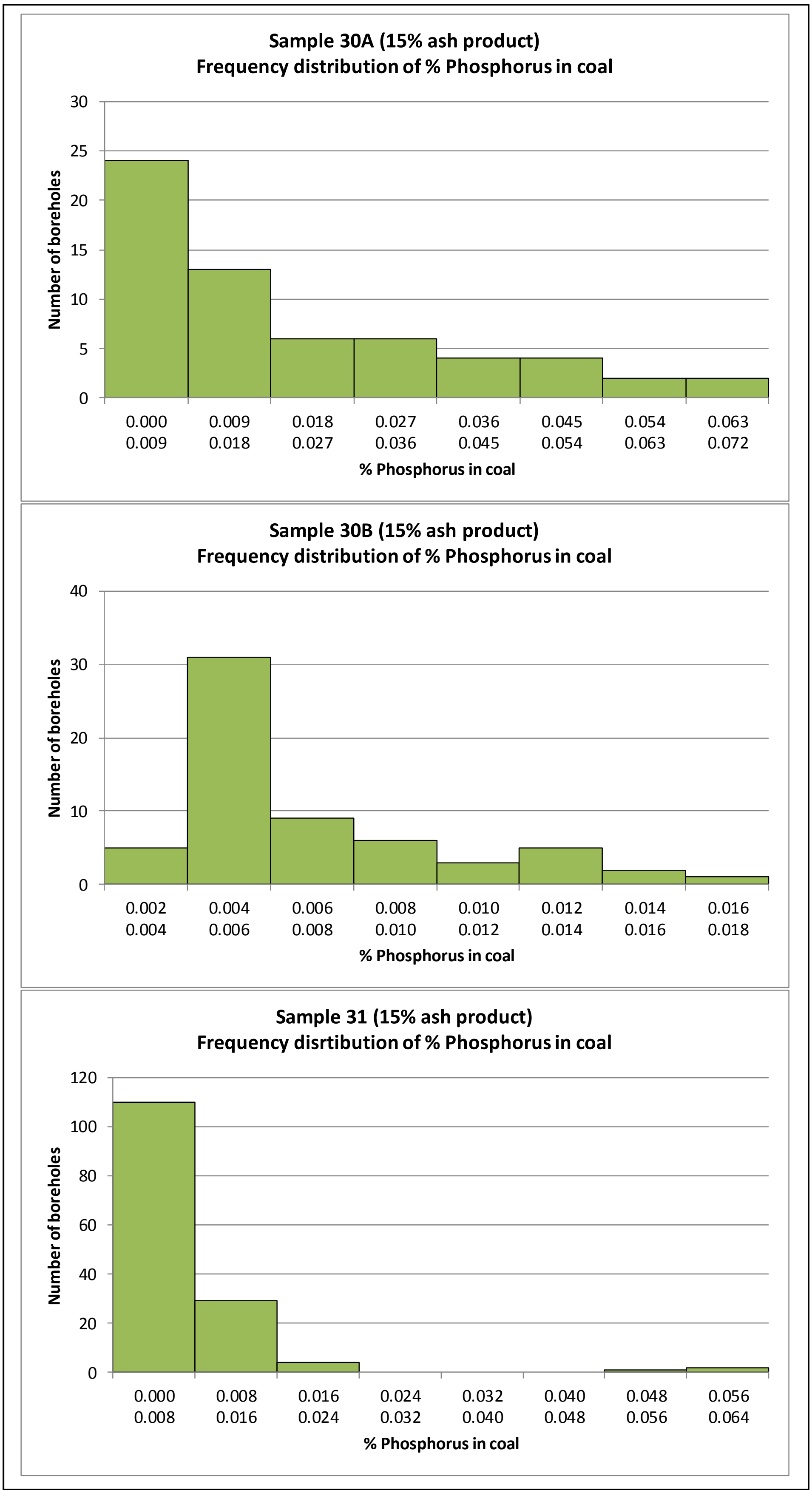

Figure 21 Compilation of the phosphorus in coal histograms of the Benches 11 samples

4.1.2.6 Zone 1 samples

Zone 1 consists of only one sample unit, namely Sample 32 (Table 9). The histogram of Sample 32 is therefore the same as for Zone 1 presented earlier in Section 4.1.1 and shown in Figure 9. Since Zone 1 has only one sample unit, it is not possible to assess the vertical phosphorus distribution of this coal seam. Due to the relative low seam thickness, it is also not recommended to divide this coal seam into smaller sample units. For completeness, the histogram of Sample 32 (Zone 1) is presented again in Figure 22.

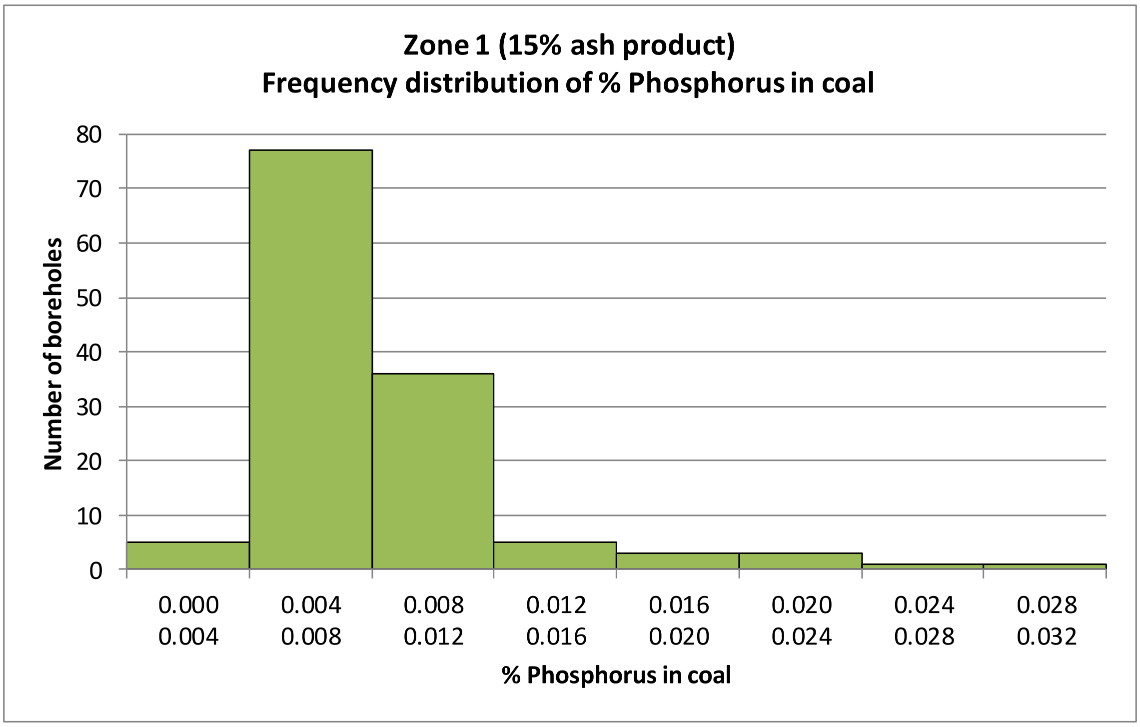

Figure 22 Histogram of the phosphorus content of Sample 32

Note: The horizontal scale of the histogram of Sample 32 has a range from 0.00% to 0.032% phosphorus in coal.

The histogram of Sample 32 (Figure 22) shows that the majority of the data reports in the lower three classes. These classes contain data of phosphorus concentrations which is suitable for char plant feed coal (Section 4.1.1).

4.1.3 Sample 30A sub-samples

The samples and analyses used in this part of the investigation were obtained from the five specially drilled cored boreholes in the open pit area through Bench 11 (Section 3.4). The results of the statistical analyses performed on the phosphorus content of the Sample 30A sub-samples are summarized in Table 10. For easy reference, the Sample 30A results as obtained from boreholes drilled across the resource area are also included in this table.

Table 10 Statistical Analyses of the phosphorus content of the Sample 30A sub-samples

Stratigraphic unit (Sub-sample)	Number of exploration boreholes containing phosphorus data	Percentage phosphorus in coal containing 15% ash				
		Minimum	Maximum	Range	Average	Standard deviation
Sample 30A-1*	5	0.0131	0.0838	0.0707	0.0533	0.0261
Sample 30A-2*	5	0.0393	0.1597	0.1205	0.0863	0.0442
Sample 30A–3*	5	0.0145	0.1205	0.1059	0.0553	0.0393
Sample 30A**	62	0.0033	0.1100	0.1067	0.0224	0.0203

Rounding-off of figures may cause computational discrepancies.
* Vertical subdivision of Sample 30A (sub-samples)
** The full Sample 30A unit from which the Sample 30A sub-samples was obtained.

Table 10 shows that the average phosphorus content is the lowest in Sample 30A-1, followed by Sample 30A-3 which is only slightly higher. The highest phosphorus content is situated in Sample 30A-2 (the middle portion of Sample 30A). In all three sub-samples, the average phosphorus concentrations are higher than the maximum allowable amount for char plant feed coal. This is also the case with the minimum values in all three sub-samples. In general, the statistical analyses of the phosphorus content of the Sample 30A sub-samples show that all vertical portions of Sample 30 are unsuitable for char plant feed coal with regards to their phosphorus content. Due to the low amount of data available for the Sample 30A sub-samples, it would be meaningless to present histograms for these units.

4.2 Geological modelling

4.2.2 Mining benches

The statistical analyses presented in Section 4.1.1 showed that the phosphorus content of Bench 6 as well as all the samples comprising Bench 6 is well above the maximum specification limit for char plant feed coal. The statistical analyses of Benches 7B and 9A have also shown very high phosphorus concentrations. Both these benches consist of only one sample going forward in the life of the mine. These benches are therefore omitted from further study through geological modelling.

4.2.2.1 Bench 9B

The statistical analysis of Bench 9B (Section 4.1.1) revealed that this bench contains medium phosphorus content coal, but the minimum value is very low. The histogram of the phosphorus content of Bench 9B indicated a fair amount of values in the lower most class of the population, and therefore the need for further investigation by means of geological modelling. This geological model will also be used to determine the significance of the low phosphorus values in this mining bench. The geological model of the phosphorus content of Bench 9B is illustrated in Figure 23.

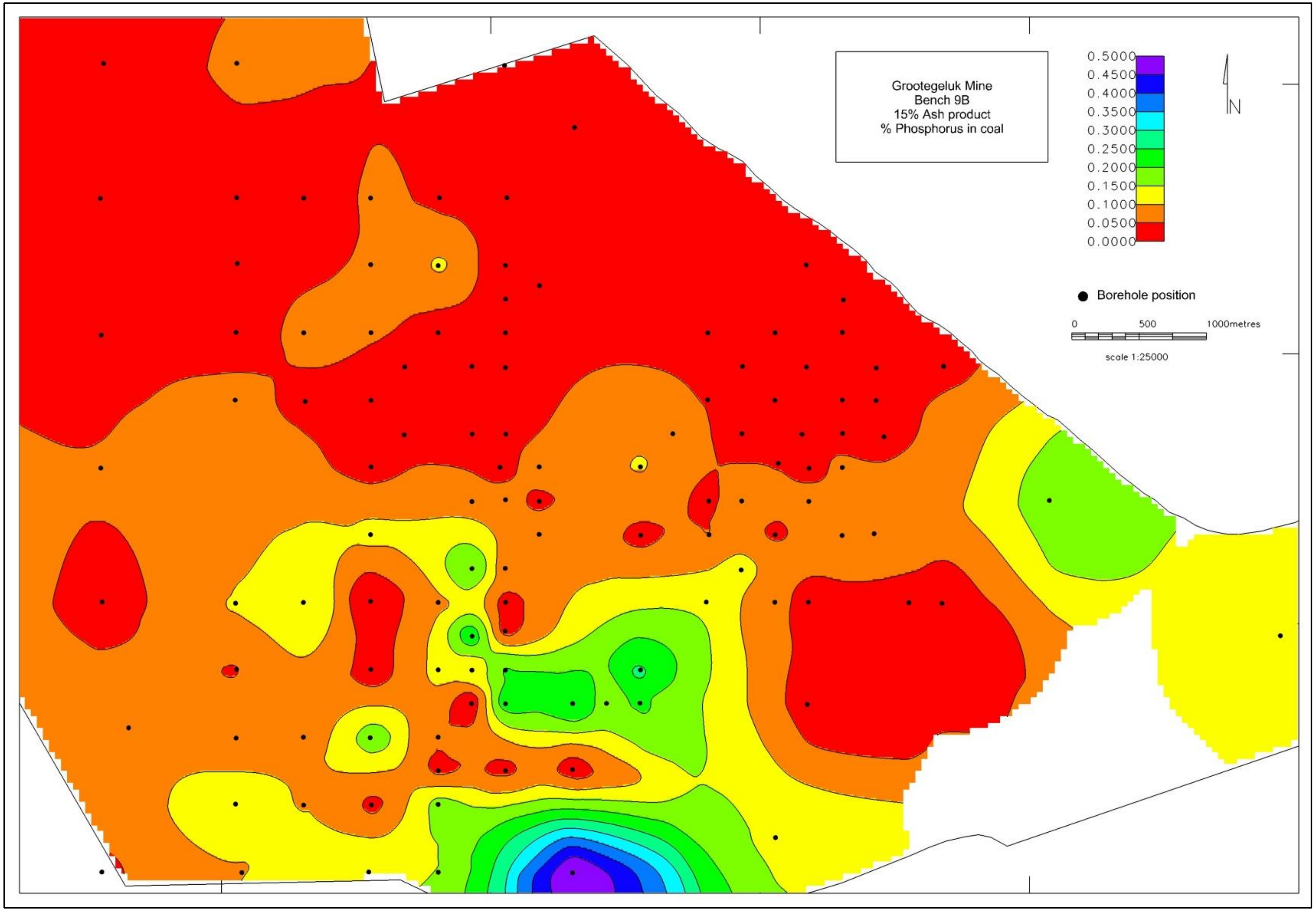

Figure 23 Colour shaded contour map of the phosphorus content of Bench 9B

The colour shaded contour map of the modelled phosphorus content of Bench 9B (Figure 23) illustrates generally lower phosphorus areas in the northern part of the resource area. It also shows that the phosphorus content in the northern part of the resource is less variable than in the southern part. The significance of the extremely low values in the population is not fully acknowledged in the model since they are clustered with higher values within a single range (0.00% to 0.05% phosphorus in coal).

A single borehole in the extreme south of the area indicates very high Bench 9B phosphorus content of greater than 0.45%. This high value was omitted from the statistical analyses since it is believed that it may be an outlier. It was however used in the geological modelling in order to evaluate the significance that this value has on the bench. Since the boreholes are fairly widely spread in the vicinity of this high value, it influences quite a large lateral area of the resource. A trend of increasing phosphorus towards this high value is observed in the surrounding boreholes, which indicates that this value might probably not be an outlier and should therefore be included for future estimations. It is envisaged that more data will improve the accuracy of the geological model in the vicinity of this high value.

4.2.2.2 Bench 11

The colour shaded contour map of the modelled phosphorus content of Bench 11 is illustrated in Figure 24. This figure shows that the phosphorus content of Bench 11 is generally lower in the northern and western parts of the resource, and higher phosphorus in the central and southern portions of the resource. The areas indicated in red on the colour shaded contour map (0.00% to 0.01% phosphorus in coal) represent lateral portions of Bench 11 that contain suitably low phosphorus coal for use as char plant feed coal. Figure 24 further illustrates that there are two very high values present in the phosphorus data of Bench 11. These values are surrounded by other values which are more typical of the average phosphorus concentration across the resource. This raises suspicion around the reliability of these high values, but with further inspection no evidence of error could be found. Although these high values influence a rather small lateral portion of the resource, they elevate the average phosphorus content of the bench.

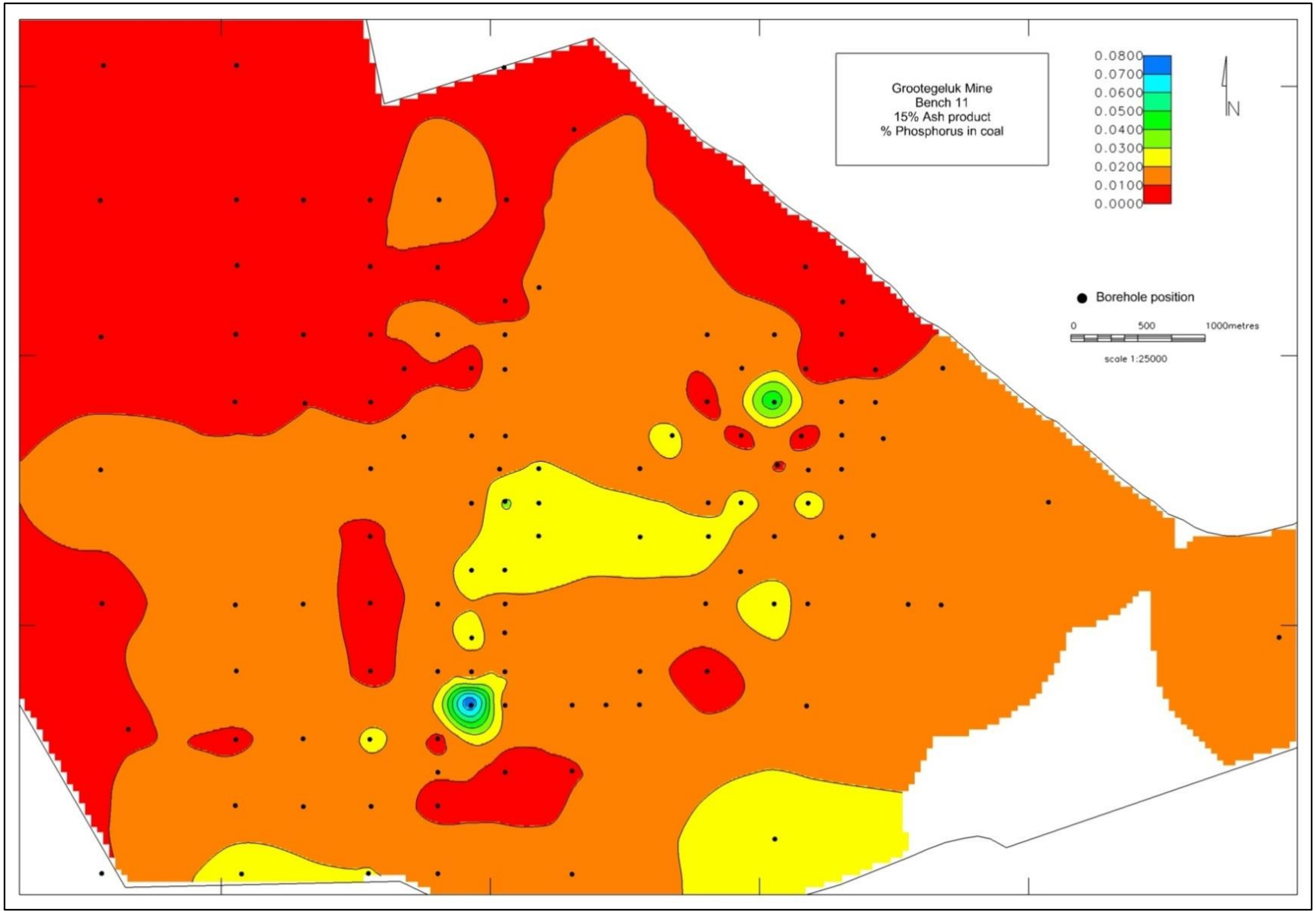

Figure 24 Colour shaded contour map of the phosphorus content of Bench 11

4.2.2.3 Zone 1

The colour shaded contour map of the modelled phosphorus content of Zone 1 is illustrated in Figure 25. This figure shows that the phosphorus content of Zone 1 is higher in the extreme southern and eastern parts of the resource where it is above 0.015%. These areas of elevated phosphorus content are still relatively low in comparison to the average phosphorus content of the other Vryheid Formation coal benches at Grootegeluk Mine. The biggest portion of Zone 1 has phosphorus concentrations which is suitable for the production of char plant feed coal. Since the phosphorus content of Zone 1 is mostly well below the maximum limit of 0.012% phosphorus for char plant feed coal, this bench may also be considered as a source of low phosphorus blending coal that can be used to increase the amount of char plant feed coal from other sources.

