DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Kobus Bergh

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ABSTRACT

South Africa remains the 5th largest producer and 4th largest exporter of coal in the world. It is also the largest supplier of coal to the European Union. This fact is significant as the European Union has recently supported the environmental lobby that threatens the combined full scale use of coal in Europe and other first world countries. This promotes the development of clean coal technologies in order to counter the ever increasing number of environmental constraints threatening the export market. One critical development in clean coal technologies is coal beneficiation, which allows the reduction of ash and inert content. Permian coals from South Africa have characteristically high ash and inertinite contents and therefore require further beneficiation. The Witbank coalfield No. 4 seam is no exception. It can be described as being more inert and having a higher mineral content compared to the No. 2 seam in the same coalfield also mined for export purposes.

With the increase in environmental legislation and the push towards "clean coal" this raises a concern in terms of the performance and marketability of export coal produced from the No. 4 seam. This seam will in the future be economically significant and is still a great source for export steam coal. Due to the nature and composition of the No. 4 seam, coal beneficiation is essential to reduce the mineral and inert content to be in line with export quality specification levels. Washability characteristics of the No. 4 seam coal indicate that the No. 4 seam is difficult to beneficiate. Until recently the main clean-ability parameters evaluated in South African export coals as per customer specification included mainly heating value, moisture and ash reduction with little to no work being done on trace element concentration reduction. This paper focuses on the partitioning of the trace elements within the seam in relation to the organic and inorganic affinity of the trace elements and possible methods of trace element reduction by removal using coal beneficiation techniques. The techniques investigated include reduction by washing using dense medium beneficiation and flotation. In each evaluation the focus was on trace-element-to-mineral and trace-element-to-organic matter relationship and hence setting the basis for liberation analysis to evaluate reducibility.

By the evaluation of the coal mineralogy, petrography and trace element relationships, methods of optimum trace element reduction can be established. With the focus on marketing it was shown that carbon loss need not be sacrificed in the reduction of specific trace elements in the No. 4 seam and that the trace element distribution itself allows for beneficiation whilst maintaining acceptable yields. Processes and possible beneficiation techniques for optimum trace element reduction and marketability in the case of the No.4 seam are proposed.

Keywords: Permian coals, Witbank Coalfield, Marketing, Partitioning, Trace Elements, Preparation, Beneficiation, Flotation, Mineralogy, Petrography

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CHAPTER ONE – INTRODUCTION

1.1 General Introduction

1.1.1 Coal characteristics and trace element content

Coal is a fossil fuel. It can be described as being a heterogeneous, combustible, metamorphic rock of sedimentary origin composed of mainly carbon, hydrogen and oxygen, containing more than fifty percent by weight and seventy percent by volume carbonaceous material, formed from vegetation which has been consolidated between other rock strata and altered by the combined effects of pressure and heat over millions of years to form coal seams (Refer to Figure 1, page 11). The different coals in turn have distinct properties and characteristics in terms of TYPE which vary upon type of plant material and the conditions during formation, RANK or the degree of metamorphism and GRADE or the degree of impurities.

All the distinct properties of coal play a role in the distribution of the trace elements within the seam. Firstly with a variation in the TYPE of plant material a variance in the trace element will occur. It has been proven that different maceral content have distinctive relationships with trace element content. In essence a variation in vegetation from plant leaves and algae to tree barks at the time of deposition would mean a variation in trace element content. There are trace elements that have a higher organic affinity being associated with the maceral content in the coal.

Many trace elements are essential for plant growth and their trace element profile is, to some extent, dependent on the composition of the soil in which they grow (Dale 2003). Decaying plant material contains humic acid and many trace elements which have an affinity to form chemical bonds with organic material are found at elevated levels in coal. See table 1, page 12 for the trace element content in different fossil fuels compared to coal.

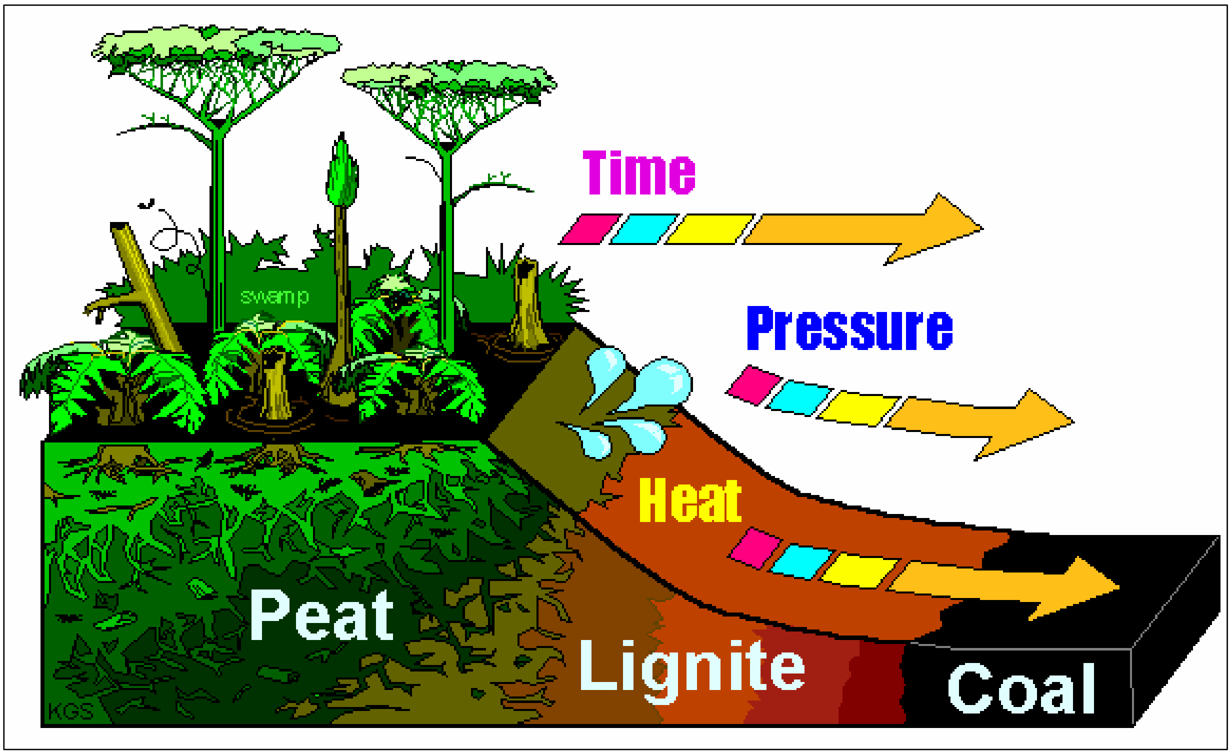
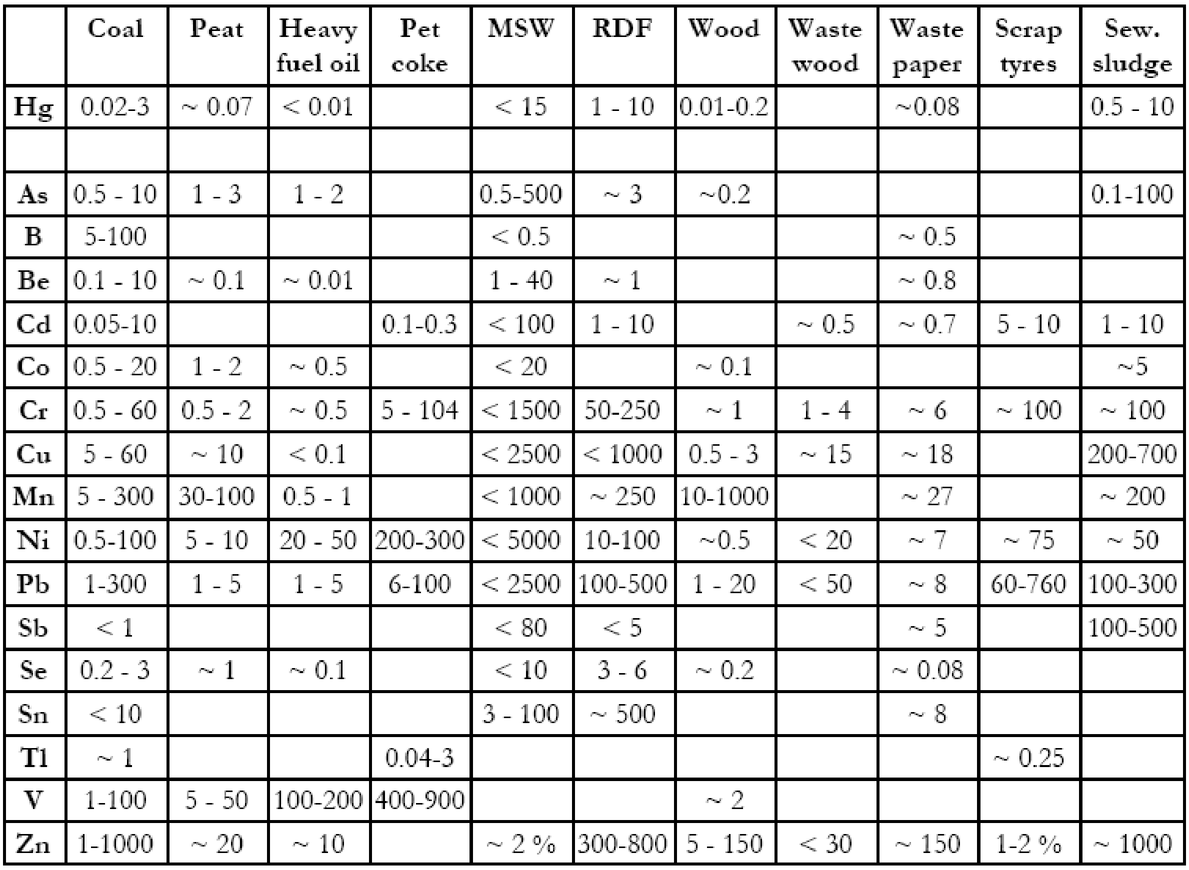


Figure 1: *The Transformation of Coal with Time, Temperature and Pressure – Degree of Coalification, U.S. National Energy Education Development*

Secondly RANK plays a role. Figure 1 gives an illustration of peat and subsequent coal formation, from low to high rank. The volatile matter and inherent moisture varies with rank variation, the volatile matter decreases with an increase in rank with the lowest found in anthracite at the highest rank. Inherent moisture also decreases with an increase in rank. With a different degree of metamorphism a different rank will be induced, the coal will have distinctive characteristics different for lower or higher ranking coal. The depositional changes would influence the chemistry for example ion exchange that would take place during metamorphism, and would therefore influence the trace element content in the coal (Wagner 2004).

Table 1: *Trace element concentrations (in ppm) in some fossil fuels and waste derived. Zevenhoven (2001).*



	Coal	Peat	Heavy fuel oil	Pet coke	MSW	RDF	Wood	Waste wood	Waste paper	Scrap tyres	Sew. sludge
Hg	0.02-3	~ 0.07	< 0.01		< 15	1 - 10	0.01-0.2		~0.08		0.5 - 10
As	0.5 - 10	1 - 3	1 - 2		0.5-500	~ 3	~0.2				0.1-100
B	5-100				< 0.5				~ 0.5		
Be	0.1 - 10	~ 0.1	~ 0.01		1 - 40	~ 1			~ 0.8		
Cd	0.05-10			0.1-0.3	< 100	1 - 10		~ 0.5	~ 0.7	5 - 10	1 - 10
Co	0.5 - 20	1 - 2	~ 0.5		< 20		~ 0.1				~5
Cr	0.5 - 60	0.5 - 2	~ 0.5	5 - 104	< 1500	50-250	~ 1	1 - 4	~ 6	~ 100	~ 100
Cu	5 - 60	~ 10	< 0.1		< 2500	< 1000	0.5 - 3	~ 15	~ 18		200-700
Mn	5 - 300	30-100	0.5 - 1		< 1000	~ 250	10-1000		~ 27		~ 200
Ni	0.5-100	5 - 10	20 - 50	200-300	< 5000	10-100	~0.5	< 20	~ 7	~ 75	~ 50
Pb	1-300	1 - 5	1 - 5	6-100	< 2500	100-500	1 - 20	< 50	~ 8	60-760	100-300
Sb	< 1				< 80	< 5			~ 5		100-500
Se	0.2 - 3	~ 1	~ 0.1		< 10	3 - 6	~ 0.2		~ 0.08		
Sn	< 10				3 - 100	~ 500			~ 8		
Tl	~ 1			0.04-3						~ 0.25	
V	1-100	5 - 50	100-200	400-900			~ 2				
Zn	1-1000	~ 20	~ 10		~ 2 %	300-800	5 - 150	< 30	~ 150	1-2 %	~ 1000

In essence GRADE will have a major influence on the trace element content in the coal. A vast majority of the trace elements are associated with the mineral matter in the coal (Valkovic, 1983). These elements portray a high inorganic affinity. There are distinctive relationships between the trace element content and the inorganic or mineralogical components in the coal. With an increase in grade higher trace element content can be expected, but most importantly the type of minerals present and its liberation characteristics have been proven to be the parameters of paramount importance.