Zone 1 has less exploration borehole data than Bench 11 and Bench 9B, and the boreholes are not evenly spaced throughout the resource area. This creates a risk in terms of the estimation accuracy of the phosphorus content of Zone 1 in certain areas. More exploration boreholes with phosphorus analyses are needed to mitigate this risk.

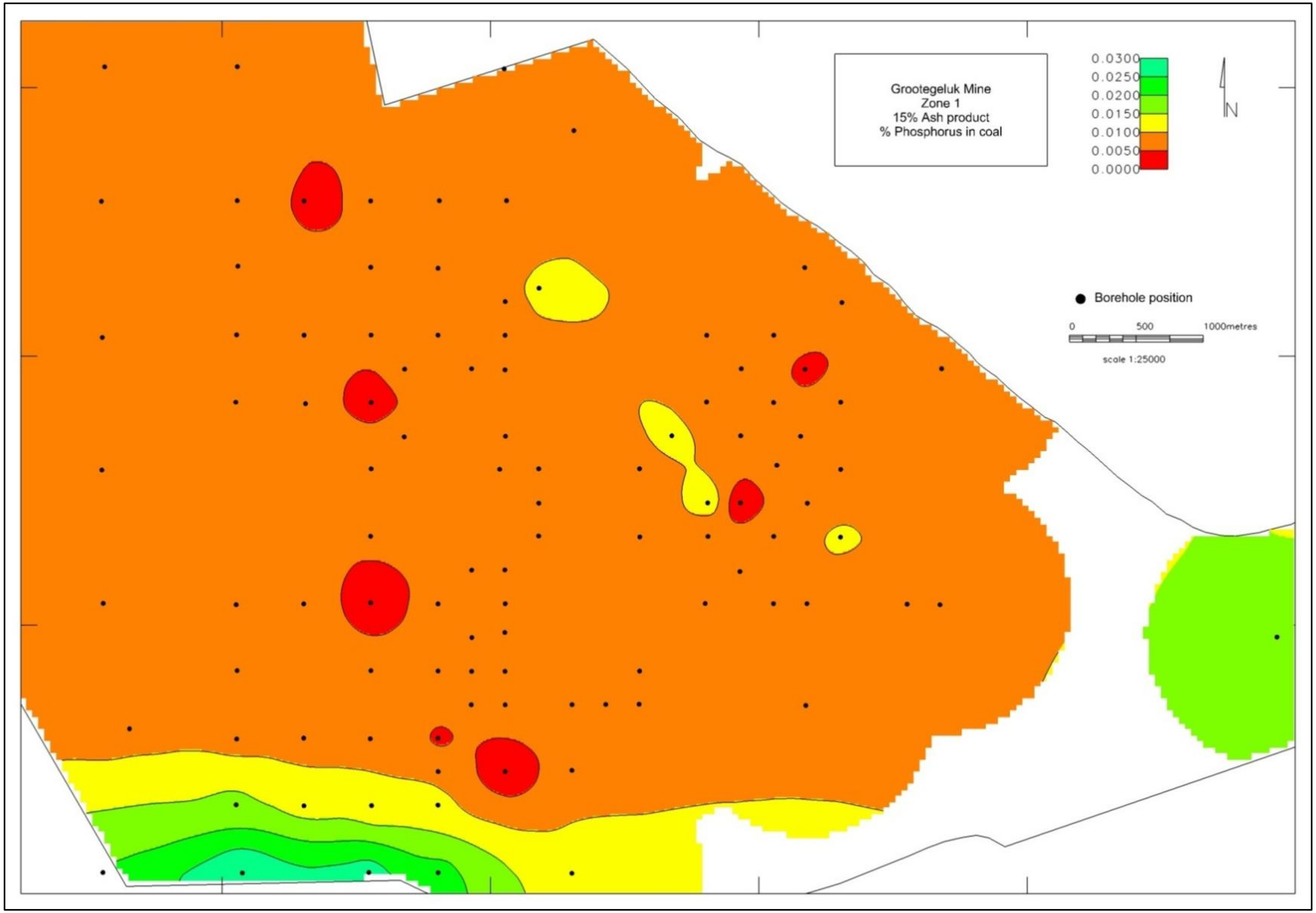

Figure 25 Colour shaded contour map of the phosphorus content of Zone 1

4.2.3 Bench 11 samples

4.2.3.1 Sample 30A

The colour shaded contour map of the modelled phosphorus content of Sample 30A is illustrated in Figure 26. The figure shows that the phosphorus content of Sample 30A is generally lower in the northern and western parts of the resource while the central to southern portions of the resource contain the highest phosphorus concentrations. One very high value influences a rather large area in the centre of the resource. The low amount of borehole data in the vicinity of this data point may be the reason for the relatively large area that is influenced by this high value.

From Figure 26 it is evident that there is no phosphorus data available of Sample 30A in the eastern portion of the resource area, hence the absence of the model in that area. This is also the case with Sample 30B. This absence of data is due to the fact that Samples 30A and 30B were introduced at a later stage of the mine’s existence, after the split in Sample 30 was introduced. Once lithological units are sampled and analysed, the analyses cannot be separated to form split sample units. The subdivision of Sample 30 from which Samples 30A and 30B originated is explained in more detail in Section 3.4.

Figure 26 illustrates that in certain areas of the resource, the phosphorus content of Sample 30A is below 0.012%; indicating that these areas are suitable for char plant feed coal. The relatively low amount of phosphorus data for Sample 30A creates a higher degree of geological uncertainty in the estimation accuracy of the phosphorus distribution in this unit. More exploration boreholes containing phosphorus analyses are needed to mitigate this risk.

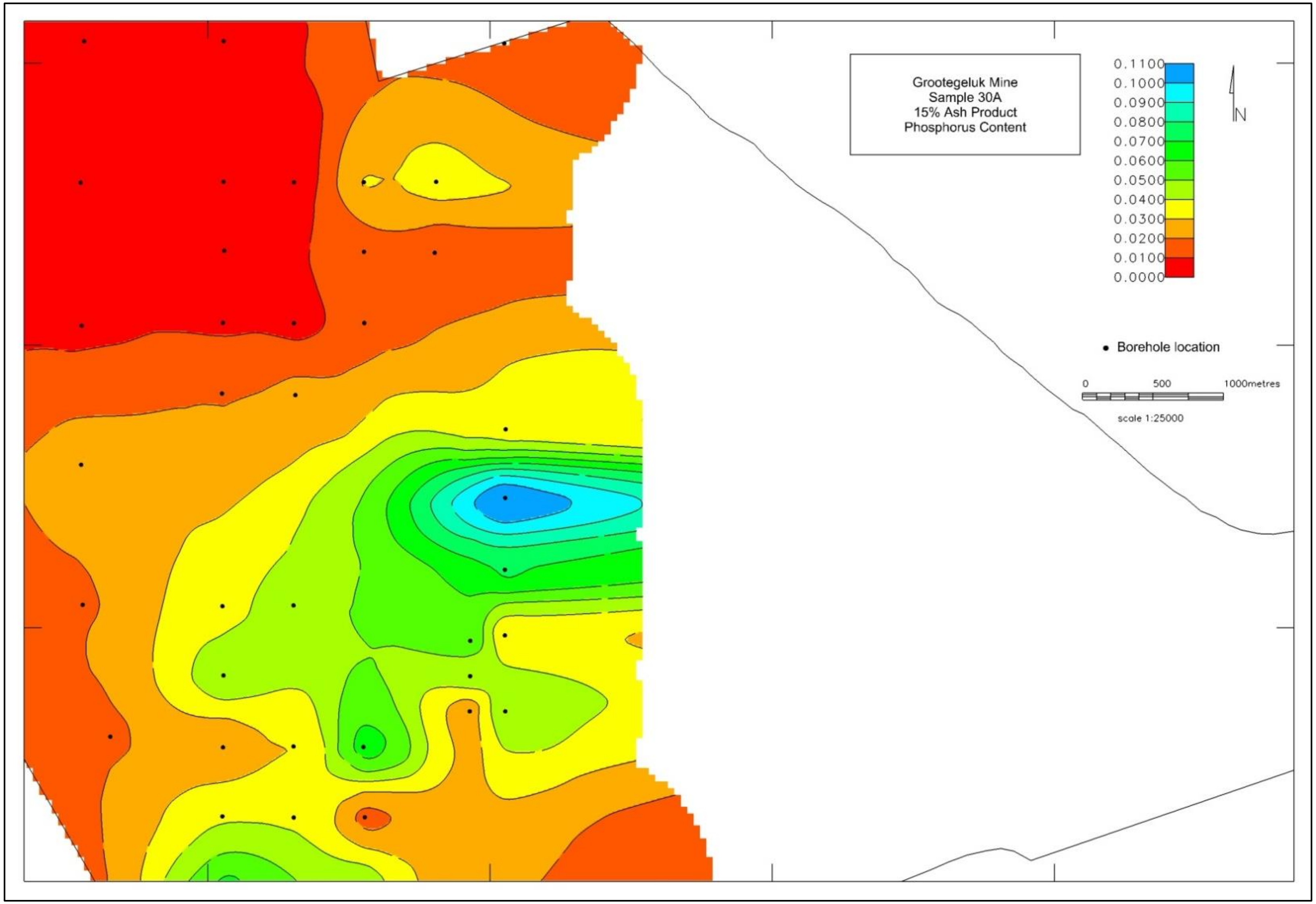

Figure 26 Colour shaded contour map of the phosphorus content of Sample 30A

4.2.3.2 Sample 30B

The colour shaded contour map of the modelled phosphorus content of Sample 30B is illustrated in Figure 27. As in the case of Sample 30A, the phosphorus content of Sample 30B is also generally lower in the northern and western parts of the resource while the highest phosphorus is present in the central to southern portions. The largest portion of the area proved to be below 0.012% phosphorus. One very high value creates a rather large area of high phosphorus in the centre of the resource. The size of this relatively high phosphorus content area may be the result of the low amount of borehole data in the vicinity of this data point.

As in the case of Sample 30A, the relatively low amount of data points for Sample 30B also creates a higher degree of geological uncertainty in the estimation accuracy of the lateral phosphorus distribution. More exploration boreholes containing phosphorus analyses are needed to mitigate this risk.

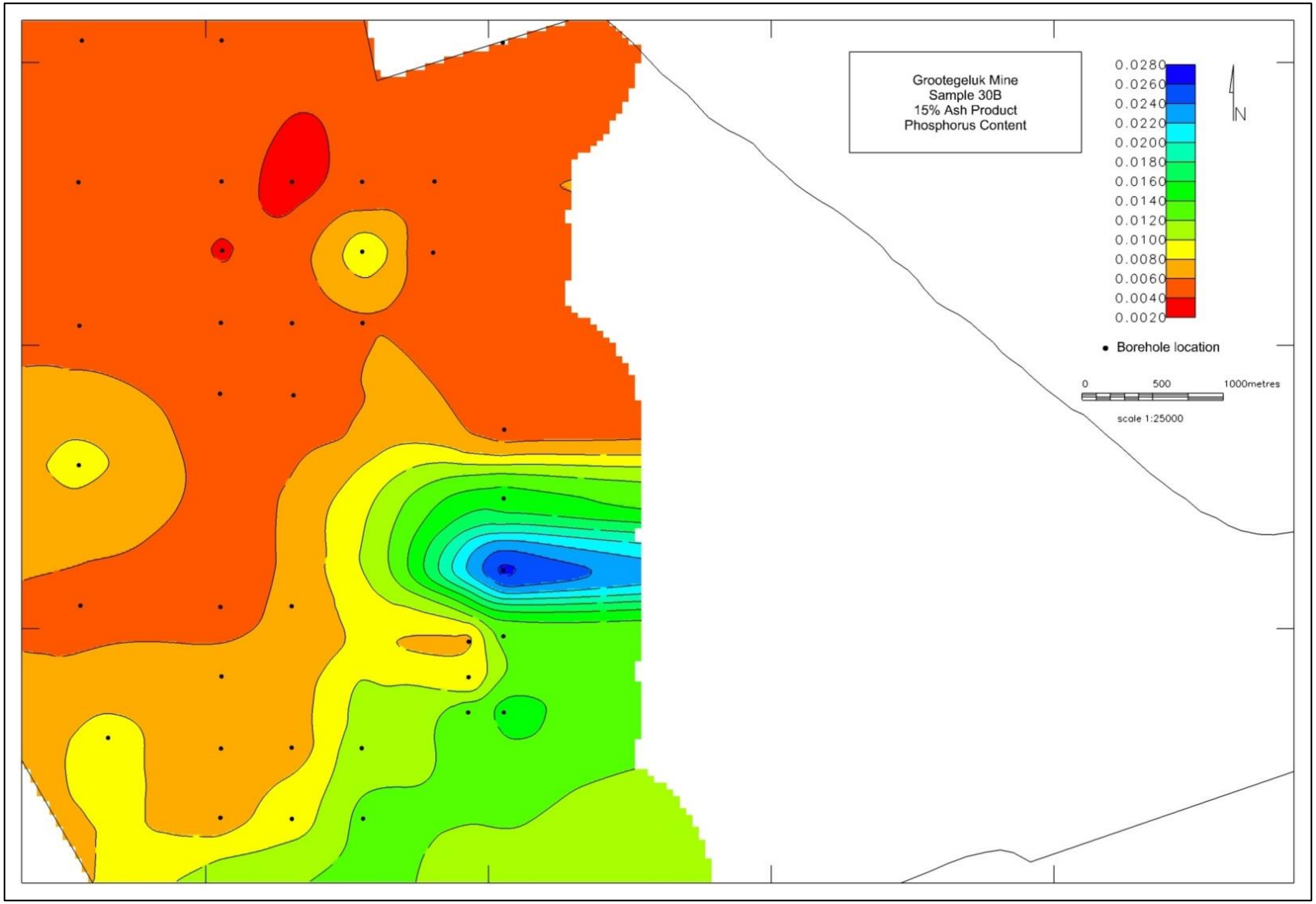

Figure 27 Colour shaded contour map of the phosphorus content of Sample 30B

4.2.3.3 Sample 31

The colour shaded contour map of the modelled phosphorus content of Sample 31 is illustrated in Figure 28. This figure shows that the phosphorus content of Sample 31 is generally below 0.012%. A few isolated patches of higher phosphorus are present in the central and southern areas. One very high value creates an area of high phosphorus in the centre of the resource. This value was deliberately not removed from the data used in the geological modelling, in order to assess its influence on the resource. The high value has an effect of elevating the average phosphorus content of Sample 31. It is evident from this geological model that the high value is surrounded with data points of low phosphorus values, and therefore the high value does not influence a very large area of the resource. The fact that the high value is surrounded by boreholes containing relatively low phosphorus values makes it easier to believe that this value may be erroneous and can therefore most likely be dismissed from the population. The only way to determine the correctness of this data point is to obtain another coal sample of Sample 31 at the same location in the resource, and compare its phosphorus analysis against the original sample analysis.

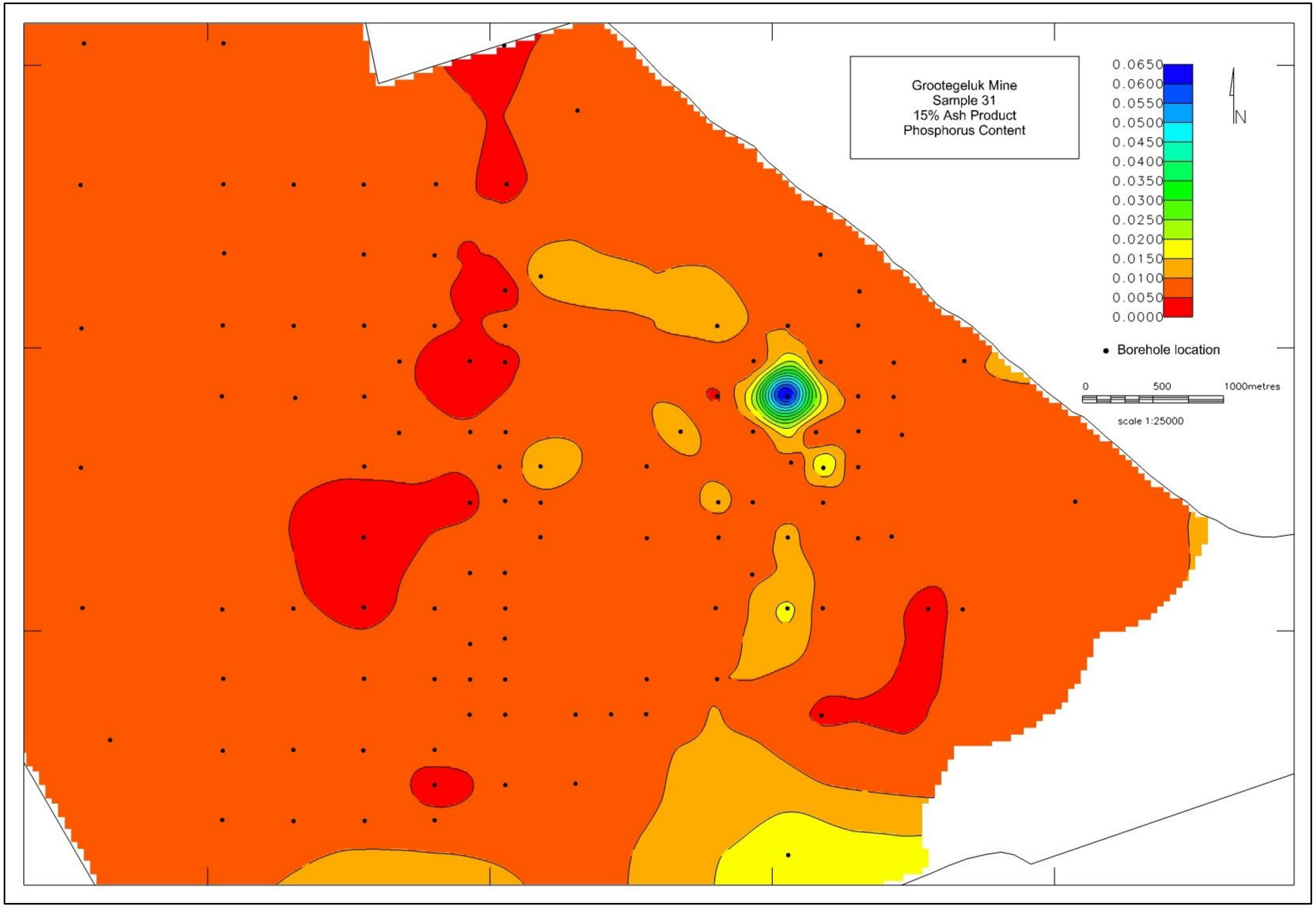

Figure 28 Colour shaded contour map of the phosphorus content of Sample 31

4.2.4 Sample 30A sub-samples

4.2.4.1 Sample 30A-1

The colour shaded contour map of the modelled phosphorus content of Sample 30A-1 is illustrated in Figure 29. This figure shows that the lateral phosphorus distribution in Sample 30A-1 is very irregular, with a high variability across the area under consideration. No definite trend in the lateral phosphorus distribution is observed.