Grade or ash content in South African coals is a major concern, the coal from Permian origin as part of the Gondwana type coals has characteristically high amounts of included mineral matter. The trace element content that is associated with the included mineral matter may therefore be expected to be difficult to reduce via beneficiation.

1.1.2 Trace element effects on environment

There are many instances where specific trace elements have proven to have profound effects on the public health and the environment. Emissions of toxic trace elements such as arsenic emitted from coal-burning power plants in Europe and Asia have been shown to cause severe health problems. In China in particular most of the health problems are caused by trace element emitted from domestic combustion. An improved understanding of the partitioning of trace elements in conjunction with the mineralogy and beneficiation and utilisation capabilities from a specific deposit such as the Witbank coalfields No. 4 seam would help to reduce the possible emissions that could result from combustion.

Trace elements from coal are classified into three classes in order of volatility (see figure 2). Mercury being highly volatile is one of the elements of greatest concern. Mercury in particular is known to cause neural and cardiovascular disease. Arsenic that is less volatile is known to be carcinogenic and cause major harm to blood vessels and the human nervous system.

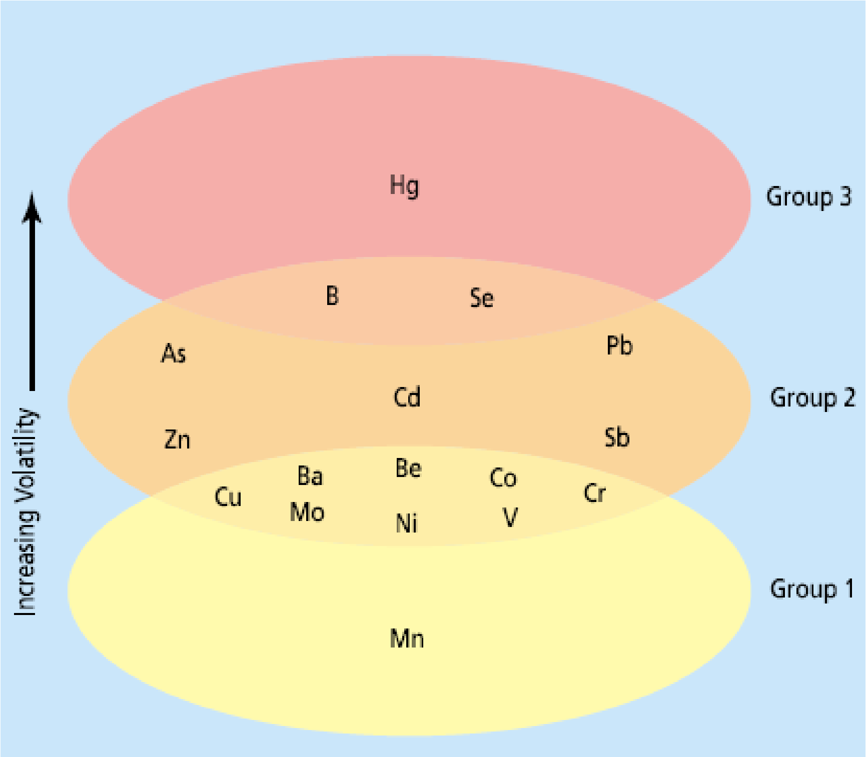


Figure 2: *Classification of trace elements according to their behaviour during combustion or gasification (picture originally from Couch, 1995)*

Toxic trace elements are not only dangerous via emissions, but also leaching into ground water tables and other public water sources. Sufficient consumption via water would result in similar diseases to those associated with airborne toxic trace elements.

1.2 Objectives

The remaining coal deposits in South Africa lie mainly within the Highveld, Waterberg and Witbank coalfields. According to the latest report by the Department of Minerals and Energy, Prevost (2004), the Highveld and Witbank coalfields account for approximately 66% of the remaining coal reserves in South Africa. In the Witbank coalfield historically the No. 2 seam was of higher economic interest, but the No. 2 seam reserves have declined drastically over the last 2 decades which in turn promoted the No. 4 seam as the main source of export product. The Witbank coalfield No. 4 seam in essence is known as a high ash and inert seam or “dirty” as described by Lurie (2000). This is extremely significant, and emphasises the fact that the 4 seam have to be cleaned or upgraded to yield an export grade product. In this instance the product obtained from the 4 seam run of mine is exported mainly as power station smalls for pulverised fuel combustion. With the advent of new and improved technologies and expanding opportunities for exporting to foreign markets, and with requirements from recent environmental legislation, the availability of trace element washability and floatability data could play a major role in promoting the utilization of coal products from the Witbank coalfield No.4 seam.

The risk associated with trace element emissions does not only lie in the financial cost implications in order to stay within legislative measures, but also in health risks from an ethical perspective. Certain trace elements known as HAP (Hazardous Air Pollutants) can have substantial implications. According to James (2004) the US Clean Air Act Amendments of 1990 specifically identified As, Be, Cd, Cr, Co, Hg, Mn, Ni, Pb, Sb, Se, and U as potential HAP’s. These trace elements are known to be toxic and have adverse effects on humans, plants and animals as identified by Dale (2003).

Since the majority of the trace elements are associated with the inorganic fractions or mineral matter, which constitute the heavier fractions in the coal combination, beneficiation could assist in reducing not only the mineral matter, but also the trace elements associated with the mineral matter. South African coals are known to have high ash or mineral content which substantiates the concern of the high trace element content in our coals. There is limited data available in this matter. South African coal companies who export to first world countries should be concerned in finding a solution to these issues. The legislative measures in most of the export countries are tight and will tighten even more so in the near future. Papers written by Cairncross (1989) and Wagner et al (2004) have led to some interesting findings. In the paper published by Cairncross (1989) the mercury content in South African coals is for instance higher than the global average. Based on previous test work by Gluskoter (1998) and Wenfeng (2006) the indication is that coal beneficiation can reduce the mercury content significantly by the removal of the related mineral matter.

What is more significant is the association of the trace elements with either the epigenetic or syngenetic ash components. One of the most detrimental constituents in coal and its subsequent processing is the inherent ash or syngenetic mineral matter. Inherent ash comprises of finely disseminated mineral matter which is part of the coal matrix. This finely distributed mineral matter in the coal presents a very difficult separation problem for its reduction from the coal, even in finely-ground material. A characteristically high level of inherent ash and near gravity material is found in Gondwana coals (India, RSA, and Australia) and is a parameter which cannot be reduced significantly. It places a severe constraint on the coal producer to achieve the desired product quality levels. In contrast to the inherent ash, the epigenetic or extraneous ash is liberated from the coal and is removed quite successfully with a relatively straightforward separation process.

By the investigation of the trace element partitioning, and hence association to the organic and inorganic components, the results generated by this project could promote the industrial utilisation of coals from the Witbank coalfield No. 4 seam.

CHAPTER TWO – LITERATURE REVIEW

Published research on trace elements in coal and more especially in South Africa has not been extensive because up until recently with the advent of the current strict environmental policies they have been of little more than academic interest. Trace elements in coal have been investigated by various mining companies, but this info is propriety and not available for review. Furthermore because the trace elements occur in such small amounts their determination is both costly and difficult.

The concentrations of most of the trace elements in coal are lower than the average concentration of the trace elements in the earth's crust, although there are exceptions. Previous work done by Cairncross (1989) on a variety of South African coals and Wagner et al (2004) specifically on the Highveld coals gave a good indication of the likely concentrations of the trace elements in South African coals. What is quite significant in those South African coals is that in situ they have higher ash and hence mineral contents on average than our counterparts in the Northern hemisphere. Despite this South African and other Permian coals of the southern hemisphere also contain lower concentrations of sulphides, halogens, and trace elements relative to their northern hemisphere Carboniferous coals (Wagner et al, 2004).

The trace element concentrations in coal mineral matter (extraneous, epigenetic and inherent) vary to a greater extent than the trace elements found in the organic fractions where the concentration variation is much narrower (Gluskoter, 1974).

Due to the variations in mineral content complications exist where the concentrations of trace elements can vary for coal from the same seam classification. In the experience of Valkovic (1983), to get the best repeatable results, the bottom and top of the seams have to be sampled since higher trace element concentrations could be found in these areas. He also found that the lowest concentrations also gave the highest variations as expected. To evaluate a coal reserve quantitatively with confidence a vast majority of the borehole samples have to be taken and analysed. In evaluating the washability characteristics of the trace elements a borehole sample will not suffice; however it will give a better indication of the depositional aspects of the seam which can be related to the mineralogical occurrences of the particular seam.

In terms of association, trace elements can occur in either the organic or inorganic form (Gluskoter, 1994). Elements like Fe, Ca, Zn, Mg and Si have been found to be present mainly in the mineral fractions, whereas trace elements like Ag, As, Pb, Hg, Co, Ni and Se were found to be distributed amongst several mineral species (Valkovic 1983). The halogen concentrations and especially Boron were found to be associated with the organic fraction of the coal. The concentrations of B, Cl, Se and As are extremely significant as these are higher than the average found of the concentrations in the earth's crust.

The vast majority of investigations on trace elements and the distribution have been done on coals in the United States. Gluskoter and Ruch (1974) et al have done extensive work on the analysis and partitioning and distribution of trace elements in coals from the United States. In work done on coals from the Illinois basin the organic and inorganic affinity of trace elements are indicated. The distribution of the trace elements was accompanied with mineral investigations. The investigations included trace element concentrations at various densities; these are indicated on a densimetric curve. In the investigation undertaken by Gluskoter et al it can be seen that the nature of the American coals (in that particular instance) is different than the coal from South Africa. The Illinois basin coals according to the washing tables are well liberated and according to the mineral investigations don't contain high amounts of inherent mineral matter. The arsenic, mainly associated with sulphide minerals (pyrite, pyrrhotiite and marcasite) distribution showed a very high inorganic affinity with a distribution closely related to the percentage ash distribution at various densities. The occurrence of the pyrite in South African coals is different. Due to these factors the reducibility characteristics of the trace elements is less complex and easier than that of South African coals with higher amounts of near-gravity material. Similar investigations by Capes et al (1996) proved similar relationships, but beneficiation of the trace elements is discussed in more detail, the flotation characteristics are discussed by evaluating the floatability of the Illinois coals. This was done by release analysis and comparisons to the ash species. Capes (1996) evaluated the floatability after grinding at varying degrees, by doing release analysis at various mesh sizes. It was also found that the cleaning of coals with high amounts of clay mineral matter is complex and that column flotation should be considered. The mineral relationships proved crucial.

The leading work done by Finkelman et al on the occurrence of trace elements in coal was paramount in the partitioning investigations undertaken. Mineral identification and correlation to minerals is discussed in great detail. Most of the work done by Finkelman is related to SEM (Scanning Electron Microscopy) mineral investigations. The coal in South Africa is very unique and the SEM mineral investigation is critical in evaluating the liberation of the minerals and their occurrence. In relation to beneficiation this plays a major role and will indicate the capacity for trace element reduction with reference to the characteristics of the associated minerals.