The significance of this geological model is that it portrays the phosphorus distribution in Sample 30A-1 as highly variable with significant changes over relatively short distances across the resource.

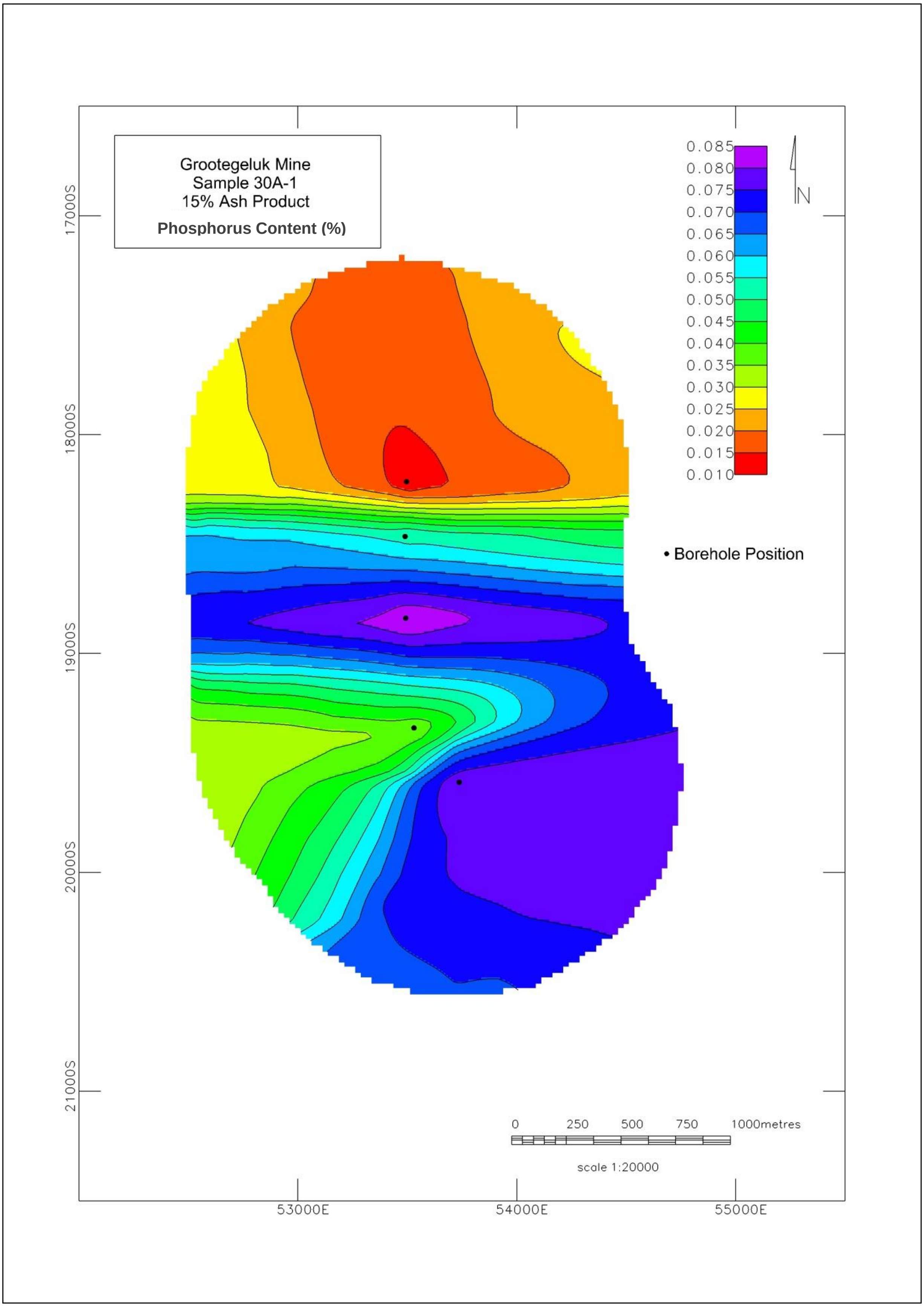

Figure 29 Colour shaded contour map of the phosphorus content of Sample 30A-1

4.2.4.2 Sample 30A-2

The colour shaded contour map of the modelled phosphorus content of Sample 30A-2 is illustrated in Figure 30. This figure shows that the lateral phosphorus distribution of Sample 30A-2 has a striking resemblance to that of Sample 30A-1 (Figure 29), except for the southern portion where the phosphorus is lower. The phosphorus concentrations are generally higher in Sample 30A-2.

Figure 30 shows that the phosphorus distribution in Sample 30A-2 is also highly variable with the highest phosphorus concentration present in the central area. Relatively low phosphorus levels are present in the northern portion of the area. No trend in the lateral phosphorus distribution of Sample 30A-2 is observed. This geological model shows that the phosphorus distribution in Sample 30A-2 is also highly variable and changes significantly over relatively short distances across the resource.

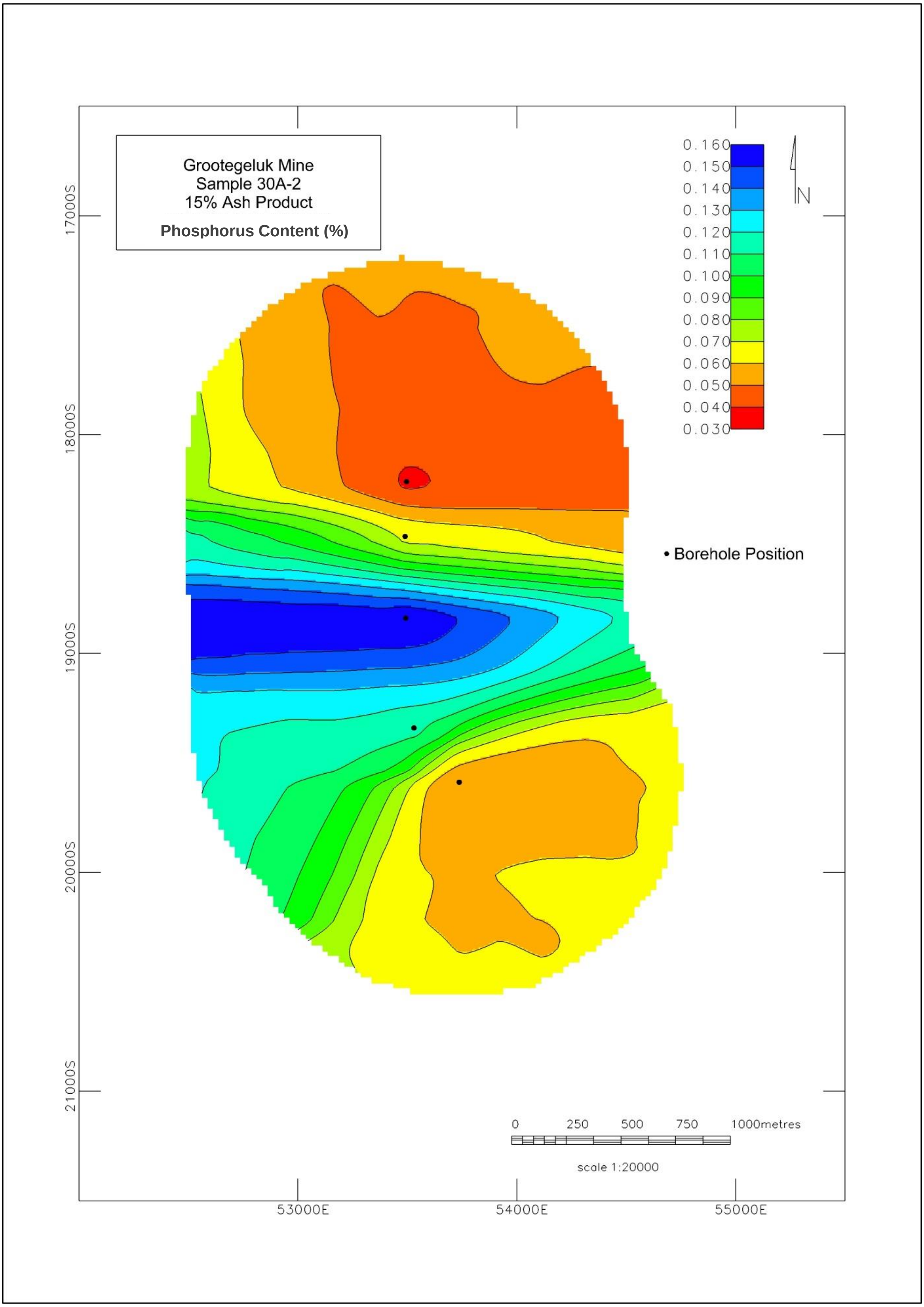

Figure 30 Colour shaded contour map of the phosphorus content of Sample 30A-2

4.2.4.3 Sample 30A-3

The colour shaded contour map of the modelled phosphorus content of Sample 30A-3 is illustrated in Figure 31. This figure shows that the lateral phosphorus distribution of Sample 30A-3 has a similar pattern to that of Sample 30A-2 (Figure 30). The phosphorus concentration of Sample 30A-3 is generally lower than that of Sample 30A-2 but somewhat higher than that of Sample 30A-1.

Figure 31 shows that the phosphorus distribution in Sample 30A-3 is rather erratic, with the highest phosphorus concentration in the central area. Relatively low phosphorus levels are present in the northern portion. No trend in the lateral phosphorus distribution of Sample 30A-3 is observed. The significance of this geological model is that it portrays the phosphorus distribution in Sample 30A-3 as highly variable and changes significantly over relatively short distances across the resource.

Due to the low amount of observation points (boreholes) from which the geological models of the Sample 30A sub-samples were created, as well as the linear nature of the borehole distribution, it is expected that these models may change significantly when additional boreholes containing phosphorus data are added, especially to the west and east of the current line of boreholes. At present the northern- and southern most boreholes produce the biggest area of influence due to the fact that they form the ends of the line of data points.

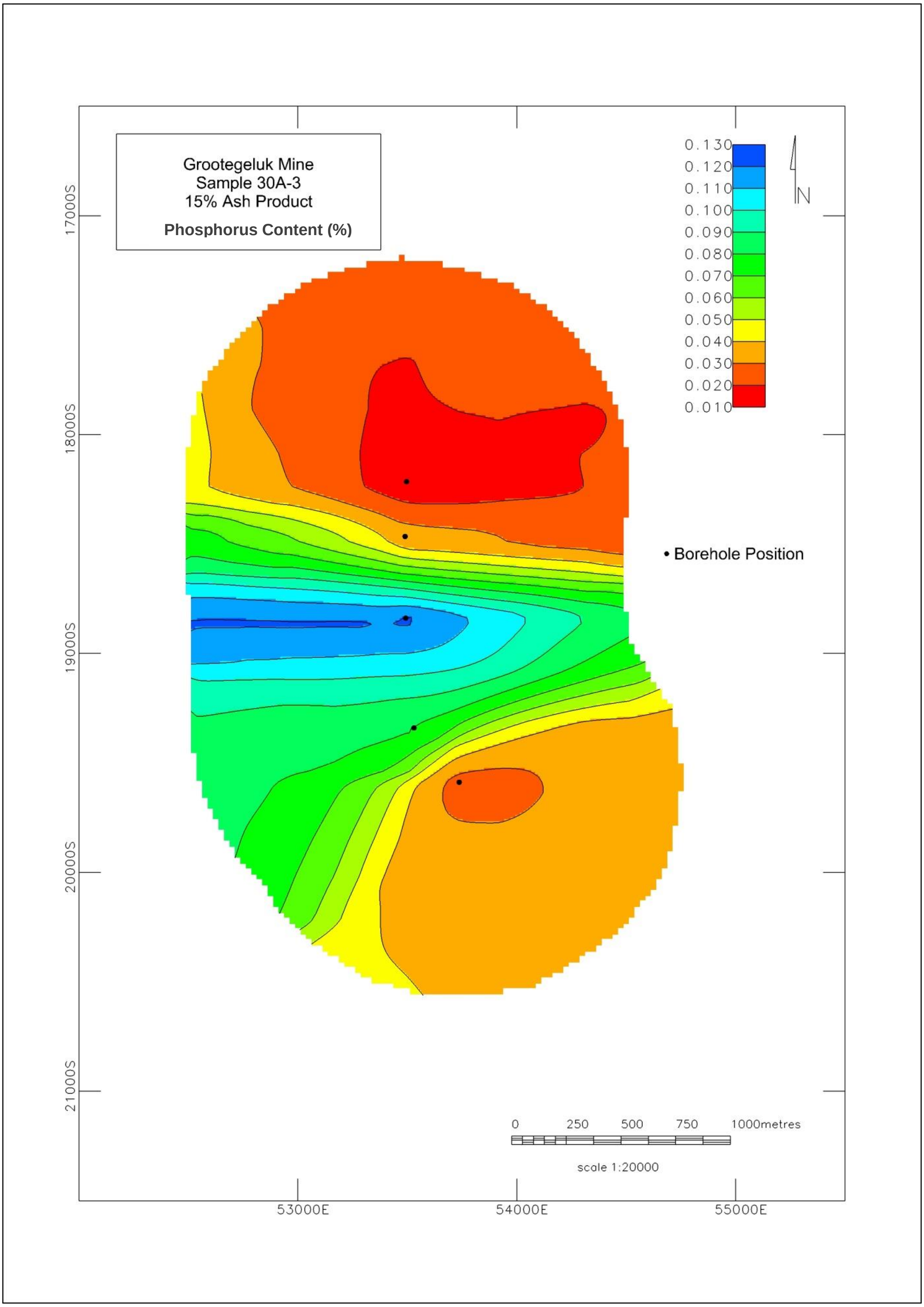

Figure 31 Colour shaded contour map of the phosphorus content of Sample 30A-3

4.3 Subdivision and selective mining of Bench 11

The current investigation was conducted to determine the smallest possible portion of high phosphorus coal that needs to be removed separately from Bench 11 in order to have as much as possible suitable coal for the char plant left in the bench. This work includes the data obtained from the five specially drilled cored boreholes in the current pit (Section 3.4). The statistical analyses of the phosphorus content of the smallest stratigraphic units comprising the full thickness of Bench 11 are presented in Table 11. The average phosphorus content in these stratigraphic units represents the average vertical phosphorus distribution through Bench 11.

Table 11 Statistical analyses of the phosphorus content of the Bench 11 samples

Stratigraphic unit	Number of exploration boreholes containing phosphorus data	Percentage phosphorus in coal containing 15% ash				
		Minimum	Maximum	Range	Average	Standard deviation
Sample 30A-1*	5	0.0131	0.0838	0.0707	0.0533	0.0261
Sample 30A-2*	5	0.0392	0.1597	0.1205	0.0863	0.0442
Sample 30A–3*	5	0.0145	0.1205	0.1059	0.0553	0.0393
Sample 30B	63	0.0033	0.0262	0.0229	0.0074	0.0039
Sample 31	147	0.0026	0.1283	0.1257	0.0092	0.0126

Rounding-off of figures may cause computational discrepancies.
* Vertical subdivision of Sample 30A (Sample 30A sub-samples)

From the statistical analyses of the sample units of Bench 11 presented in Table 11 and individually discussed in Section 3.2, it is clear that the high phosphorus portion is present in the upper portion; of the Bench (Sample 30A sub-samples). The high phosphorus coal can therefore be removed from the top of the bench. Further investigation is required to determine the minimum amount of Sample 30A that has to be removed separately, without exceeding the maximum phosphorus limit for char plant feed coal in the remaining portion of the bench.

Table 12 depicts the resultant phosphorus content of the different combinations of the lithological unit in Bench 11 (from top to bottom of the bench). The yield of a coal product containing 15% ash and the thickness of each lithological unit were used as the weighting factors to determine the weighted average phosphorus content for the different sample combinations. Due to the sensitive nature of this information, the actual values of the weighting factors are not disclosed.

Table 12 Phosphorus concentrations in different vertical proportions of Bench 11

Lithological units used to composite Bench 11					Result	
Sample 30A-1	Sample 30A-2	Sample 30A–3	Sample 30B	Sample 31	Percentage of current Bench 11 thickness*	Percentage phosphorus in coal**
√	√	√	√	√	100	0.0140
	√	√	√	√	93	0.0129
		√	√	√	84	0.0100
			√	√	75	0.0063
				√	50	0.0048

Rounding-off of figures may cause computational discrepancies.
* Average thickness of the combined lithological units expressed as a percentage of the average current full thickness of Bench 11.
** Weighted average percentage phosphorus in coal as obtained from five boreholes distributed linearly across the current pit area.

The results of the phosphorus concentrations in the different vertical portions of Bench 11 (Table 12) show that roughly 84% of Bench 11, measured from the floor of the bench, is suitable for char plant feed coal with respect to the phosphorus content in coal. The upper 16% of the bench, consisting of Samples 30A-1 and 30A-2, needs to be removed separately and used for different coal products, in order for the remaining portion of the bench to contain less than the maximum allowable phosphorus for char plant feed coal. The average coal thickness at the top of Bench 11 that needs to be removed separately therefore amounts to 700 mm of the bench, i.e. the Sample 30A sub-samples are on average 350 mm thick each. The exact thickness that needs to be removed at the position of extraction, for instance in a specific blast block, will depend on the phosphorus content, yield, and thickness of the different lithological units comprising Bench 11 at that specific position.

4.4 Coal Beneficiation

The aim of this portion of the study is to determine whether the phosphorus level in the coal from the Waterberg Coalfield can be reduced by means of coal beneficiation (Section 3.5).

4.4.2 Mining Benches

The mining benches used in this part of the study are those identified for further investigation in the preceding sections, namely Bench 9B, Bench 11 and Zone 1. The weighted average phosphorus content of the mining benches as obtained at different ash levels (different coal ash products) are illustrated in Figure 32.

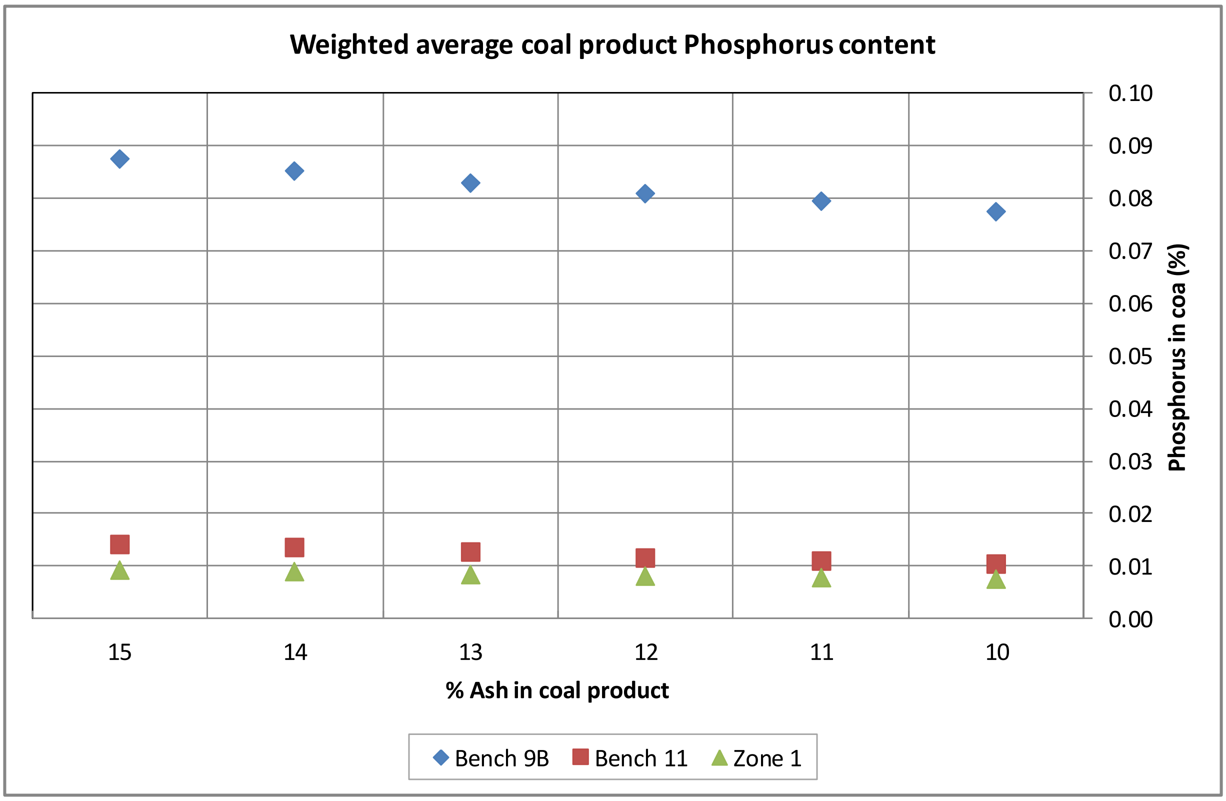

Figure 32 Phosphorus content of the mining benches for different coal ash products

4.4.2.1 Bench 9B

Figure 32 illustrates that the weighted average phosphorus content of Bench 9B decreases somewhat with a reduction in the final product's coal ash content. The phosphorus content decreases from just below 0.09% in a coal product containing 15% ash to just below 0.08% phosphorus in a coal product containing 10% ash. This accounts for a reduction of roughly 0.01% phosphorus over a 5% reduction in the coal ash. From these results it is evident that the phosphorus content in the coal of Bench 9B cannot be sufficiently lowered by means of coal beneficiation to a level suitable for use as char plant feed coal.

4.4.2.2 Bench 11

Figure 32 illustrates that the weighted average phosphorus content of Bench 11 is slightly reduced with a reduction in coal ash content. The weighted average phosphorus level of Bench 11 in a coal product containing 15% ash is above 0.012%; but in a coal product containing 12% ash, the required phosphorus level is reached. This study therefore indicates that the phosphorus in Bench 11 may possibly be lowered sufficiently by means of coal beneficiation.

4.4.2.3 Zone 1

Figure 32 illustrates that the weighted average phosphorus content of Zone 1 is slightly reduced with a reduction in coal ash content. The weighted average phosphorus content of Zone 1 in a coal product containing 15% ash is already below the maximum allowable limit for char plant feed coal, and therefore does not require further beneficiation.

4.4.3 Bench 11 Samples

The weighted average phosphorus content of the different sample units comprising Bench 11, as simulated for the different coal ash content products, are illustrated in Figure 33.

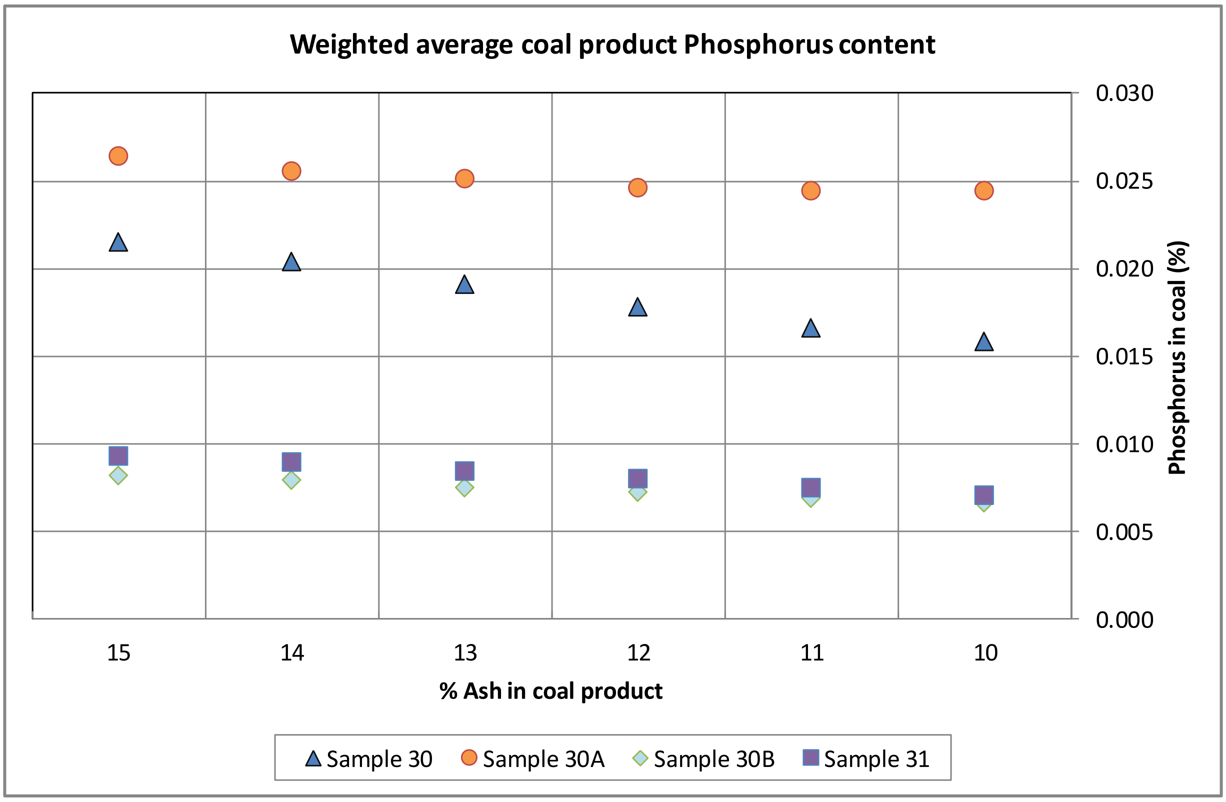

Figure 33 Phosphorus content of the Bench 11 samples at different coal ash levels

4.4.3.1 Sample 30

Sample 30 is no longer sampled as such at Grootegeluk Mine, but is subdivided and sampled in two separate units (Samples 30A and 30B). The data used here is from exploration boreholes that were drilled before the subdivision of Sample 30 was introduced and is used here for completeness. Figure 33 illustrates that the weighted average phosphorus content in Sample 30 decreases gradually with a reduction in the coal ash content. The phosphorus content decreases from above 0.02% in a coal product containing 15% ash to just above 0.015% in a coal product containing 10% ash. This accounts for a reduction of more than 0.005% phosphorus with a reduction of 5% in the coal ash. Sample 30 shows the largest reduction in phosphorus content by means of coal beneficiation of all the samples in Bench 11. The phosphorus content of Sample 30 remains too high for use as char plant feed coal.

The Sample 30 results show that the phosphorus content in a coal product containing 15% ash is closer to that of Sample 30B, but moves gradually towards the average between Sample 30A and Sample 30B as the ash content of the coal is reduced to 10%. The reason why the phosphorus in Sample 30 does not constantly represent the average phosphorus content of Samples 30A and 30B combined may be the fact that the populations from which the borehole data was derived are drilled at different locations in the resource. Boreholes containing Sample 30 data are mainly positioned in the eastern portion of the resource while those containing Samples 30A and 30B are mainly positioned in the western portion of the resource.

4.4.3.2 Sample 30A

Figure 33 shows that the weighted average phosphorus content in Sample 30A gradually decreases from above 0.025% in a coal product containing 15% ash to just below 0.025% in the coal product containing 11% ash. No further reduction of the phosphorus content of Sample 30A is obtained in coal products containing less than 11% ash. The phosphorus content of Sample 30A therefore remains too high for use as char plant feed coal, irrespective of lowering of the coal ash content.

4.4.3.3 Sample 30B

Figure 33 shows that Sample 30B contains the lowest phosphorus concentration of all the Bench 11 samples in each of the different coal products used. The weighted average phosphorus content of Sample 30B decreases very little with a reduction in the final product’s coal ash content. The weighted average phosphorus content of Sample 30B is below 0.01% in all the coal products used.

4.4.3.4 Sample 31

Figure 33 illustrates that Sample 31 has similarly low concentrations of phosphorus to that of Sample 30B in all the different coal products used. The weighted average phosphorus content of Sample 31 also shows very little decrease with a reduction in the coal ash. The weighted average phosphorus content of Sample 31 remains below 0.01% in all the different coal products used.

4.4.4 Sample 30A Sub-samples

The weighted average phosphorus content of the Sample 30A sub-samples in the different coal ash products are illustrated in Figure 34. This data was derived from the analyses of the five specially drilled core boreholes through Bench 11 in the pit.

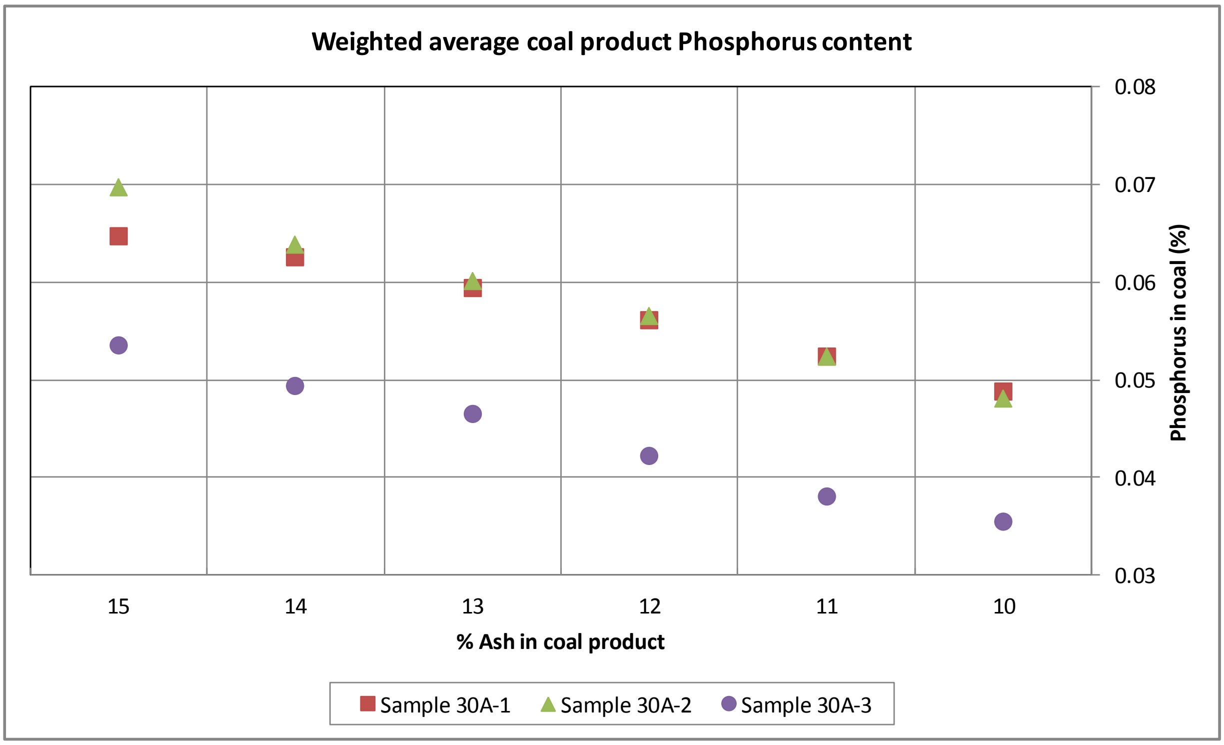

Figure 34 Phosphorus content of the sub-samples at different coal ash levels

4.4.4.1 Sample 30A-1

Figure 34 illustrates that the weighted average phosphorus content of Sample 30A-1 gradually decreases from about 0.065% in coal product containing 15% ash to just below 0.05% in a coal product containing 10% ash. Although this decrease in phosphorus content with a reduction in the coal ash is apparent, the desired phosphorus level for char plant feed coal of less than 0.012% phosphorus is not achieved.

4.4.4.2 Sample 30A-2

Figure 34 illustrates a small reduction in the phosphorus content of Sample 30A-2 with a reduction in the coal ash content. The rate at which the phosphorus decreases in Sample 30A-2 is somewhat higher than that of Sample 30A-1. The weighted average phosphorus content of Sample 30A-2 decreased from almost 0.07% in a coal product containing 15% ash to less than 0.05% in a coal product containing 10% ash. The decrease obtained in the phosphorus content of Sample 30A-2 by means of coal beneficiation is not sufficient enough for it to be used as char plant feed coal.

4.4.4.3 Sample 30A-3

Figure 34 illustrates that the weighted average phosphorus content of Sample 30A-3 gradually decreases from about 0.054% in a coal product containing 15% ash to about 0.036% in a coal product containing 10% ash. This amounts to a phosphorus reduction of roughly 0.02% over a 5% reduction in the coal ash. The decrease obtained in the phosphorus content of Sample 30A-3 by means of coal beneficiation is not sufficient enough for it to be used as char plant feed coal.

The rate of the decrease in the phosphorus content of the Sample 30A sub-samples with a reduction in the coal ash is generally greater than that of the full Sample 30A from which the sub-samples originated (Section 4.4.3.2). The fact that the borehole populations from which these results were derived are completely different, as well as the lateral variability of phosphorus in the coal, is the reason for this phenomenon.

4.5 Comparison of Phosphorus with other coal quality data

The aim of this part of the investigation is to investigate the relationship between the phosphorus in coal and other coal quality parameters (Section 3.6). The weighted average coal qualities of the different lithological units at a total float density of 1.50 g/cc are tabulated in Table 13.

Table 13 Coal qualities of the lithological units pertaining to Bench 11

Lithological Unit	Weighted average coal qualities at total float 1.50 g/cc							
	Inherent Moisture Content (%)	Ash Content (%)	Volatile Matter Content (%)	Free Swelling Index	Roga Index	Total Sulphur Content (%)	Calorific Value (MJ/kg)	Phosphorus in coal (%)
Sample 30A-1	2.61	7.09	30.48	1.90	15.61	0.92	30.63	0.0363
Sample 30A-2	2.69	14.01	20.29	0.04	0.36	0.61	27.48	0.0659
Sample 30A-3	2.61	12.31	22.61	0.18	1.22	0.68	28.12	0.0475
Sample 30B	2.79	10.17	24.59	0.41	3.16	0.74	29.08	0.0095
Sample 31	2.74	10.19	23.65	0.27	2.60	0.66	28.95	0.0048

4.5.2 Inherent Moisture Content

Table 13 depicts that the inherent moisture content is fairly similar in all three Sample 30A sub-samples but somewhat higher in Samples 30B and 31. Figure 35 illustrates the relationship between the weighted average inherent moisture content and the phosphorus content of the different lithological units. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the inherent moisture content and the phosphorus in coal of the different lithological units are illustrated in Figure 36.