Partitioning of trace elements of a Chinese coal at different size fractions from beneficiation was done by Wenfeng et al (2006). The research by Wenfeng et al (2006) did however not include extensive mineralogical analysis and float-sinks analysis.

The work done in the United States has not been performed on South African coals. With the specialised characteristics of the mineral and maceral content in South African coal, these investigations are critical, Gondwana coal compared to Carboniferous coal specifically have distinct differences. In essence the comparison between the washability index of the US coals and coals from South Africa indicates that a specialised approach has to be implemented.

CHAPTER THREE – METHODS AND MATERIALS

3.1 Geological description and seam to be investigated

Due to coal being heterogeneous in nature in terms of both the organic and inorganic composition, the concentrations of the trace elements have been found to vary within the coal seam associated significantly with the sedimentology. Coal seams in the northern hemisphere (Laurasian) coals are known to be overlain by strata of marine origin, and therefore tend to have higher pyretic concentrations sulphur and, in general, higher trace element concentrations than those associated with mostly non-marine sediments found mostly in South Africa, Wagner et al (2004). The elemental-geological relationship has therefore moved to be important in establishing the sulphur and hence trace element associations. Earlier investigations by Cairncross (1990) proved that coal-bearing Vryheid Formation (Karoo Sequence) in the Witbank Coalfield was associated with both marine and non-marine depositional events. The trace element distribution in this coalfield is therefore likely to vary significantly and therefore needs to be investigated.

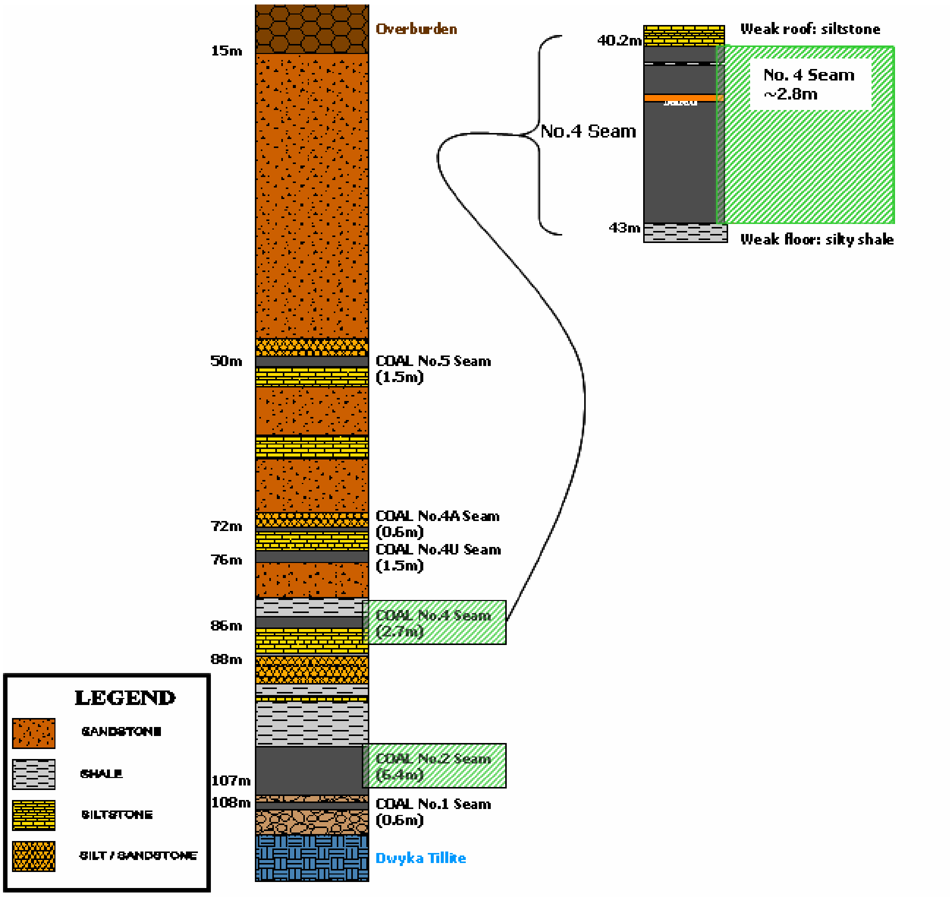


Figure 3: *Witbank coalfield No. 4 seam stratigraphy*

At the mine where the samples were taken the particular section of the No. 4 Seam ranges in thickness from 2.2 to 3.3 m, averaging 2.8 m (see figure 3). In the Witbank coalfield No.4 seam splits exist above the main seam, called the Upper 4 and Upper 4A seams. These are not mined and are not of economical importance. In this instance an in-seam limonitic mudstone parting of up to 0,2m in thickness typically separates a lower better quality zone of mainly dull lustrous coal with an average thickness of 1.9 m from an upper poorer quality zone of mixed dull and bright coal averaging 0.7m.

3.2 Sampling

Due to coal being heterogeneous, the representative evaluation thereof is extremely difficult. Different coals also have distinct inherent properties even though they may be from the same seam . The presence of extraneous and inherent mineral matter could also vary to such an extent vertically and laterally in one seam that band to band in one seam and particle upon particle varies. Especially in the case of inherent mineral matter, its presence even on beneficiated coal can cause huge quality differences. In order to understand that not only mineral content, but also macerals and trace element content can affect quality parameters the definition of coal has to be applied.

The nature of peat formation and the degree of coalification have a great influence on the physical and chemical properties of a particular coal. These inherent property variances affect the end qualities and assessment of a specific coal. The heterogeneity caused by these factors alone is cause for very thorough sampling procedures and reliance on vigorous statistical approaches to coal sampling. In the case of trace element content evaluation, these factors cannot be over emphasised as small influences due to inhomogeneous sampling or contamination would have catastrophic consequences. The samples need to be isolated and quarantined properly and analysis and preparation need to be swift and thorough. These approaches were taken in the course of sampling and handling of coal during this research.

3.2.1 Sampling ROM and Flotation samples

Two sets of 4 seam run of mine (ROM) were collected. From a mine that produces steam coal from the Witbank coalfield No. 4 seam these samples were taken over a period of 24 hours with the aid of an automated mechanical sampler. The samples were taken in accordance to the SABS ISO 13909-2 Standard “Sampling of Moving Streams” for general analysis at a top-size of 150 mm.

Figure 4: *Illustrating the conveyor falling stream mechanical sampler and mechanism.*

It was critical that sufficient sample was taken to satisfy statistical requirements. The calculated mass required for general analysis at a top size of 150mm is 2600 kg. The incremental mass of the sampler is in the order of 58 kg; with increments taken every 20 minutes after a period of 24 hours the actual sampled bulk mass is over 4176 kg.

Figure 5: *Illustrating the sampling point from sampler discharge.*

Samples of froth flotation plant feed, product and tailings were also collected by means of mechanical samplers. These samples were taken in accordance to SABS

ISO 20904 “Sampling of Hard Coal Slurry Streams”. The feed samples were consequently used to do bench scale flotation tests.

Figure 6: *An illustration of the flotation plant and mechanical slurry stream samplers with which the samples were taken. The plant consists of three modules of three sets of primary and secondary cells each.*

Figure 6 illustrates the method in which the slurry stream samples were taken. In order to ensure that there were no outside influences, the plant was running in steady state to obtain a representative sample. The minimal volume required per increment according to ISO 20904 is 300 mℓ; the current sampler cutter with a width of 10 cm gives on average 500 mℓ.

3.2.2 Sample preparation

The ROM samples taken were mixed several times, flattened and cone and quartered to produce a single set of samples for washability analysis. Extreme care was taken to isolate the samples from any source of possible contamination. The samples were transported to Anglo Coal Central Laboratories (ACCL) within less than 2 hours. The samples were not stored for extended periods of time, but were stored at ACCL in a controlled environment indoors to retain the condition of the coal as sampled. See figure 7.

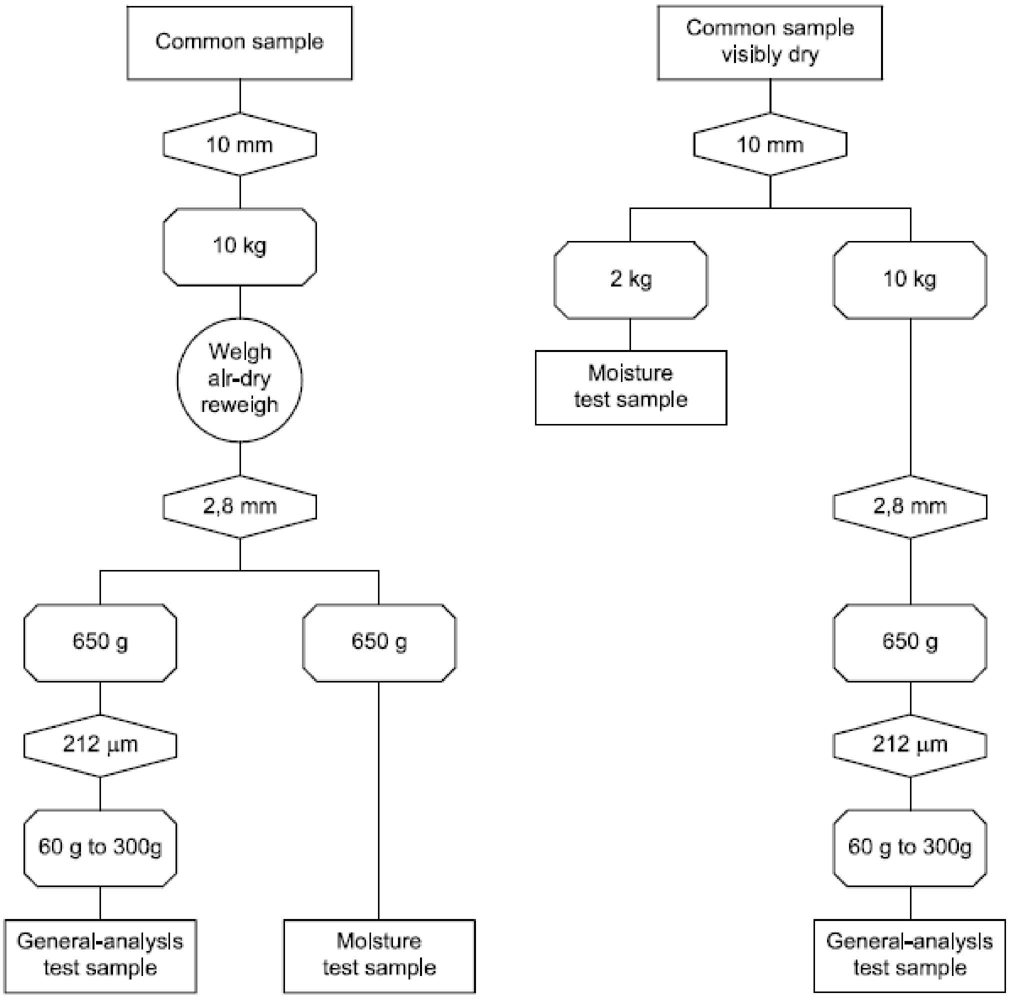


Figure 7: *Flow diagram for division of test samples for analysis from ISO 13909-4.*

3.3 Analysis

A general summary of the analysis undertaken is given in diagram 1, page 24. Note the samples used for QEMSCAN analysis were not pulverised, but were pulverised for XRD analysis.

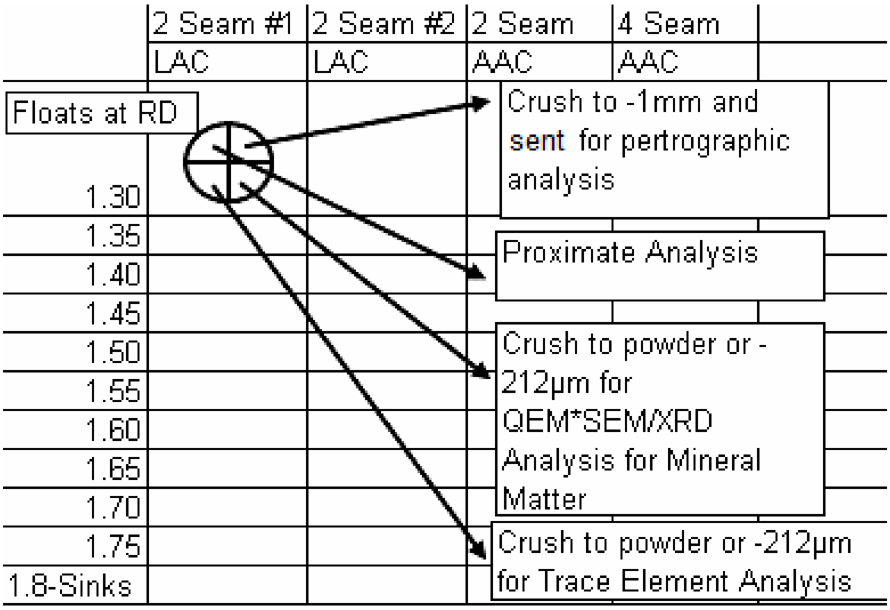


Diagram 1: *Illustrating the sample splitting for various preparations for analysis via quarter and coning.*

3.3.1 Washability analysis

A conventional float and sink analysis with the use of Zinc Chloride (ZnCl) as the dense medium was carried out at Anglo Coal Central Laboratories (ACCL). The total sample was floated including the fine fraction which was not removed prior to the washability analysis. The separate density fractions were then split to allow different sets of analyses on the samples. Proximate analysis and calorific value analysis was done on each density fraction.

Figure 8: *An illustration of the dense medium washing baths used at ACCL.*

The potential effect on the accuracy of trace element determination of the coal by the purity of the Zinc Chloride as dense medium was taken into account as the Zinc Chloride could adhere to the pores in the coal and hence affect the results. In terms of the Zn and Cl contents these concentrations would be affected, the remainder of the elements should remain unaffected as the order of the affect would not exceed parts per billion (ppb) based on the amounts of the dense medium that could adhere in a hygroscopic nature.

3.3.2 Floatability analysis

For the bench scale tests a conventional Denver froth flotation cell was used. A combination of 200 grams of 4 seam flotation plant feed ultra-fines at minus 200 μm and 3 litres of water was preconditioned without air and reagent. Figure 9 illustrates the bench scale flotation used in the analysis.

Figure 9: *An illustration of the Denver flotation cell utilised to do the bench scale flotation tests.*

The reagents used in the test work were a combination of 80% collector (mainly kerosene) and 20% frother (glycol and emulsifiers), 0.3mℓ reagent was dosed into the slurry and further conditioning time of 30 seconds was allowed. Upon the addition of air, a further 2.5 minutes was allowed for flotation with scraping done every 20 seconds. Proximate and calorific value analyses were carried out at ACCL on each of the flotation fractions feed, tailings and product. Again the trace element content of the reagent used could have played a role; however, based on the low dosage of the reagent and the low trace element content therein, the influence was considered to be minimal on the sample trace element concentration and should not exceed an order of parts per billion (ppb).

3.3.3 Proximate Analysis (Percentage Ash, Volatile, Inherent Moisture & Fixed Carbon Content)

The proximate analysis being a combination of the proportions of ash, inherent moisture, and volatile matter and by difference fixed carbon by percentage were undertaken at ACCL. The samples were crushed down to 3mm, homogenised and pulverised down to 212µm for the analysis.

3.3.4 Mineral Matter and Liberation Analysis

The XRD (X-Ray Diffraction) analysis was outsourced to the University of Pretoria mainly for the identification and quantification of mineral species. The method of Quantitive Evaluation of Materials by Scanning Electron Microscopy (QEM SEM) or QEMSCAN was undertaken at ESKOM Research & Development. Figure 10, page 27 illustrates the QEMSEM microscope.

Figure 10: *The QEM SCAN microscope used at ESKOM Research and Development for the minerogical investigations.*

The QEMSEM analysis was undertaken for the identification and the determination of the mass percentage, liberation characteristics and distribution of mineral species.

3.3.5 Trace Element Analysis

The trace element analysis, and total sulphur and forms of sulphur (organic, pyritic and sulphate originated sulphur) contents were outsourced to UIS (Unique Innovative Scientific) Analytical Services laboratory. The trace element analysis was done by UIS analytical services and comprised of microwave digestion followed by Inductively Coupled Plasma Mass Spectroscopy.

Figure 11: *Illustration of the ICP MS spectrometer at UIS analytical services.*

Figure 12: *Illustrating the microwave digestion experimental setup.*

In the microwave digestion test a mixture of nitric acid, hydrochloric acid and hydrofluoric acid were used. The samples were heated to approximately 210°C at 20 atm pressure. After a first stage of digestion a second stage digestion was performed to ensure that all the material is dissolved. Stock solutions were used for the determination of a variety of trace elements in the digests by ICP-MS.

CHAPTER FOUR - RESULTS

4.1 Introduction

All results are presented in tabular form in the appendix.

In the appendix table I presents a results summary of the mineral composition determined by the QEMSEM in the froth flotation feed, product and tailings. Tables II and III presents results of the proximate analysis on samples from the batch froth flotation. Table VII presents the batch froth flotation trace element concentrations in the feed, product and tailings.

Table IV and V presents the mineral composition determined by Quantitative XRD in the various floats fractions, from the ROM float and sinks tests. Table VI illustrates the mineral composition determined by the QEMSEM in different density fractions. Table VIII and IX present the trace element concentrations at the different density fractions. Table X and XI present the proximate analysis at the different density fractions.

Table XII and XIII present statistical correlation factors between the minerals and trace elements based on the washability trends of the plant feed samples.

4.2 Composite sample results

The feed composite or run of mine samples (figure 13) were analysed for a range of trace elements. The ICP-MS analysis allowed for the analysis of multiple elements during a single test. The results proved to indicate a relatively good repeatability. All the results remained of the same order. There were, however, trace elements which had concentrations that were quite variable between tests, especially thorium. More importantly the distribution trends of the trace elements during the washability tests were maintained for the large majority of trace elements.

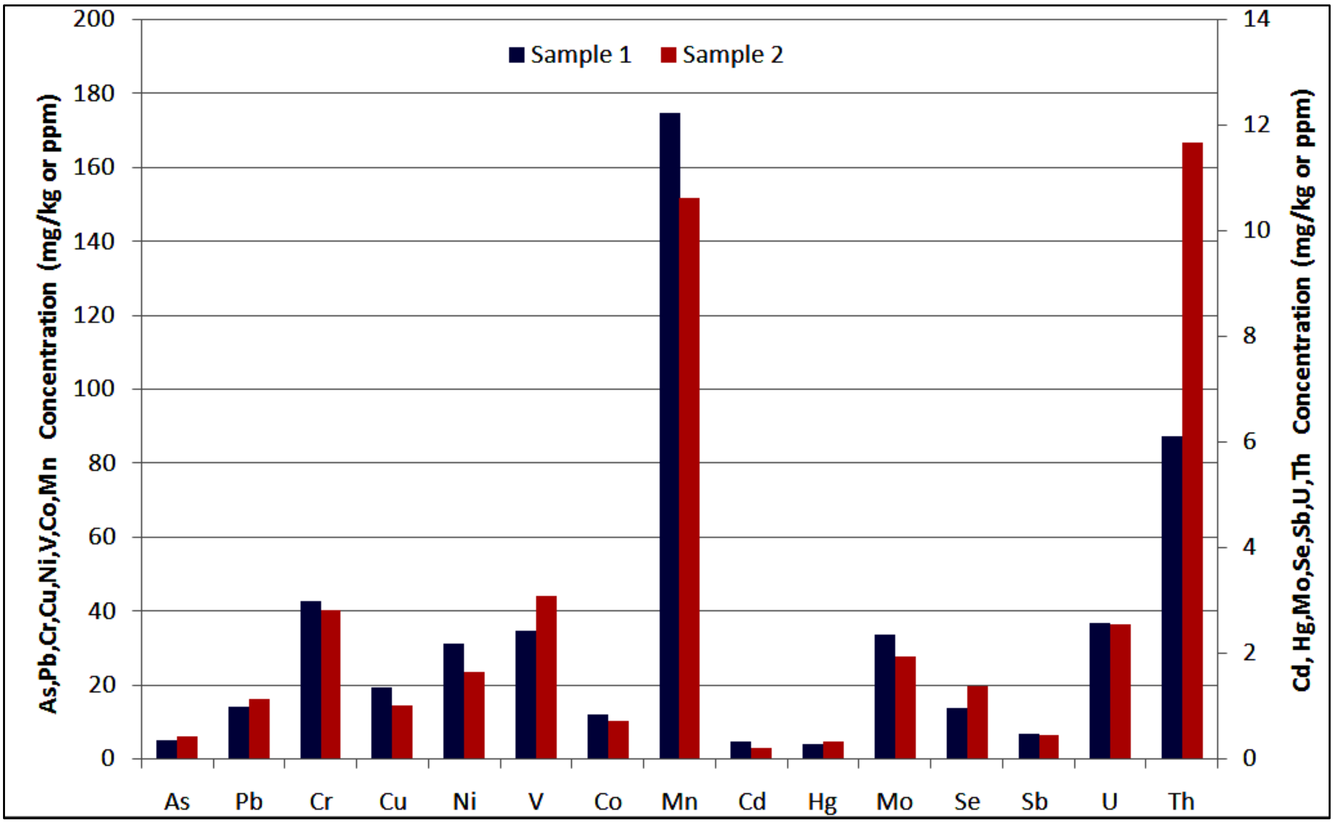


Figure 13: *Comparison between first and second ROM sample set trace element analysis.*

4.3 Partitioning of trace elements at different densities

4.3.1 General

Note: *In all figures where the elements are labelled 1 and 2, the reference is to the first and second set of samples. For example: As 1 and As 2 refers to the arsenic concentration in the first and second set of samples.*

The graphs illustrated in this following section show the washability curves of the various trace elements. This in turn is likely to reveal the organic or inorganic affinities of the trace elements. See table 2, page 31 for a comparative summary of the degree of association of the various trace elements with the inorganic and organic components. Manganese presents itself as the element with the highest inorganic affinity and vanadium the highest organic affinity.

From the results it is clear that the majority of the trace elements are within the sink fraction. If the specific trace element concentration increases with an increase in the washing density and ash content an inorganic affinity can be established. In contrast if the trace element concentration increases with a decrease in the washing density an organic affinity is assumed. These trends are however not followed clearly by all the trace elements and the relationship to organic or mineral matter in these cases is more complex.

The main method used in evaluating and deducing the mode of occurrence of the trace elements in this project is washability characteristics. This can be done, but only with a concurrent evaluation of the mineral species and their liberation. Heavy minerals in particular, may not be sufficiently liberated and might occur in the finely distributed form in the low density float fraction. This was found to be the case not only for pyrite, but also for the radioactive element bearing minerals. The other indirect method employed for deducing the trace element's mode of occurrence was by evaluating other coal quality parameters, for instance the relationship of certain trace elements with the sulphuric species and phosphorous. However, this approach was undertaken cautiously as it could potentially be misleading, a thorough mineralogical evaluation is required to verify the relationships.

In most instances the anomalies can be explained by the mineral or maceral partitioning and the liberation characteristics of the minerals and maceral contents.

Table 2: *Summary of trace elements in/organic affinity. Sinks fraction included.*

←Increased inorganic affinity/Increased organic affinity→														
Mn	**Cr**	**Pb**	**As**	**Ni**	**Th**	**Cu**	**Se**	**Hg**	**Cd**	**Sb**	**Mo**	**U**	**Co**	**V**

These results are based upon data found in table 3. Most of the trace elements prove to be associated with the sulphuric species in, especially, pyrite. More importantly all the trace elements that are of major concern (As, Hg, Pb, Mo, Cd, Se) show similar cleanability trends to that of the pyritic sulphur. The radioactive trace elements indicate good correlation to zirconium and pyrite. The zirconium follows a similar trend to the pyrite.