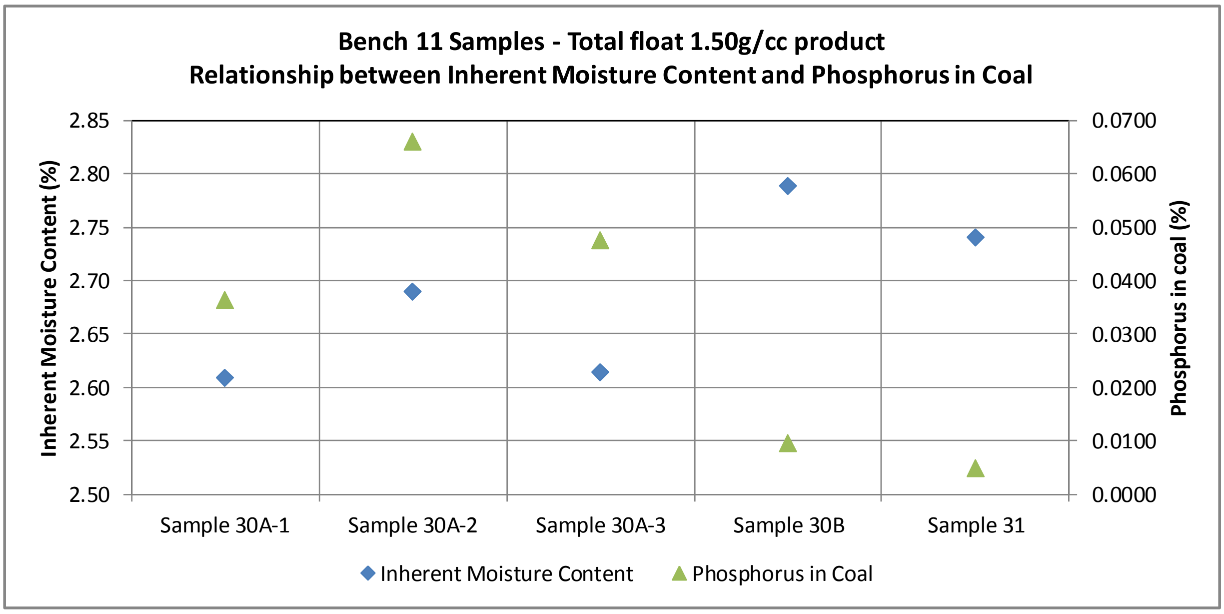

Figure 35 Comparison between Inherent Moisture content and Phosphorus in coal

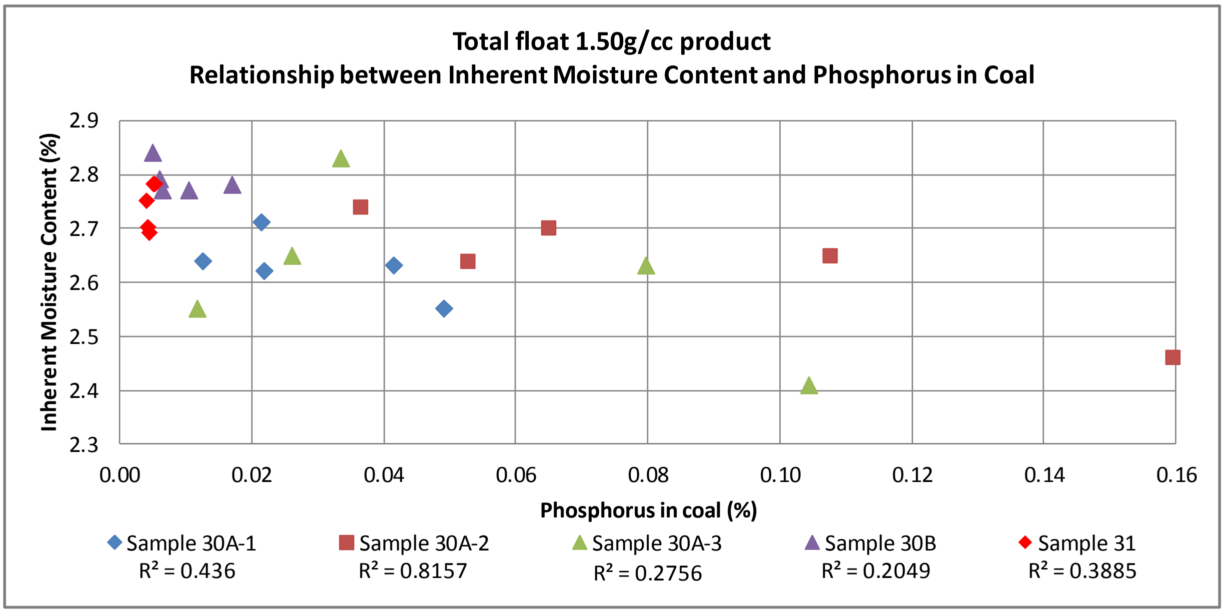

Figure 36 Scatter plot of the Inherent Moisture content versus the Phosphorus in coal

Figure 35 illustrates that the inherent moisture content is lower in the three Sample 30A sub-samples (Samples 30A-1, 30A-2 and 30A-3) and higher in Samples 30B and 31. In contrast, the phosphorus content is higher in the Sample 30A sub-samples and is lower in Samples 30B and 31. This observation is confirmed by the scatter plots of the individual sample data illustrated in Figure 36. It is therefore concluded that no correlation exists between the inherent moisture content and the phosphorus content of these coal units.

4.5.3 Ash Content

Table 13 depicts that the ash content varies considerably within the three Sample 30A sub-samples. On average only 7% ash is obtained in Sample 30A-1 while 14% is obtained in Sample 30A-2. The ash content of Samples 30B and 31 is more or less similar at just above 10%. Figure 37 illustrates the relationship between the weighted average ash content and the phosphorus content of the different lithological units. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the ash content and the phosphorus in coal of the different lithological units are illustrated Figure 38.

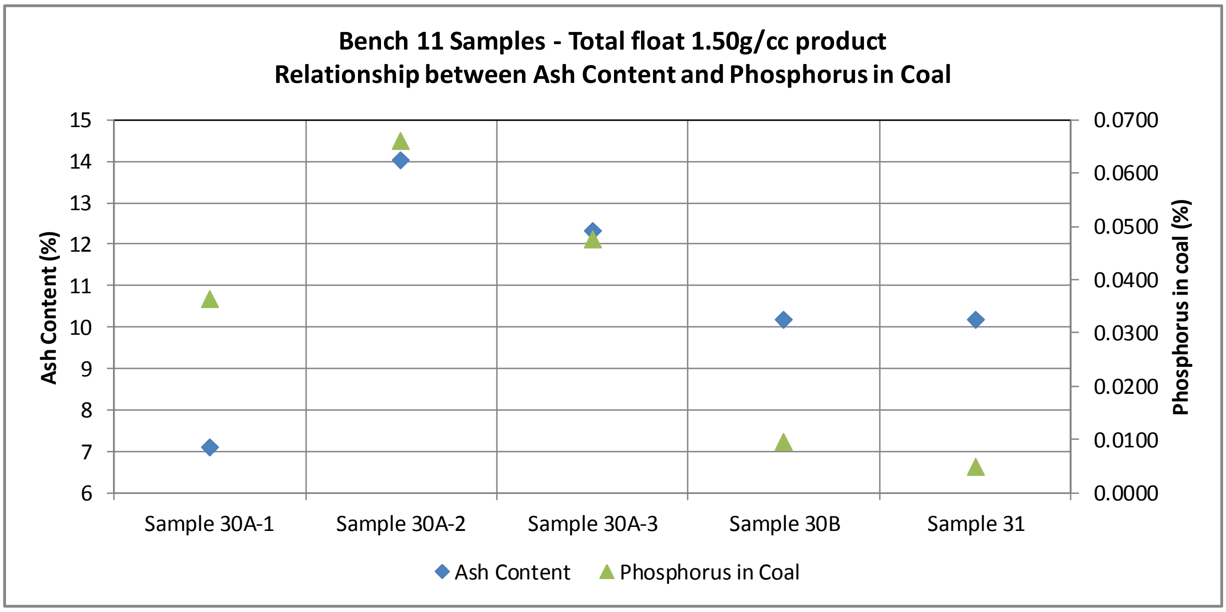

Figure 37 Comparison between Ash content and Phosphorus in coal

Figure 37 illustrates that the ash content and the phosphorus content of the different lithological units vary independently of each other. The ash content is generally lower in the top and bottom samples of Bench 11, while somewhat higher in the middle portion of the bench. The phosphorus is low in the bottom portions of the bench and high at the top and middle portions. It can therefore be concluded that no correlation exists between the ash content and the phosphorus content of the coal. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 38.

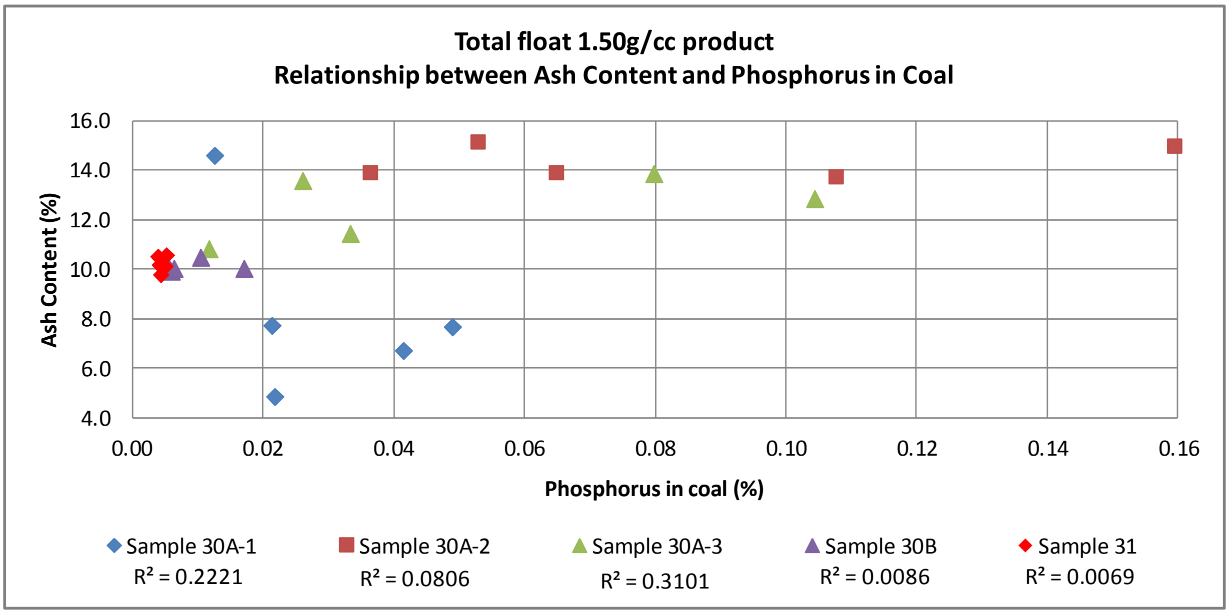

Figure 38 **Scatter plot of the Ash content versus the Phosphorus in coal**

4.5.4 Volatile Matter Content

Table 13 depicts that the volatile matter content of the different sub-samples varies considerably. Sample 30A-1 has the highest value at 29.46% and Sample 30A-2 the lowest at 19.77%. The relationship between the volatile matter content and the phosphorus content is illustrated in Figure 39. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the volatile matter content and the phosphorus in coal of the different lithological units are illustrated Figure 40.

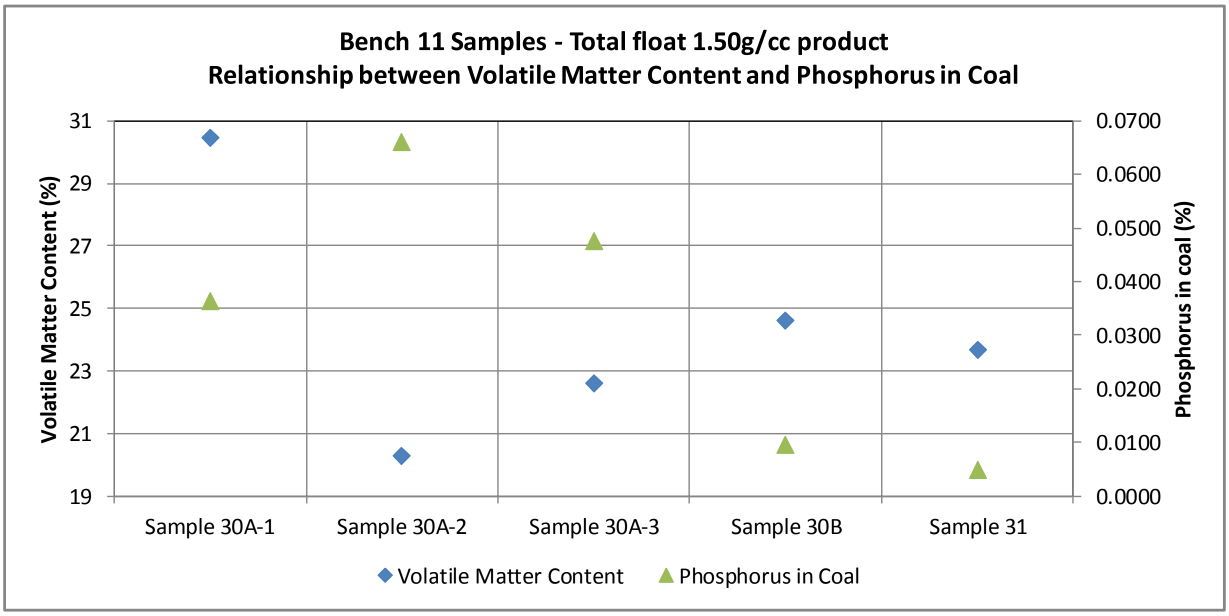

Figure 39 **Comparison between Volatile Matter content and Phosphorus in coal**

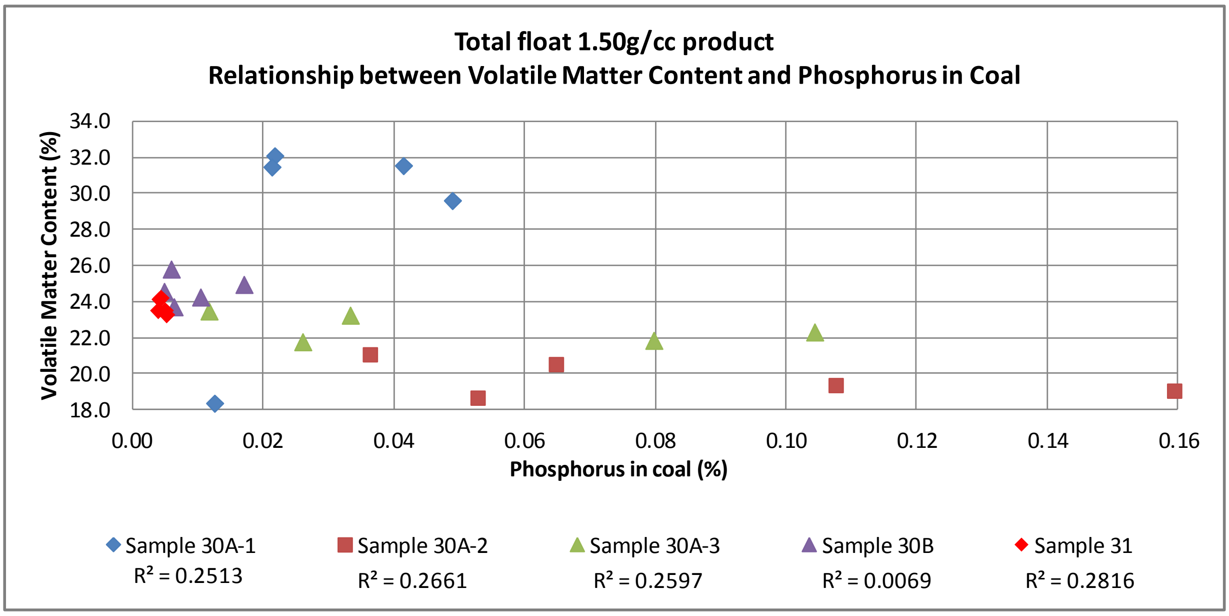

Figure 40 Scatter plot of the Volatile Matter content versus the Phosphorus in coal

From Figure 39 it is evident that there is no correlation between the volatile matter content and the phosphorus content of the different lithological units comprising Bench 11. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 40.

4.5.5 Free Swelling Index

The free swelling index of coal is not additive and therefore it is not possible to derive accurate average values for this coal parameter. With this in mind, the weighted average free swelling index of the different lithological units is examined for the purpose of completeness of this study. The coal quality data depicted in Table 13 shows that the weighted average free swelling index of Sample 30A-1 is much higher than that of the other lithological units. This is due to a higher concentration of vitrinite present in Sample 30A-1. The lowest weighted average free swelling index is obtained in Sample 30A-2. Figure 41 illustrates the relationship between the weighted average free swelling index and the phosphorus in coal of the different lithological units. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the free swelling index and the phosphorus in coal of the different lithological units are illustrated in Figure 42.

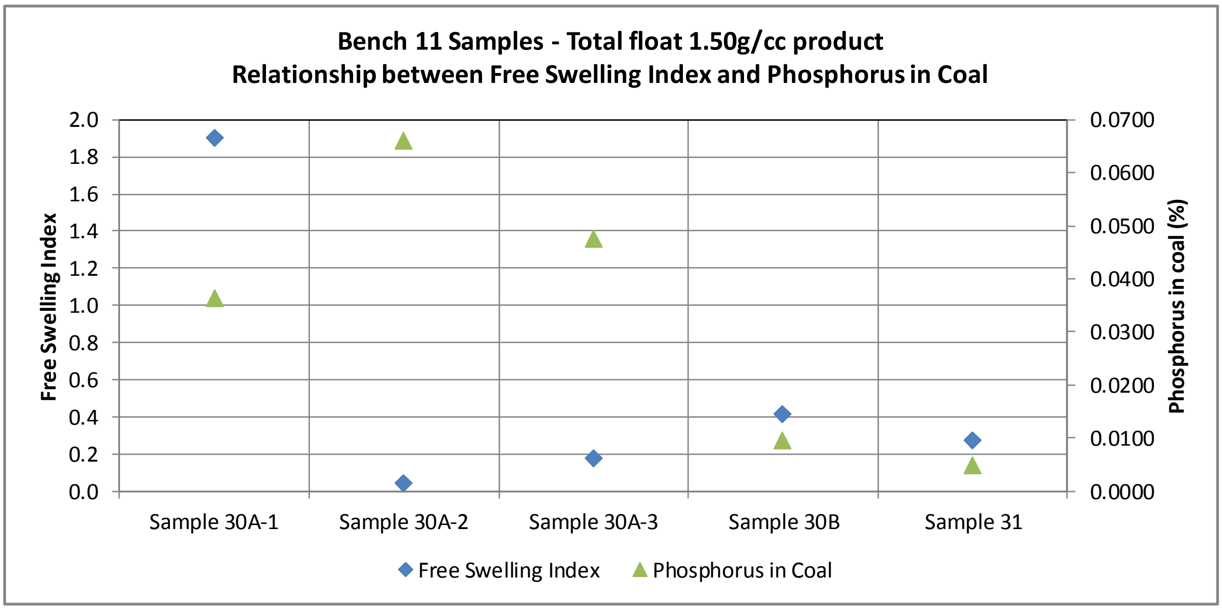

Figure 41 Comparison between Free Swelling Index and Phosphorus in coal

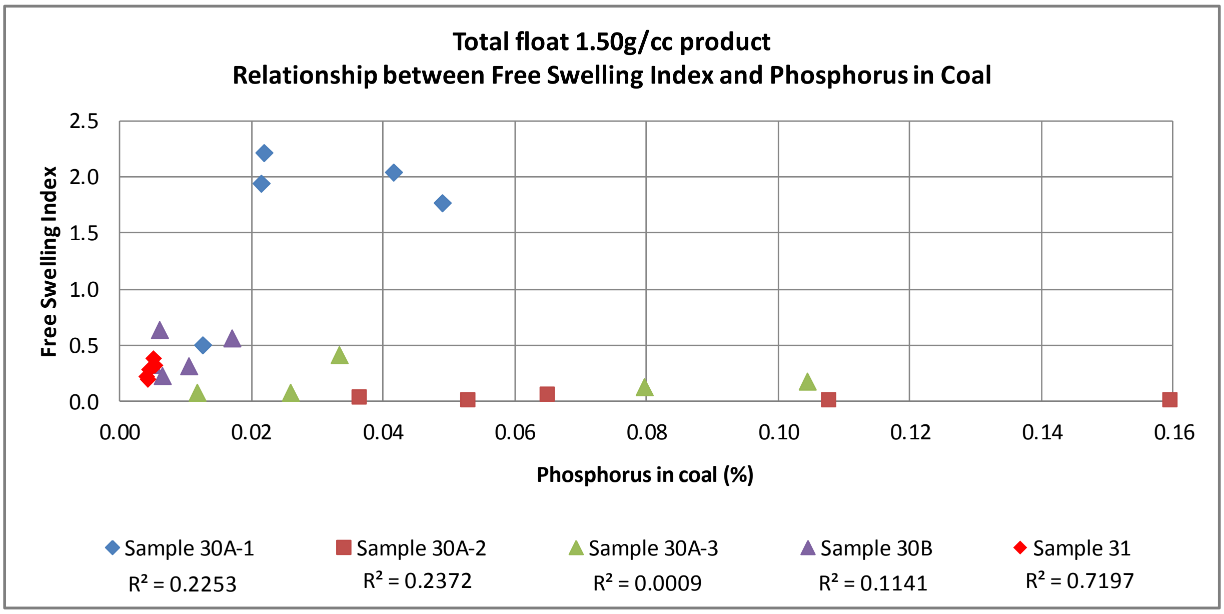

Figure 42 Scatter plot of the Free Swelling Index versus the Phosphorus in coal

From Figure 41 it is evident that the weighted average free swelling index of the different lithological units does not follow a similar distribution pattern to that of the phosphorus content. This study therefore shows that no correlation exists between the free swelling index and the phosphorus in coal for these lithological units. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 42.