Table 3: *Trace elements and associated minerals. Adapted from Dale (2003).*

Mineral	Associated element
Pyrite	As, Cd, Co, Cu, Hg, Mo, Ni, Pb, Se, Cr
Apatite	F,Cl
Clays (kaolinite and illite)	Cr, Mn, V
Monazite	U, Th

A similar explanation can be given for the arsenic, cobalt, nickel and mercury to pyrite association. In the QEMSCAN results it was observed that fine pyrite nodules (syngenetic to authigenic) occur in the lower density fractions. The particular relationship of the HAP trace elements to sulphur was found to be well established. The trace element washing data correlated well to the sulphur washing data. In most instances the ash to trace element relationship does not correlate as well as that to sulphur.

4.3.2 Elements of major concern

In figure 14 the washability tables for As, Cd, Pb, Hg, Se and Mo are given. It can be seen that in the case of As, Cd, Pb, Hg and Mo there is a high residual peak concentration in the 1.30 RD fractions. The concentration then decreases between RD 1.55 and 1.60 after which the concentration increases sharply from RD 1.70 to Sinks at +1.80 RD. Selenium follows a similar trend, but the high residual concentration is maintained from RD 1.30 to RD 1.45 and drops from RD 1.55 and then increases sharply towards the Sinks fraction.

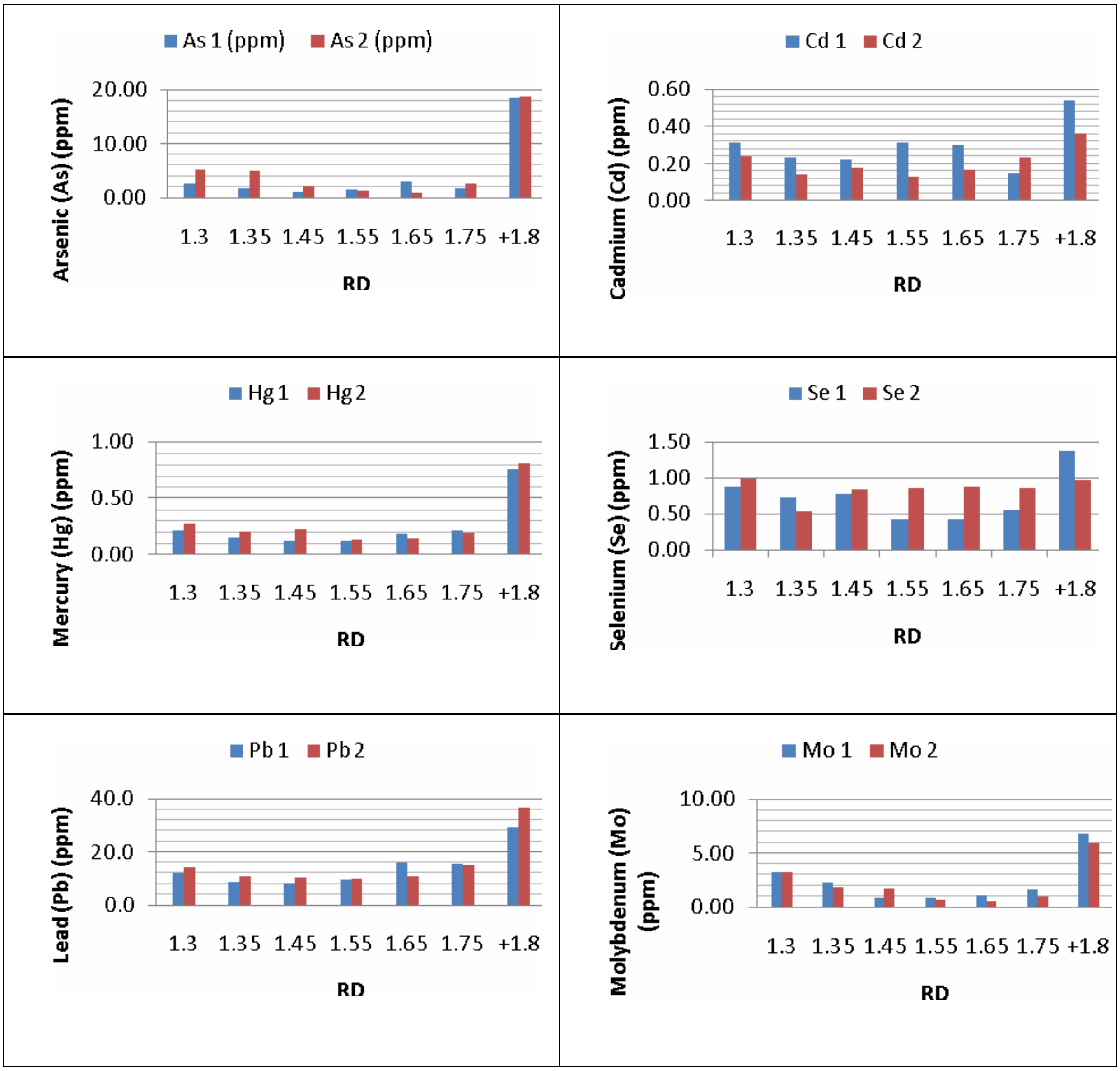


Figure 14: *Concentrations of trace elements of major concern: As, Cd, Pb, Hg, Se and Mo at different washing densities.*

4.3.2a) Arsenic

The strongest correlation factor found for arsenic is with pyrite at 99 percent. Arsenic has been found to be present predominantly in pyrite in bituminous coals, Dale (2003). Indications are that a variable portion is organically bound. This relationship is found by evaluating the organic sulphur and arsenic relationship. Figure 15 illustrates the relationship of arsenic with pyrite from the washability analysis.

However, in figure 49, page 66 a better relationship with organic sulphur is observed.

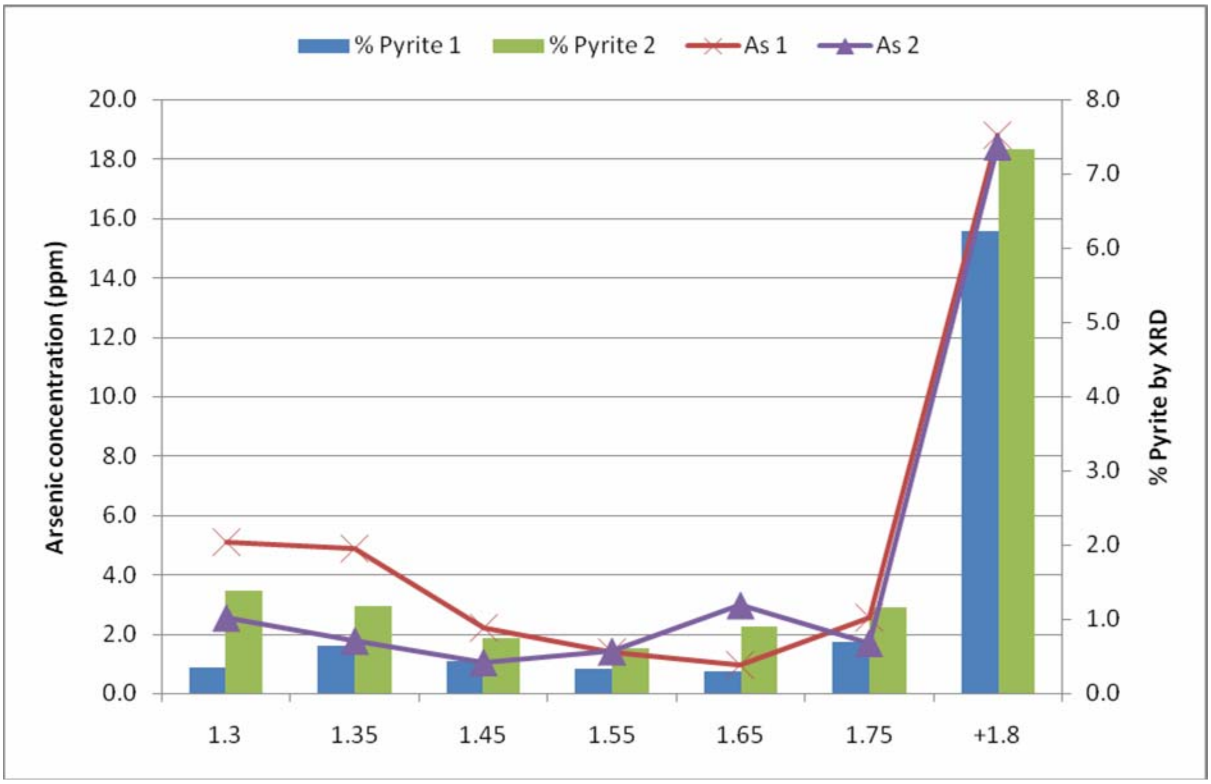


Figure 15: *Illustrating the relationship between the pyrite content and arsenic concentration in the coal at various relative densities.*

4.3.2b) Cadmium

The strongest correlation factor found for cadmium is with pyrite at 86 percent. Cadmium mainly occurs in sphalerite (ZnS) and in pyrite, the relationship is illustrated clearly via the similar trends in figure 16.

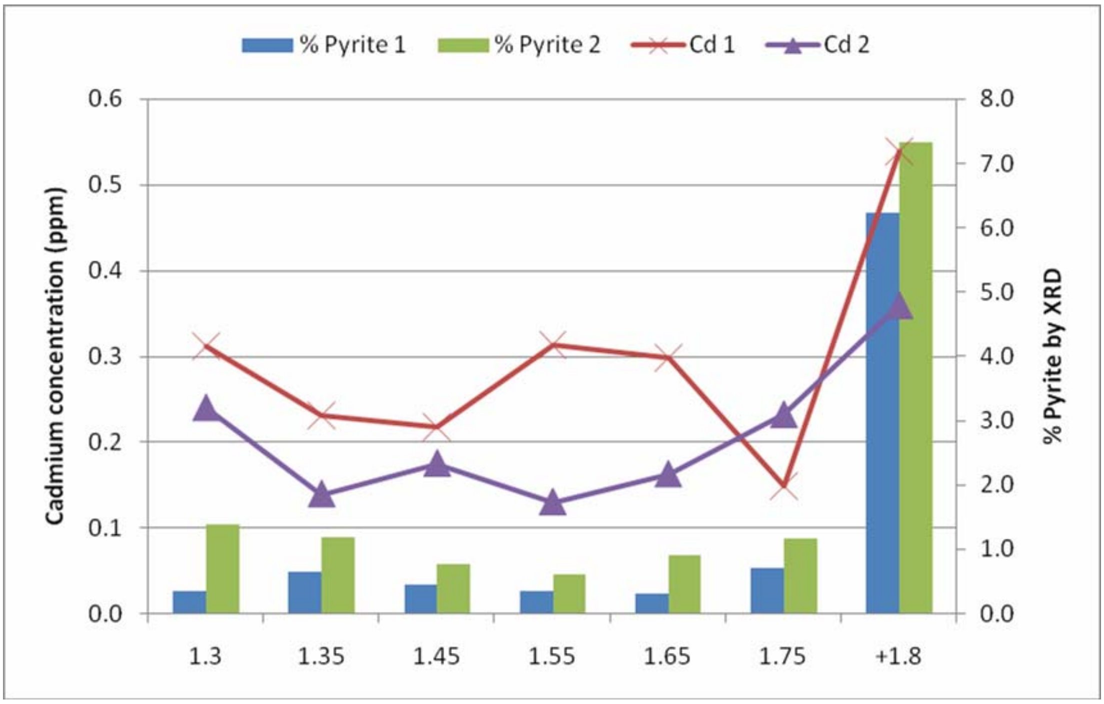


Figure 16: *Illustrating the relationship between the pyrite content and cadmium concentration in the coal at various relative densities.*

Cadmium has a very close relationship with the zinc concentration as illustrated in figure 16. Even though the use of zinc chloride would most likely influence the concentration of zinc in the samples (as it may occur with the hygroscopic hydro components) the relationship is still clear.

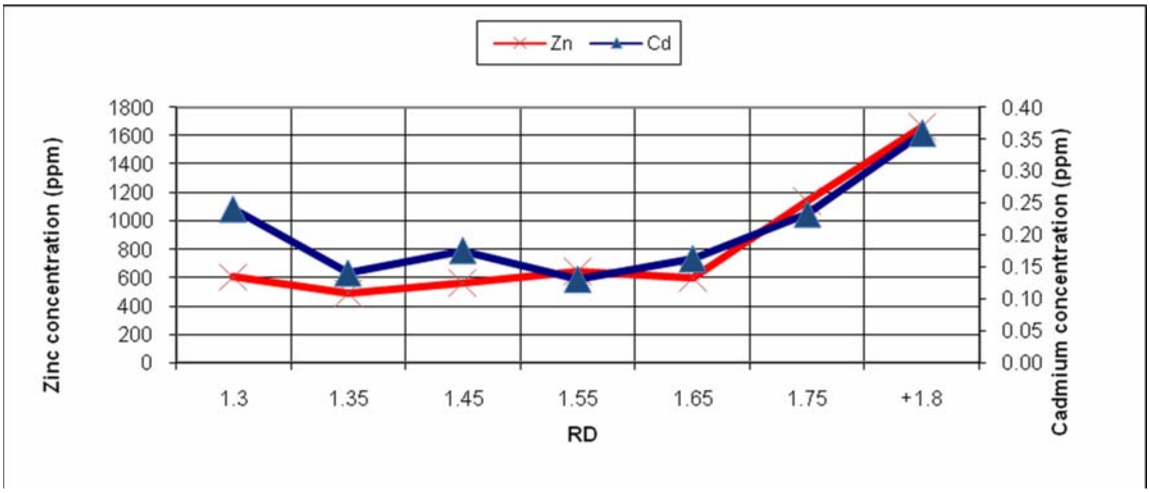


Figure 17: *Illustrating the relationship between cadmium and zinc (thought to be mainly from sphalerite present).*

4.3.2c) Lead

The strongest correlation factor found for lead is with pyrite at 86 percent. In literature lead is present predominantly in pyrite and other sulphide minerals in bituminous coals (Dale, 2003).

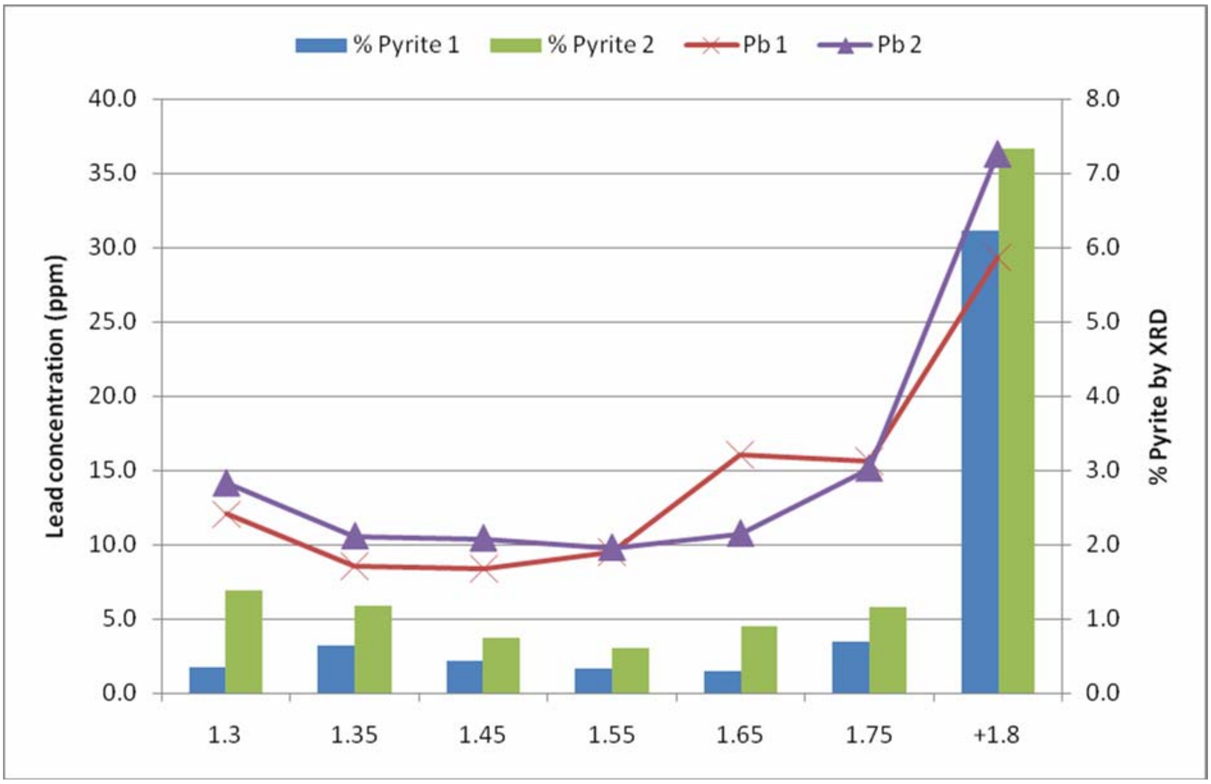


Figure 18: *Illustrating the relationship between the pyrite content and lead concentration in the coal at various relative densities.*

Occurrences of lead selenide have been reported Dale (2003). No lead selenide has been detected; however there is a strong relationship between the lead and selenium, but this cannot be proved conclusively due to its common relation to pyrite, see figure 19.

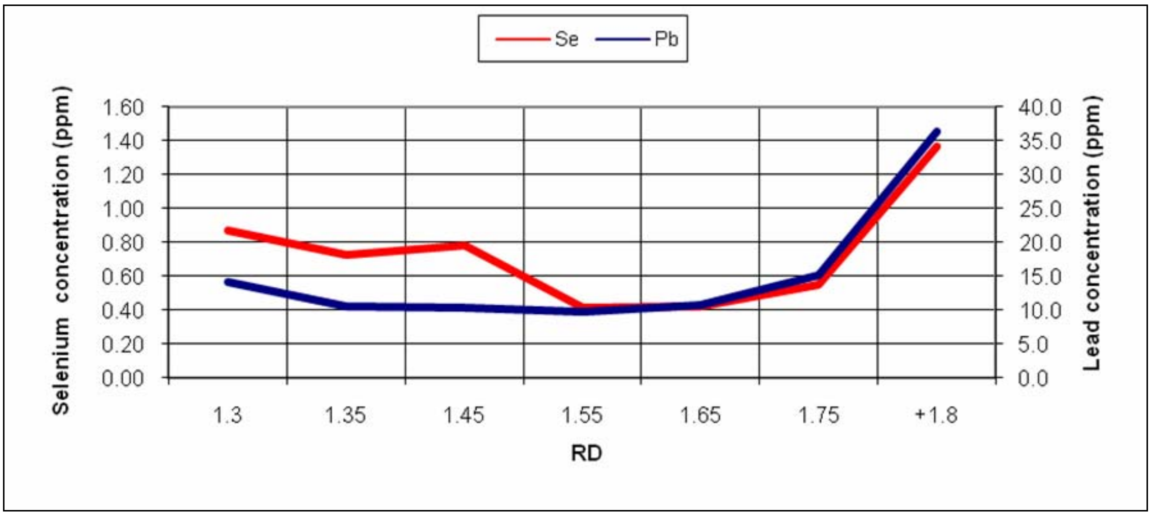


Figure 19: *Illustrating the relationship between selenium and lead.*

4.3.2d) Mercury

The strongest correlation factor found for mercury is with pyrite at 99 percent, but there is also a strong relation to calcite at 97 percent. In literature mercury is mainly present in pyrite and other sulphide minerals like pyrrhotite and marcasite in bituminous coals (Gluskoter 1994), this is confirmed in the research undertaken. In this particular project it was also found that mercury is also related to the organic fraction in the coal and more specifically the organic sulphur bearing fraction.

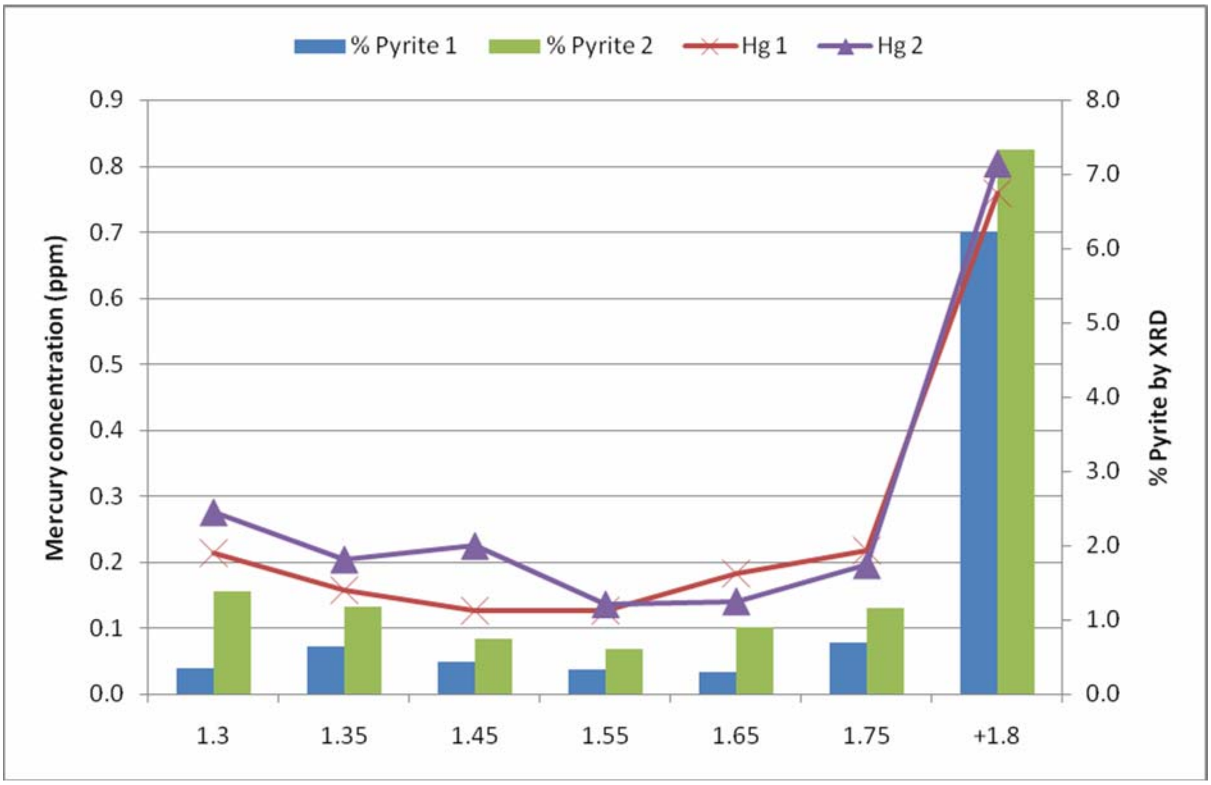


Figure 20: *Illustrating the relationship between the pyrite content and mercury concentration in the coal at various relative densities.*

The distribution of the mercury at various density fractions in the Witbank coalfield No. 4 seam as can be seen in figure 20 can be compared to figure 21 where the distribution of mercury in a coal from the Illinois basin the USA is illustrated.