4.5.6 Roga Index

As in the case of free swelling index, the Roga index of coal is also not additive and therefore it is not accurate to use average values for this coal parameter. With this in mind, the weighted averages of the Roga index of the different lithological units are used here for the purpose of completeness of the study only.

The coal quality data depicted in Table 13 shows that the weighted average Roga index of Sample 30A-1 is much higher than that of the other lithological units. This is also the result of higher vitrinite concentrations in Sample 30A-1. Figure 43 illustrates the comparison between the weighted average Roga index and the phosphorus in coal of the different lithological units pertaining. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the Roga index and the phosphorus in coal of the different lithological units are illustrated in Figure 44.

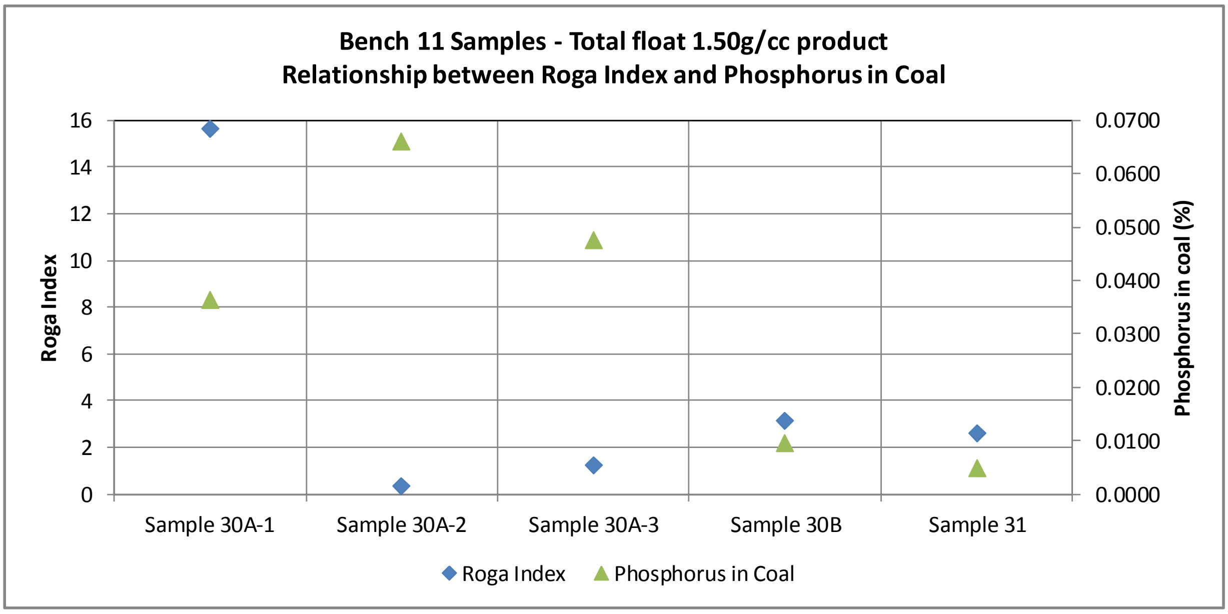

Figure 43 Comparison between Roga Index and Phosphorus in coal

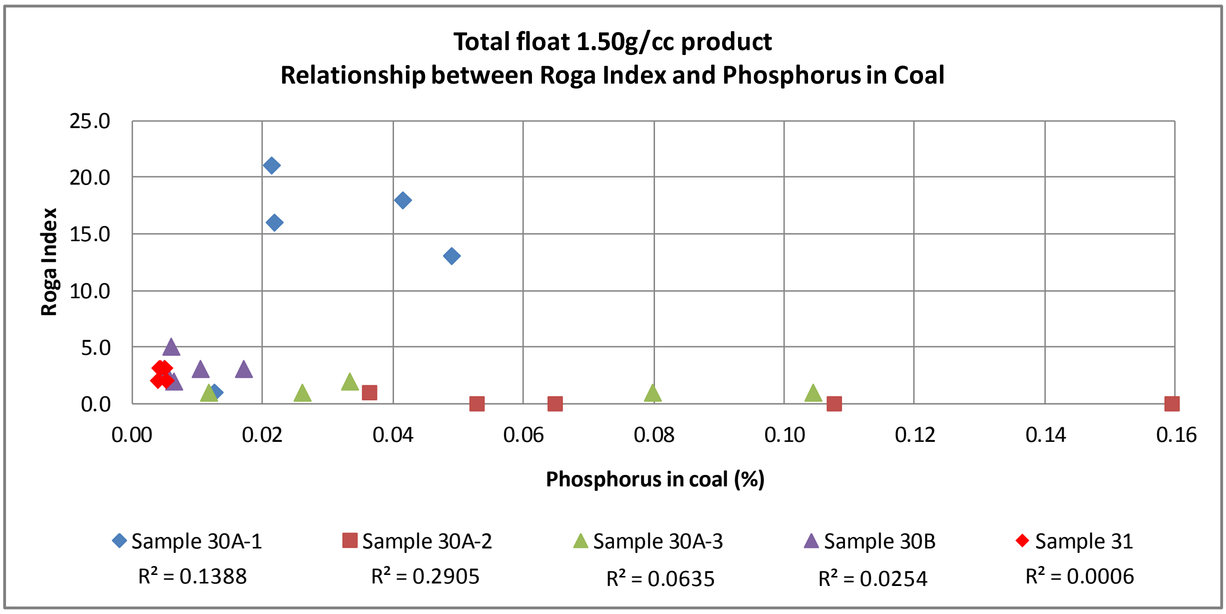

Figure 44 Scatter plot of the Roga Index versus the Phosphorus in coal

Figure 43 shows that the weighted average Roga index and the phosphorus content of the different lithological units vary independently from each other. It can therefore be concluded that no correlation exits between the Roga index and the phosphorus in coal of these lithological units used. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 44.

4.5.7 Total Sulphur Content

Table 13 depicts that the highest total sulphur content is present in Sample 30A-1 while Sample 30A-2 has the lowest total sulphur content. The total sulphur values of the other samples are marginally higher than that of Sample 30A-2. Figure 45 illustrates the comparison between the total sulphur content and the phosphorus content of the different lithological units pertaining to Bench 11. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the total sulphur content and the phosphorus in coal of the different lithological units are illustrated in Figure 46.

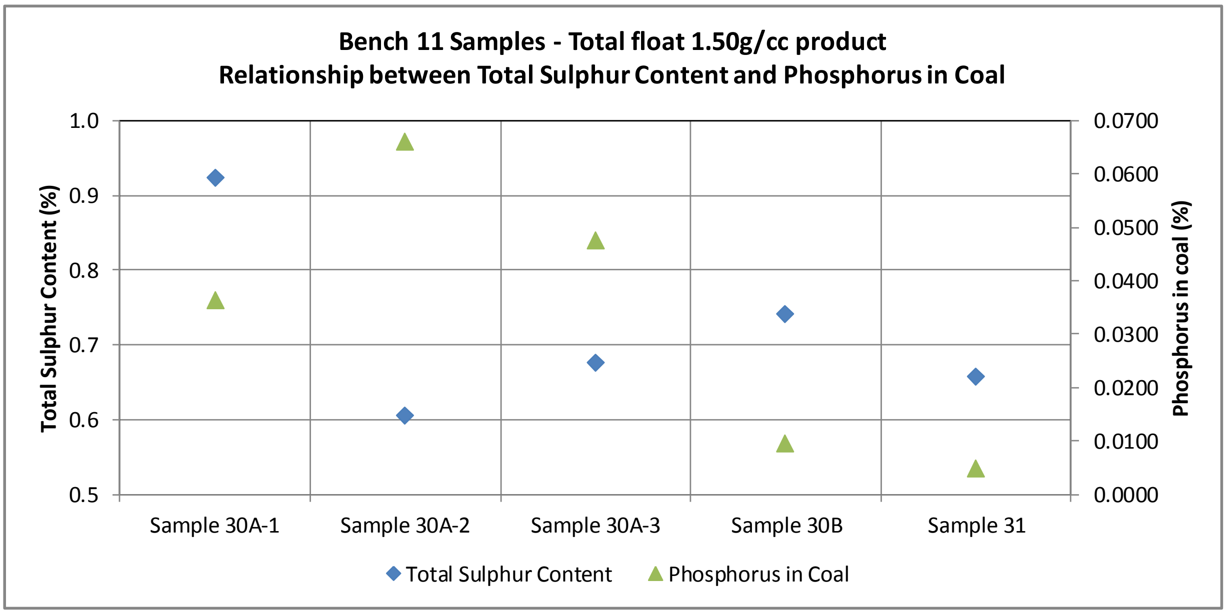

Figure 45 Comparison between Total Sulphur content and Phosphorus in coal

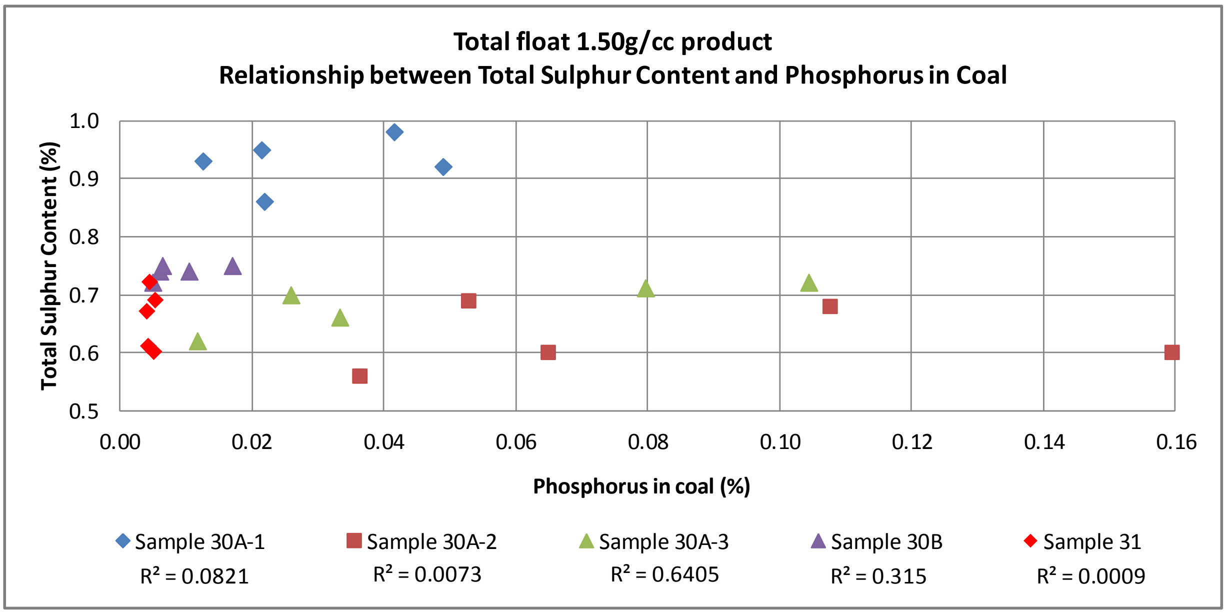

Figure 46 Scatter plot of the Total Sulphur content versus the Phosphorus in coal

Figure 45 illustrates that the weighted average total sulphur content and the phosphorus content of the different lithological units vary independently from each other. It can therefore be concluded that no correlation exists between the total sulphur content and the phosphorus content of the different lithological units of Bench 11. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 46.

4.5.8 Calorific Value

Table 13 depicts that Sample 30A-1 has the highest weighted average calorific value at 30.63 MJ/kg. Sample 30A-2 has the lowest weighted average calorific value at 27.48 MJ/kg. The comparison between the calorific value and the phosphorus content of the different lithological units pertaining to Bench 11 is illustrated in Figure 47. For reference, scatter plots of the raw data (value obtained from each borehole) comparing the calorific value and the phosphorus in coal of the different lithological units are illustrated Figure 48.

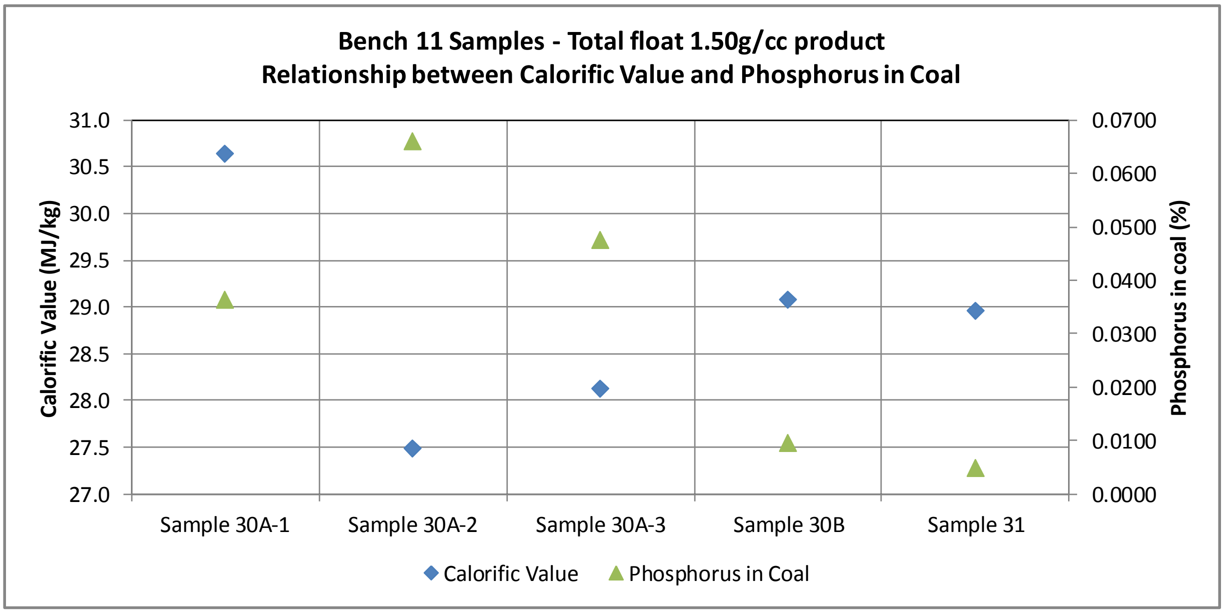

Figure 47 Comparison between Calorific Value and Phosphorus in coal

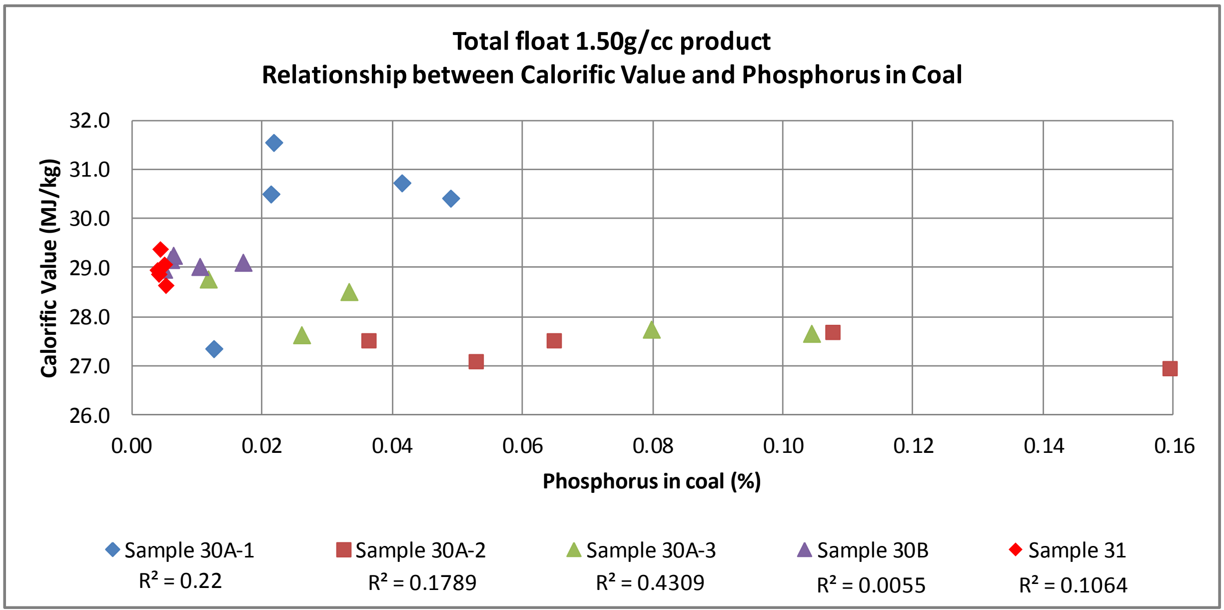

Figure 48 Scatter plot of the Calorific Value versus the Phosphorus in coal

Figure 47 illustrates that the weighted average calorific value and the phosphorus in coal varies independently from each other. As with the other coal quality parameters investigated in this study, no relationship could be found between the calorific value and phosphorus in coal in the lithological units of Bench 11. This observation is confirmed by the scatter plots of the individual sample data presented in Figure 48.

The compilation of the figures used to compare the different coal quality parameters with the phosphorus in coal for the different lithological units of Bench 11 is shown in Figure 49 and Figure 50. These figures present an overview of the various coal qualities compared to the phosphorus in coal of the different lithological units used. The compilation of the scatter plots of the raw data of the different coal qualities versus the phosphorus in coal is shown in Figure 51 and Figure 52.