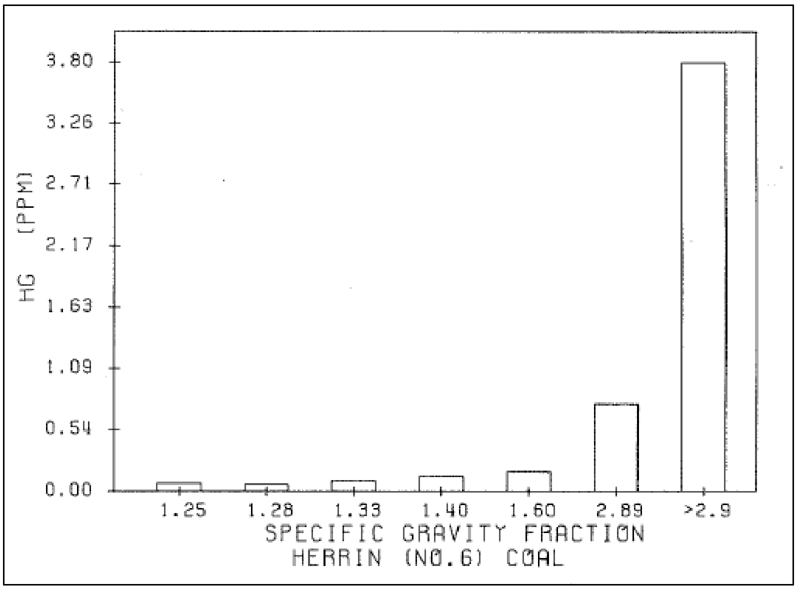


Figure 21: *Illustrating the distribution of the mercury content in coal from the Illinois basin in the USA. Ruch, Gluskoter (1974).*

In figures 20 and 21 it can be noted that the concentration of mercury in the USA increases to 0.25% and higher in RD of 1.60 and above, whereas in the Witbank coalfield No. 4 seam, the higher concentrations occurs in the sink fraction. This is due mainly to liberation of the pyrite in the form of easily liberated pyrite nodules.

4.3.2e) Selenium

Selenium is associated with pyrite and the organic matter. In this research this trace element has been shown to have little correlation to the kaolinite. Selenium has a 74-85% correlation with the pyrite content in the coal. Based on the trend in figure 22 the relative trends of the pyrite and selenium do not correspond at the lower densities, it is believed this is due to the association of selenium with the organic sulphur bearing coal or maceral content.

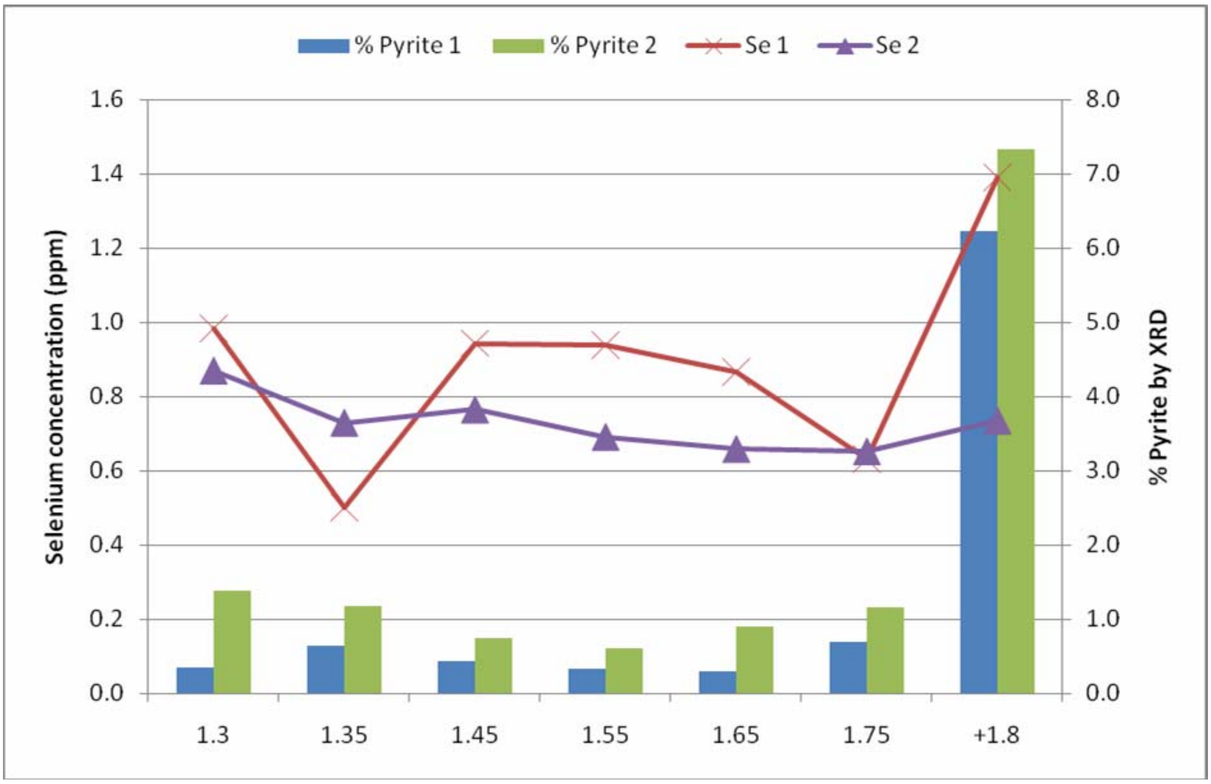


Figure 22: *Illustrating the relationship between the pyrite content and selenium concentration in the coal at various relative densities.*

4.3.2f) Molybdenum

There is a high level of uncertainty concerning the occurrence of molybdenum in coal, Dale (2003). The strongest correlation factor found for molybdenum is with pyrite at 99 percent, but there is also a strong relation to calcite at 97 percent.

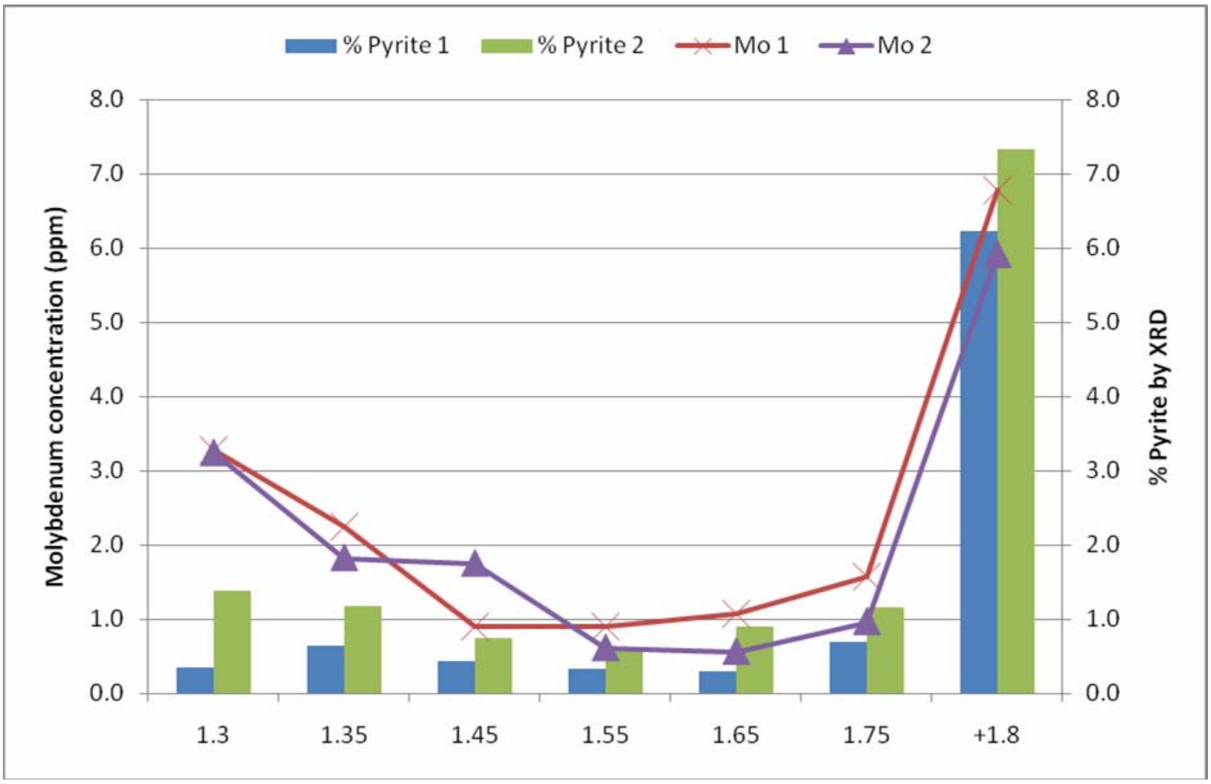


Figure 23: *Illustrating the relationship between the pyrite content and molybdenum concentration in the coal at various relative densities.*

4.3.2g) Ash

The washability data of most of the trace elements at the lower density fractions do not generally follow the trend in ash reduction with a reducing relative density. This observation is indicated in figure 23a, page 41. The ash, as expected, increases with an increase in the relative density and does not exhibit residual peaks at particular density fractions.

In table 4 the level of trace element concentrations of the beneficiated fractions at particular densities are in most instances well below the data obtained from export production data. The export steam coal trace element data was collected from an annual shipping export quality database.

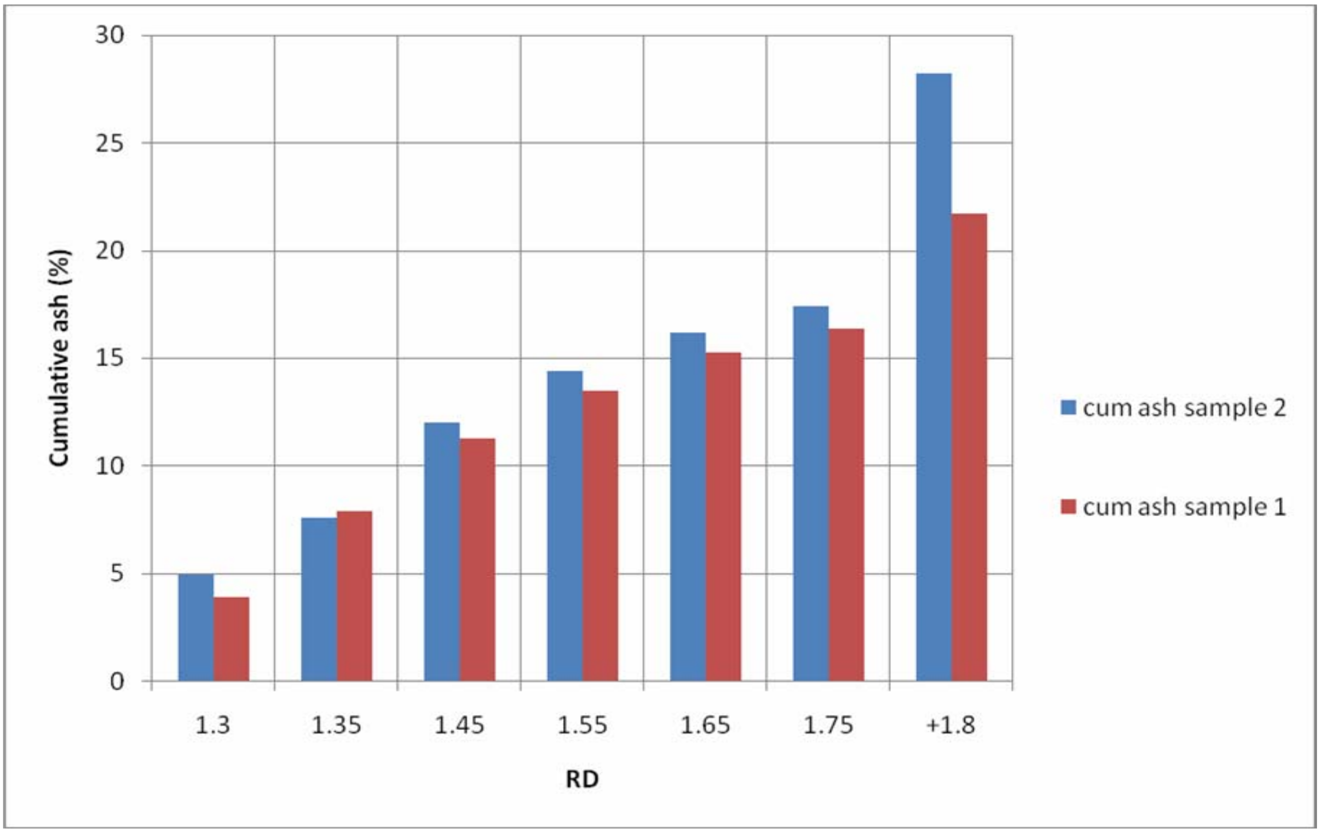


Figure 23a: *The cumulative ash washability curve.*

4.3.3 Trace elements of moderate concern

The trace elements of moderate concern in the No. 4 seam coal are mostly associated with the sulphide and to a lesser extent carbonate content (dolomite and calcite) in the coal. The correlation coefficients of Ni, Cu, Cr and V with the their respective associated minerals are generaly low. The only element that has an excellent correlation to the carbonate mineral calcite is chromium. This is also believed to be associated with the kaolinite content.