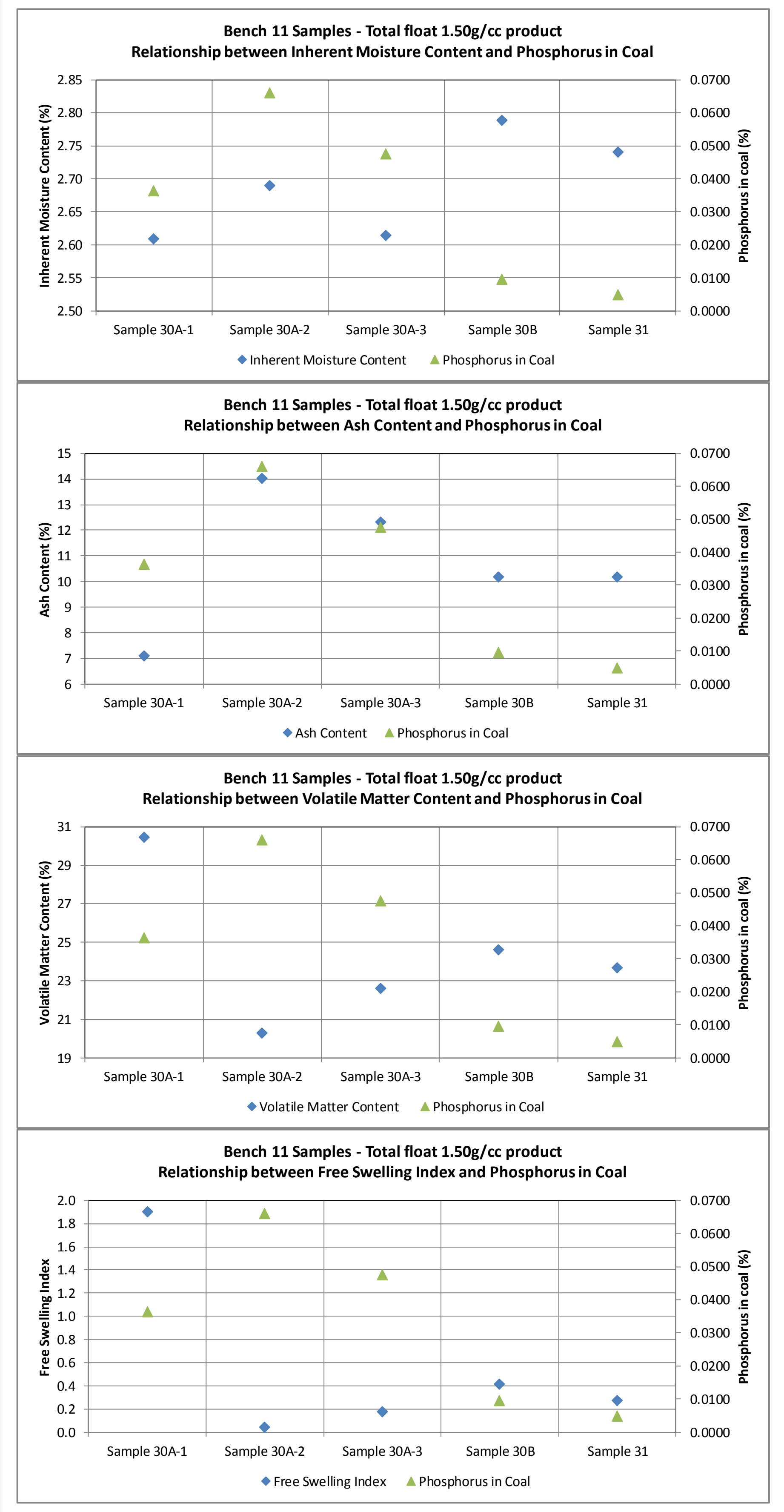

Figure 49 Compilation of coal qualities compared to phosphorus in coal

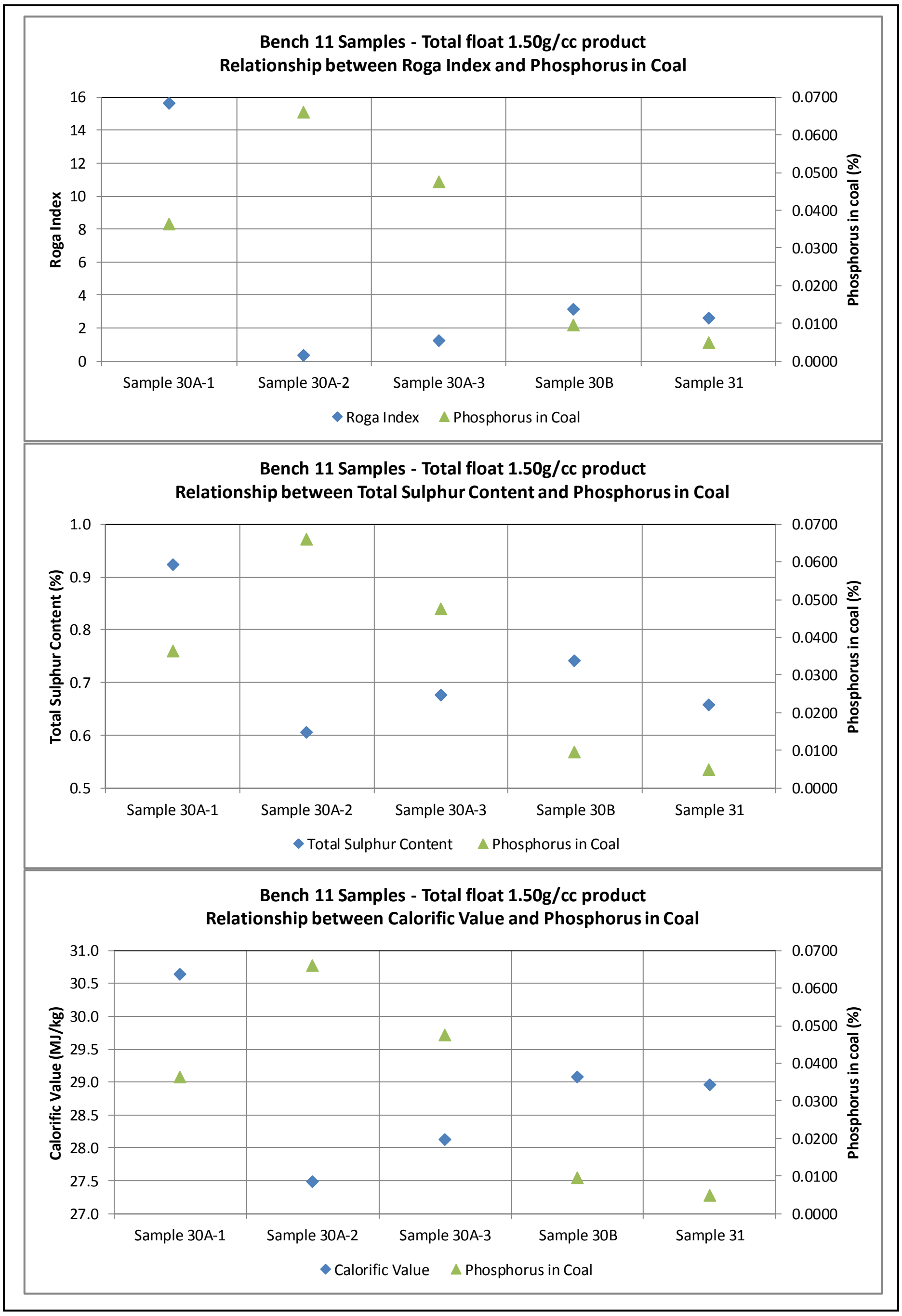

Figure 50 Compilation of coal qualities compared to phosphorus in coal

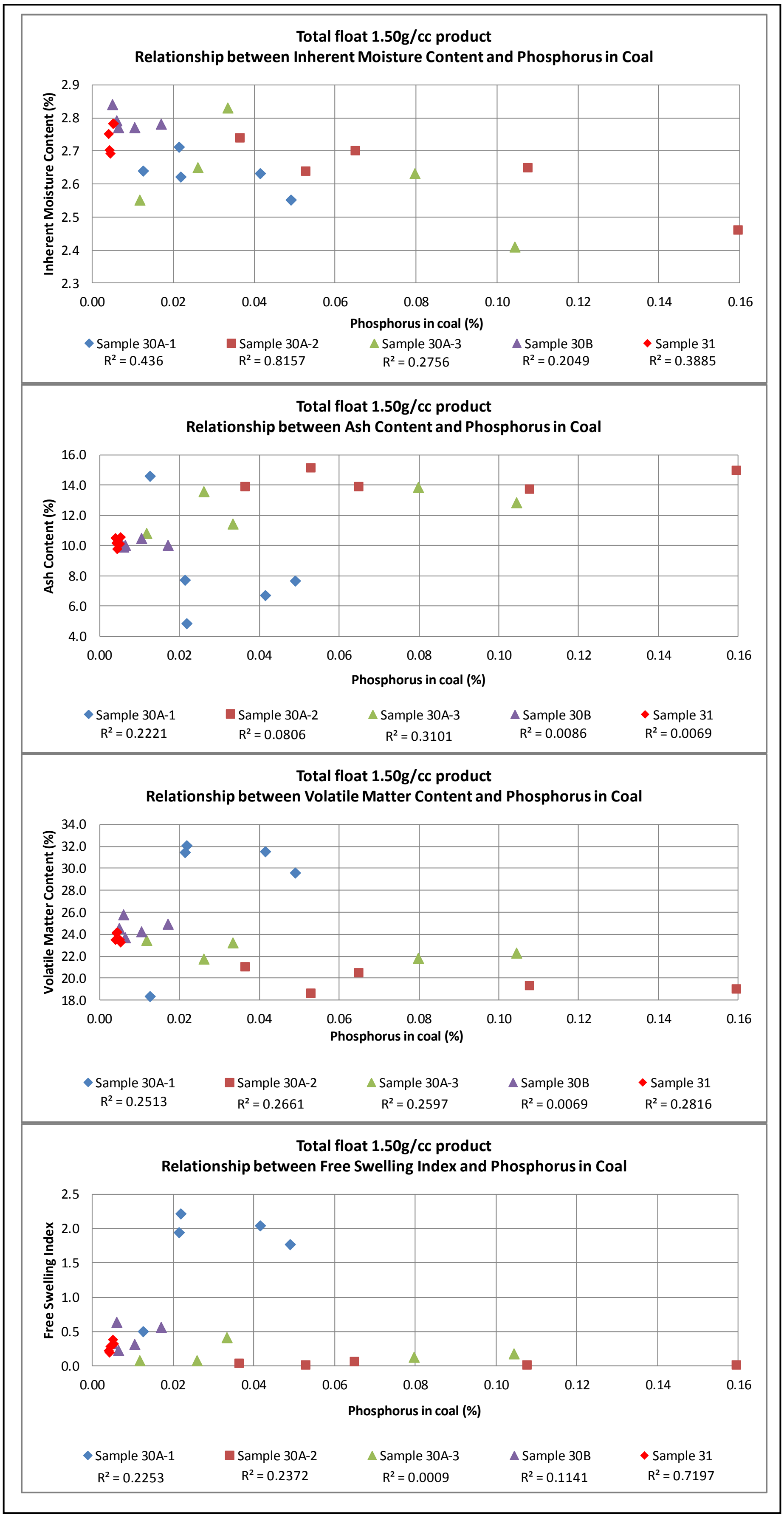

Figure 51 Compilation the scatter plots of coal qualities versus the phosphorus in coal

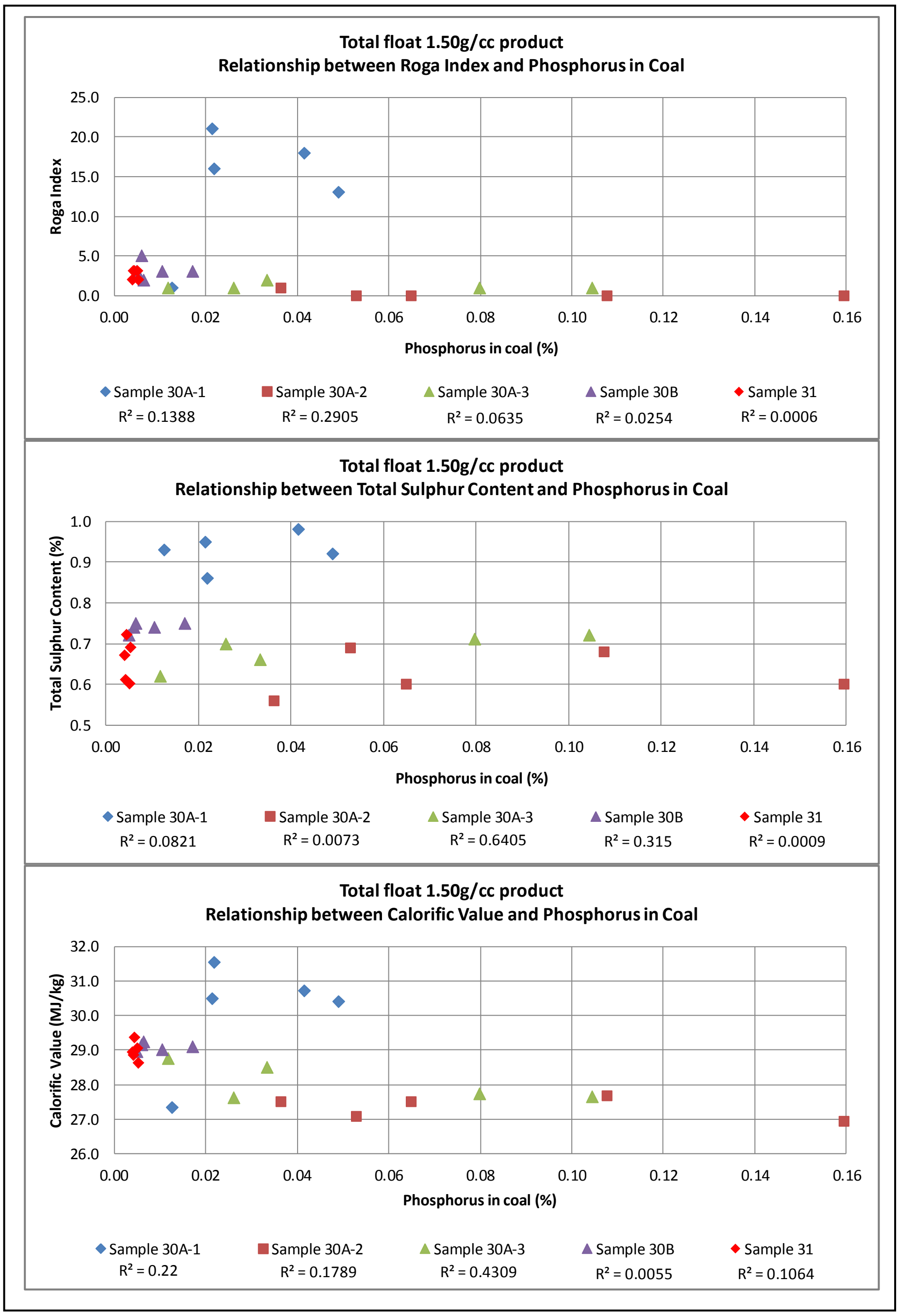

Figure 52 Compilation the scatter plots of coal qualities versus the phosphorus in coal

4.6 Blending potential of Zone 1

The weighted average yield and phosphorus content for the different mining benches in a coal product containing 15% ash are tabulated in Table 14.

Table 14 Zone 1 coal blending ratios

Stratigraphic Unit (Mining Bench)	Weighted average coal product containing 15% ash		Coal blending ratio (Mining bench : Zone 1)
	Coal Product Yield (%)	Phosphorus in coal (%)	
Bench 6	36.5	0.2205	1 : 28
Bench 7B	12.2	0.1589	1 : 7
Bench 9A	60.0	0.2889	1 : 61
Bench 9B	80.9	0.0655	1 : 16
Bench 11	80.3	0.0135	1 : 0.5
Zone 1*	79.0	0.0085	not applicable

Rounding-off of figures may cause computational discrepancies.
* Zone 1 is currently not extracted at Grootegeluk Mine.

From Table 14 it is evident that the weighted average product yields of Benches 6 and 7B and Bench 9A are different and much lower than that of Zone 1. The lower product yields of these benches means that much more run-of-mine from these benches will be required to produce the same amount of product than what is produced from Zone 1. In contrast, the high weighted average phosphorus content in these benches result in the opposite, i.e. much more Zone 1 material will be required to counter for the high phosphorus in the run-of-mine mix.

The weighted average product yield of Bench 9B and Bench 11 is quite similar to that of Zone 1. In these benches more or less equal amounts of coal are therefore expected in the final product when the same amounts of raw coal are mined from each bench. Since the weighted average phosphorus in these benches is higher than that of Zone 1, more material from Zone 1 will be required to lower the phosphorus in the run-of-mine to suitable phosphorus levels.

The ratios in which the mining benches need to be blended with coal from Zone 1, in order to reduce the phosphorus in the resultant coal product to acceptable levels for char plant feed coal are also depicted in Table 14. From these results it is evident that it will be feasible to lower the phosphorus of Bench 11 by means of blending with coal from Zone 1. The required ratio to achieve this is 1:0.5. This means that for each tonne of Bench 11 run-of-mine, a half tonne of Zone 1 material is required to lower the phosphorus in the final product to a suitable level for the production of char plant feed coal.

Apart from Bench 11, all other benches require too much material from Zone 1 to realistically reduce the phosphorus in the final coal to a suitable level for use as char plant feed coal. It is interesting to note that Bench 7B requires the second least amount of Zone 1 material to obtain a coal product that has less than 0.012% phosphorus. For each tonne of Bench 7B run-of-mine, seven tonnes of Zone 1 run-of-mine is required to produce a coal product at 15% ash with phosphorus in coal of less than 0.012%. This ratio is the result of the low product yield of Bench 7B at 15% ash; hence on average only 12.2% of the Bench 7B run-of-mine will go to the final coal product.

5 Discussion and Conclusions

5.1 Lateral phosphorus distribution of the mining benches

Zone 1 has the lowest average phosphorus content of all the coal seams in the Vryheid Formation at Grootegeluk Mine. Zone 1 is also the only coal seam which complies (on average) with the phosphorus content specification of char plant feed coal of 0.012%. Although Zone 1 has generally low phosphorus coal, the geological model of its phosphorus content indicated that the south western portion of this coal seam is above the phosphorus limit for char plant feed coal. Zone 1 is not mined currently.

Bench 11 has the second lowest average phosphorus content of the coal seams and has the lowest phosphorus of the benches that are currently being mined. Bench 11 is also currently the only source of char plant feed coal at Grootegeluk Mine due to its relatively low phosphorus content. On average the phosphorus content of Bench 11 is 0.0135% in a coal product containing 15% ash. This phosphorus content is too high for the production of char plant feed coal. The geological model of the phosphorus content of Bench 11 indicates areas in the northern and western portions of the resource that are below the 0.012% limit for char plant feed coal. Only in these areas, is it considered feasible to utilize Bench 11 for char plant feed coal in its current state.

The geological model of the phosphorus content of Bench 11 also indicates large areas in the resource where the phosphorus content is above the stipulated maximum level for char plant feed coal. It is therefore evident from this study that Bench 11 will not be of suitable quality, in its entirety, for the production of char plant feed coal at certain stages during the life of the mine. This poses a risk leading to interrupted char plant feed coal production if relying on Bench 11 as the only source of char plant feed coal.

The geological model of the phosphorus content of Bench 9B indicated that the phosphorus distribution of Bench 9B is quite variable. Bench 9B has phosphorus levels that are on average too high for use as char plant feed coal. The average phosphorus content is 0.0655% in a coal product containing 15% ash, and therefore this bench is regarded as having medium phosphorus coal.

The geological model of the phosphorus content of Bench 9B also indicated that there are certain areas in the norther portion of the resource that is below the maximum phosphorus specification for char plant feed coal of 0.012%. This means that coal from Bench 9B within these lateral areas of the resource may be feasible to utilize as char plant feed coal with regards to the phosphorus content. These areas are currently far from the production face of the mine and will only become available for mining in many years from now.

The phosphorus histograms of Zone 1, Bench 11 and Bench 9B (the low and medium phosphorus coal benches) display positively skewed distributions. These distributions indicate that there are generally a few relatively high values present in the populations of these benches which have an escalating effect on the average phosphorus content of these benches. The influence of the relatively high phosphorus values on the lateral extent of the coal seams could be assessed by means of the geological models.

Bench 9A proved to have the highest average phosphorus content of all the Vryheid Formation mining benches at Grootegeluk Mine. The phosphorus content of Benches 7B and 6 are also very high. Benches 9A, 7B and 6 (the high phosphorus content benches) all have fairly normal frequency distributions of their phosphorus content. This indicates that the phosphorus of these benches only vary slightly and is fairly evenly distributed throughout the resource. By means of the statistical analyses alone, it is concluded that Benches 6, 7B and 9A don’t contain any suitable char plant feed coal with regards to their phosphorus content.

By using statistical analyses, it was possible to determine how much phosphorus content is in each bench and how the phosphorus is dispersed in each bench. Through the geological modelling, it was possible to determine the lateral phosphorus distribution in the mining benches, i.e. how the phosphorus content varies laterally through each mining bench across the resource area at Grootegeluk Mine. It must be noted however that the number of boreholes containing phosphorus data is limited in certain areas of the resource. This creates a risk on the estimation accuracy of the geological models in certain areas. Additional exploration boreholes containing ash composition analyses may change the current geological models quite significantly, especially in the areas where current borehole information is limited.

5.2 Vertical phosphorus distribution of the mining benches

The method followed to investigate the vertical phosphorus distribution of the mining benches was to examine the individual sample units which make up the different mining benches. Statistical analyses and geological models of the phosphorus content in the individual samples were used in this component of the research. The hypotheses that were tested and proved in this component of the research are the following:

- 1.) Geological models based on sample units across Grootegeluk Mine's resource area will provide the means for selecting mining benches that are of suitably low phosphorus content to provide feed coal for the char plant.
- 2.) The coal reserves at Grootegeluk Mine can be optimized by means of selective mining to produce coal of suitably low phosphorus content for the production of char plant feed coal.

The results from the statistical analyses of the phosphorus content of the sample units showed that phosphorus varies vertically through the mining benches. This was clearly illustrated in Benches 6, 9B and 11 which all comprise more than one coal sample (correlated vertical subdivision of the bench). In Benches 6 and 9B, the average phosphorus concentration is lowest in the bottom sample and increases upwards, with the highest phosphorus concentration in the upper sample of the bench. In Bench 11 the lowest phosphorus occurs in the middle of the bench (Sample 30B) and is the highest in the upper portion of the bench (Sample 30A).

The statistical analyses showed that only Samples 30B and 31 in Bench 11 as well as Sample 32 (Zone 1) have average phosphorus concentrations below the specified maximum phosphorus limit required for char plant feed coal. This means that the bottom portion of Bench 11 (Sample 30B and 31) may still be suitable to produce low phosphorus coal when the full thickness Bench 11 is out of specification for char plant feed coal. This proved the second hypothesis that the coal reserves can be optimized by means of selective mining to produce coal of suitably low phosphorus content for the production of char plant feed coal.

The histograms of the phosphorus content in the sample units however indicated that all samples have values exceeding the char plant feed coal specification. This means that all samples will have areas in the resource where it does not qualify for char plant feed coal with regards to its phosphorus content. These areas could be identified by means of the geological models of the phosphorus content in the samples.

The geological models of the phosphorus content of the samples also confirmed that the phosphorus varies laterally and independently through the different samples. Even in the sample units containing low phosphorous, there are also lateral areas across the resource where these units contain phosphorus concentrations exceeding char plant feed coal specifications. The first hypothesis can therefore partially be justified because the geological models of the sample units can be used to select sample combinations that may provide for mining benches of suitably low phosphorus content. These selected samples need to be composited and re-modelled before a final decision on the respective mining bench can be made.

Due to certain areas in the resource where Samples 30B and 31 have phosphorus above the 0.012% level, it is inevitable that alternative methods to the selective mining of Bench 11 will have to be investigated in order to ensure continual supply of char plant feed coal throughout the life of the mine.

5.3 The use of geological models to evaluate the phosphorus distribution in coal

In general, the geological models of the phosphorus content of the different lithological units could be used to present the lateral phosphorus distribution of each unit across the resource. Areas containing high and low phosphorus are easily recognized by visual inspection of the colour shaded contour maps. The positions of the extremely high phosphorus values that were identified through the statistical analyses could also be easily recognized on the colour shaded contour maps that were compiled using geological modelling.

The advantage of using geological models is the ability to estimate the coal phosphorus content in areas of the resource that fall between and beyond the points of observation (exploration boreholes). The distribution of phosphorus content across the resource is best displayed using the geological models of units that have a good borehole distribution. In areas where borehole data is of a higher density, the accuracy of the phosphorus estimates is also higher. In the case of the geological models of the Sample 30A sub-samples, not enough points of observation are available and they are not adequately distributed in order to produce accurate models of the surrounding areas.

The significance of the geological models of the phosphorus content in the different lithological units is that they highlight the variability of the phosphorus content within the lithological units and show the occurrences of lower or higher phosphorus trends in the data. Units with higher phosphorus variability will be less accurately estimated than units with lower variability. Geological models also indicate areas in the resource where the phosphorus content in the mining benches, in particular Bench 11, is below the stipulated maximum char plant feed coal specification. While mining these low phosphorus areas, Bench 11 can be utilized in its full seam thickness to supply char plant feed coal with minimal risk of exceeding the specified maximum phosphorus limit. The risk of having no suitable low phosphorus coal at other times however, remains real.

5.4 Subdivision and selective mining of Bench 11

The statistical analyses of the phosphorus content of the different samples clearly indicated that Sample 30A (upper sample of Bench 11) has by far the highest phosphorus concentration of the samples pertaining to Bench 11. Sample 30A has an average vertical thickness of about 1 m, i.e. it represents about 25% of the full thickness of Bench 11. Since Sample 30A is situated at the top of Bench 11, it can be extracted selectively and utilized for the production of the normal suite of metallurgical coal products. The remaining portion of Bench 11 (Samples 30B and 31) has an average phosphorus concentration of 0.0063%, which is about half of the maximum allowable phosphorus required for char plant feed coal. This option will therefore mostly comply with the phosphorus requirements of char plant feed coal, but will decrease the potential char plant feed coal from Bench 11 by approximately 25%.

The geological models of the phosphorus content of Bench 11 as well as the sample units comprising Bench 11 indicated areas in the north-western portion of the resource where the phosphorus in coal is below 0.012%. In these areas Bench 11 can be mined in its full seam thickness and will still comply with the requirements of char plant feed coal with regards to its phosphorus content. These areas are still far from the current mining position and will only be mined in many years from now. In the area where mining is taking place currently (central resource area), the average full seam thickness phosphorus content of Bench 11 is above the limit for char plant feed coal.

The statistical analyses and geological models of the phosphorus content of the Sample 30A sub-samples indicated that the phosphorus varies both vertically and laterally through Sample 30. The study showed that all three of these vertical units contain phosphorus concentrations in excess of the allowable 0.012% required for char plant feed coal. The highest concentration of phosphorus is present in Sub-sample 30A-2, the middle portion of Sample 30A. It will be impractical to extract only Sub-sample 30A-2 separately from Bench 11, since the uppermost portion of the bench (Sub-sample 30A-1) will also need to be removed in order to liberate Sub-sample 30A-2.

Calculations based on the weighted average phosphorus content of the different lithological units comprising Bench 11 indicated that the upper two sub-samples need to be removed separately from the bench in order for the phosphorus in the remainder of the bench to be lowered below 0.012%. This option relates to a loss of about 16%, or 700 mm of the upper portion of Bench 11, that needs to be removed separately in order to lower the phosphorus in the remaining portion of the bench to a suitable level for use as char plant feed coal. This option results in a much smaller loss of potential char plant feed coal as opposed to removing the entire Sample 30A (25%) from Bench 11.

It must be noted that the specially drilled boreholes used for this study, with regards to the sub-sampling of Sample 30A in Bench 11, only covers a small portion of the total resource pertaining to Grootegeluk Mine. The phosphorus content of the Sample 30A sub-samples was found to be extremely variable over relatively short distances in the portion where mining is currently taking place, but it may be significantly different in other parts of the resource. Once more data becomes available that can be added to the current investigation, the philosophy to remove the upper 700 mm of Bench 11 may change. More exploration boreholes containing phosphorus analyses are needed to confirm the vertical phosphorus distribution and variability in the Sample 30A sub-samples in order to ensure suitable char plant feed coal from Bench 11 at all times.

5.5 The reduction of phosphorus in coal by means of coal beneficiation

The coal beneficiation study was conducted to determine whether the phosphorus in coal can be sufficiently reduced by means of coal beneficiation. According to Ryan and Grieve (1996) it is difficult to remove phosphorus from coal by conventional washing techniques. This hypothesis was tested in the current investigation in order to complete the study and establish whether this theory is also applicable to the coals of the Waterberg Coalfield.

Three different levels of lithological units were evaluated, namely benches, samples and sub-samples, to ensure the possible masking effect of the results due to the combination of minor lithological units is ruled out.

The phosphorus in the coal of all the mining benches decreases slightly with a reduction in ash content of the final product. The rate of change in phosphorus content varies very subtly in the different mining benches. A correlation therefore appears to exist between the rate at which the phosphorus is reduced and the decrease in the coal ash content. Bench 9B has the highest phosphorus content and this unit showed the highest reduction in phosphorus while Zone 1 has the lowest phosphorus content and showed the least reduction in phosphorus by lowering the product coal ash content.

Bench 11 is the only mining bench of which the phosphorus could be lowered to acceptable char plant feed levels. This was obtained for a coal product containing 12% ash. This reduction in phosphorus however is insignificant and uneconomic, if taking the associated product yield loss into consideration.

From a sample perspective, the phosphorus content also reduced slightly with a reduction in the coal ash content, but the rate of change varies somewhat more among the different sample units. In Sample 30 A, no reduction in phosphorus was obtained below 11% ash in the coal. In the case of Sample 30, the phosphorus decreased at a higher rate than in the other samples used in the investigation.

A rather interesting observation is that the weighted average phosphorus content of Sample 30 in the different coal products does not represent that of Sample 30A and Sample 30B combined, although these two samples originated from Sample 30. The rate of phosphorus reduction is much higher in Sample 30 than in either Sample 30A or Sample 30B. This occurrence may be due to the different borehole populations from which the analytical data of the different samples were derived, since phosphorus varies laterally across the resource.

The rate of change in phosphorus of the three Sample 30A sub-samples is very similar to that of Sample 30A. However, in none of the Sample 30A sub-samples was the phosphorus content sufficiently reduced to be of char plant feed quality.

In conclusion, this study confirmed that a very subtle reduction in phosphorus is obtained from the coals of the Waterberg Coalfield by means of coal beneficiation, but not sufficient enough to be considered as an alternative to produce more low phosphorus coal. Results show that Bench 11 reached average phosphorus levels of less than 0.012% in a coal product containing 12% ash. For this bench, the yield loss between coal products containing 15% ash and 12% ash is quite significant and therefore makes this alternative of little value. Coal beneficiation would not be economical or practical in order to produce low phosphorus coal at Grootegeluk Mine. The hypothesis that the phosphorus content in the coal at Grootegeluk Mine cannot be sufficiently reduced by means of coal beneficiation for use as char plant feed coal, was therefore proved.

5.6 The use of other coal qualities to improve the estimation of phosphorus in coal

It is believed that if a relationship between the phosphorus in coal and one or more other coal qualities can be established, then those coal quality parameters can be used to support or improve the estimation of the phosphorus content in coal, especially in areas of the resource where phosphorus data is limited. The hypothesis that was tested in this component of the research is the following:

- The phosphorus content in coal cannot be associated with other coal quality parameters and therefore these coal qualities cannot be used to compensate for proper phosphorus analyses nor enhance the existing phosphorus analyses.

The lithological units pertaining to Bench 11 were used by assessing the data obtained from the five specially drilled core boreholes through Bench 11 in the pit area. The different averaged coal qualities were compared with the average phosphorus in coal for each lithological unit. The coal quality parameters used for comparison to phosphorus in coal were the ash content, moisture content, volatile matter content, total sulphur content, calorific value, free swelling index and Roga index. The coal quality parameters were calculated for a coal product at a total float density of 1.50 g/cc in order to be able to also use the ash content of the coal as one of the quality parameters. The thicknesses of the lithological units and the coal yield as obtained at a total float density of 1.50 g/cc in the different boreholes were used as the weighting factors for the calculation of the weighted average qualities.

In general this study confirmed that the phosphorus content in the different lithological units comprising Bench 11 vary independently from any of the coal quality parameters used in this investigation. It is therefore concluded that no correlation exists between the phosphorus content and any of the other coal quality parameters used. It was therefore proved that other coal qualities cannot be used to compensate for proper phosphorus analyses nor enhance the existing phosphorus analyses.

5.7 Blending potential of Zone 1 to increase the amount of char plant feed coal

In this part of the investigation, the following hypothesis was tested:

- The amount of low phosphorus metallurgical coal at Grootegeluk Mine can be increased by blending coal of the existing mining benches with coal from Zone 1.

Results from the statistical analyses showed that Zone 1 yields the lowest phosphorus content of all the coal seams in the Waterberg Coalfield, which is on average far below the maximum phosphorus content required for char plant feed coal. Zone 1 can therefore generally be regarded as a source of blending coal to mix with other higher phosphorus content coals in the Vryheid Formation; consequently increasing the amount of usable char plant feed coal from the resource. The geological model of Zone 1 indicated an area of relatively high phosphorus content in the south western portion of the resource. In this area of the resource, Zone 1 cannot be considered for this purpose but can still be utilized for the normal suite of metallurgical coal products.

From the results obtained in this study, it is evident that the phosphorus content of Bench 11 can be practically lowered by blending it with coal from Zone 1. The average required ratio in which the run-of-mine from Bench 11 should be blended with coal from Zone 1 is 1:0.5. This means that for every tonne of Bench 11, a half tonne from Zone 1 is required in order to obtain an average run-of-mine blend with less than 0.012% phosphorus in the final coal product.

It was also found that the phosphorus content of Bench 7B (Zone 4A) can be lowered to below 0.012% by blending it with coal from Zone 1 in the ratio of 1:7. This however is impractical and uneconomical to execute for two reasons: Firstly, the average product yield of Bench 7B at 15% ash content is only 12.2%, meaning the majority of the Bench 7B material will end up as beneficiation plant waste. Secondly, the amount of Zone 1 material needed for this action is not sustainable because of the low seam thickness of Zone 1 (~1.5 m). As a result of the type of deposit and the mining method applied where the mining benches follow each other from top to bottom in a specific rate of extraction to maintain the geometry of the open pit, it is not possible to mine excessive volumes from any particular bench at a time.

Bench 11 is the only bench which does not require too much material from Zone 1 to suitably lower the phosphorus content in the final product. The required average blending ratio of Bench 9B with Zone 1 is 1:16 while that of Bench 9A is 1:61 and Bench 6 is 1:28. It is therefore concluded that Bench 11, when blended with Zone 1, realises the only potential source which could extend the char plant feed coal in the reserves at Grootegeluk Mine. The hypothesis that the amount of low phosphorus metallurgical coal at Grootegeluk Mine can be increased by blending coal of Bench 11 with coal from Zone 1, was therefore proved.

It is important to keep in mind that the obtained blending ratios from this investigation are rough estimates of what is actually required, since the phosphorus varies both laterally as well as vertically through the resource. It is therefore unlikely that the desired average coal quality from these two coal seams will be obtained at any given point of extraction when using the ratio of 1:0.5 with Bench 11 and Zone 1. Diligent management of the blending operation is therefore required to ensure that the desired phosphorus concentration is obtained in the final coal product. The latest geological models of the phosphorus content of the mining benches as well as their product yield should always be used to guide such calculations. Even so, small discrepancies in the resource due to lateral phase changes in the depositional environment during coal formation may result in imprecise estimates.

The relatively high mining cost relating to the extraction of coal from Zone 1 should be weighed against the opportunity cost of not having low phosphorus char plant feed coal available through periods of the life of the mine when Bench 11 is out of specification. Implementing the extraction of coal from Zone 1 will increase the resource utilization at Grootegeluk Mine because more coal could be used for char plant feed coal if blended with Zone 1. The extraction of Zone 1 could therefore ensure the continuous supply of low phosphorus coal to the char plant throughout the life of the mine.

6 Recommendations

The phosphorus content of Bench 11 can be reduced by the selective removal of the upper portion of the bench. The exact portion that needs to be removed is dependent on the mining position in the resource because phosphorus varies both laterally and vertically in the coal seams of the Waterberg Coalfield. At the current position of extraction of Bench 11, the upper 0.7 m of the bench needs to be removed in order to realise the phosphorus in the remaining portion of the bench below the current maximum phosphorus limit of 0.012% for the production of char plant feed.

The phosphorus content of Bench 11 can also be reduced by using coal from Zone 1 as a "sweetener" for phosphorus in the run-of-mine mix. The required ratio to lower the phosphorus content of Bench 11 with coal from Zone 1 to char plant feed specifications is 1:0.5. This method of reducing the phosphorus in Bench 11 is considered feasible and will ensure enough char plant feed coal for current and future requirements. The surplus material from Zone 1 which is not used for blending with Bench 11, can be used as an additional source of char plant feed coal or for metallurgical coal. It is therefore recommended that the mining of Zone 1 should be introduced in order to mitigate the risk of having Bench 11 as the solitary source of char plant feed coal, and to be able to lower the phosphorus content of Bench 11 when required. Currently Zone 1 is sterilised for future mining due to the backfilling of waste material in the bottom of the open pit. If mined, Zone 1 will also contribute towards the extension of the life of the mine, and will be saved from sterilization.

The exploration borehole data that contain ash composition analyses at Grootegeluk Mine is wide spread in certain areas of the resource. This has a negative effect on the estimation accuracy of the geological models of the phosphorus concentrations in the different lithological units. It is recommended that the following steps be considered in order to improve the estimation accuracy of the phosphorus in coal:

- Additional drilling and sampling must be conducted to increase the amount of phosphorus data across the resource. The additional information may change the current view of the phosphorus distribution in the different lithological units. This is especially important for the coal seams that are currently, or in future will be utilized for char plant feed coal.

- The extremely high phosphorus values as observed in some of the lithological units are a concern and require thorough investigation. Additional drilling and analyses in the vicinity of the high values are recommended in order to fully evaluate their influence on the surrounding resource.

- If the proposed subdividing of Bench 11 is implemented to lower the phosphorus content of the bench, then additional geological information of the Sample 30A sub-samples is needed across the resource area, in order to determine the phosphorus content and its distribution in these smaller lithological units.

Results from this study proved that it is impractical to reduce the phosphorus levels of the Vryheid Formation coal seams by means of coal beneficiation. The use of coal beneficiation to reduce the amount of phosphorus in coal is therefore not recommended for the Vryheid Formation coal seams of the Waterberg Coalfield.

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