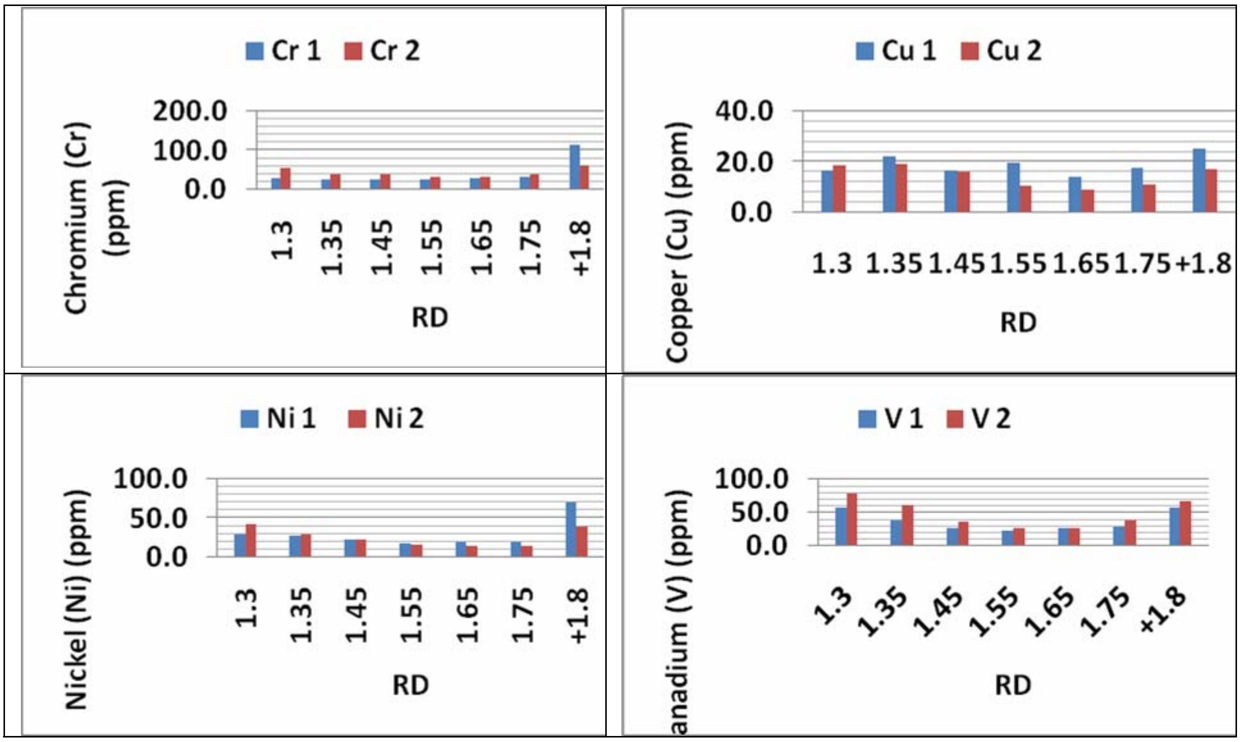


Figure 24: *Concentrations of trace elements of moderate concern: Cr, Cu, Ni and V at different washing densities.*

4.3.3a) Chromium

The chromium content illustrated a good correlation with both pyrite (99%) and calcite (98%), see figure 25. In literature there is significant uncertainty about the most likely association of chromium in bituminous coals. The occurrence in clay could not be verified with the density distribution trends.

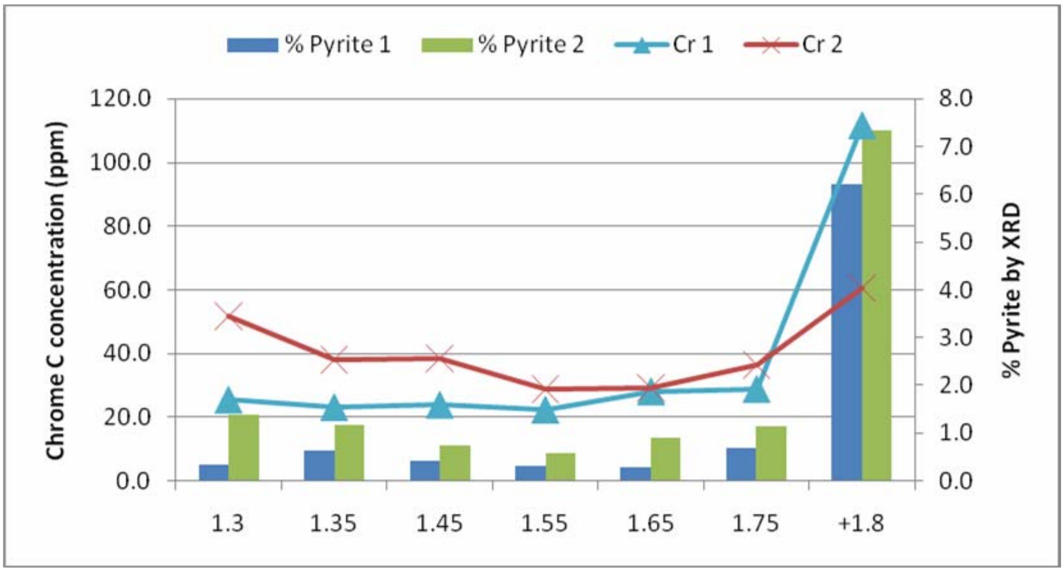


Figure 25: *Illustrating the relationship between the pyrite content and chromium concentration in the coal at various relative densities.*

From previous work done by Gluskoter (1976) chromium is present in Cr(III) forms but may be associated with sulphides, organic matter or clays. The occurrence of toxic chromium (VI) is a major concern, but was not identified in this instance. In figure 26 dissimilar trends between chromium and kaolinite are observed.

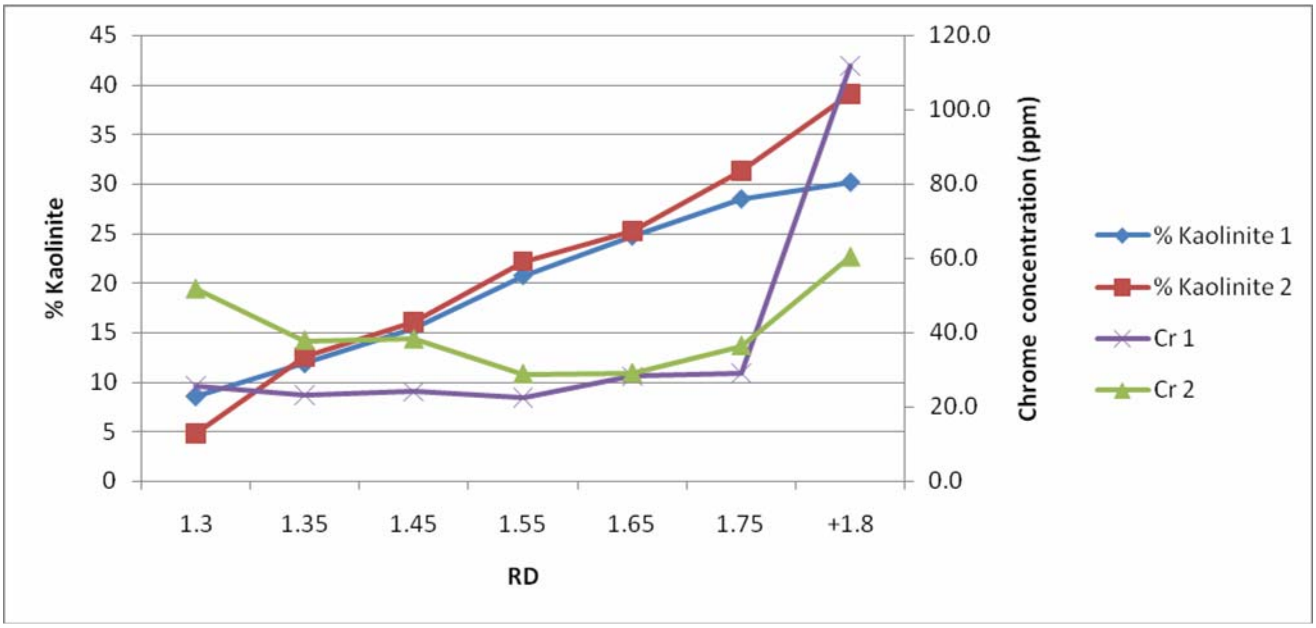


Figure 26: *Illustrating the relationship of chromium with kaolinite.*

4.3.3b) Copper

From literature the association of copper is complex and no fixed relation can be established (Dale 2003). In this research undertaken copper has a correlation coefficient of 75% with the pyrite. According to literature this element should be present as chalcopyrite, but the correlation coefficient is relatively good at 75 percent. From figure 27 it would appear that copper has a strong association with the organic matter in the coal. Copper is known to be an essential element in plant material.

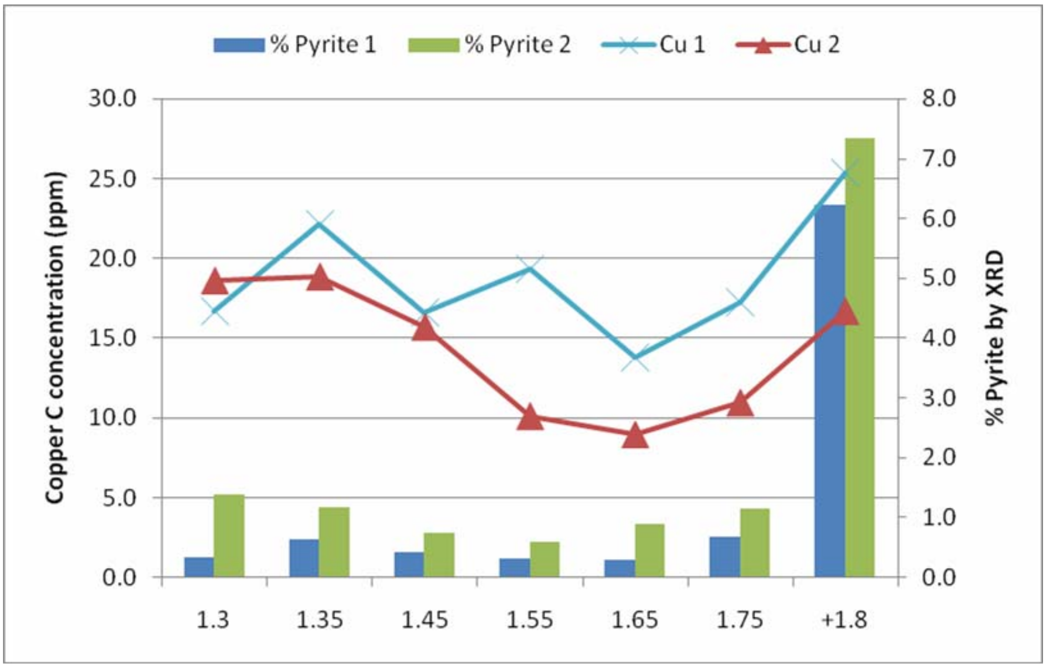


Figure 27: *Illustrating the relationship between the pyrite content and copper concentration in the coal at various relative densities.*

4.3.3c) Nickel

Nickel has proven to have an excellent correlation with the pyrite in the coal at 98.8%. In previous work nickel has proven to have an uncertain relationship. An association with organic matter or maceral content is also observed, see figure 28.

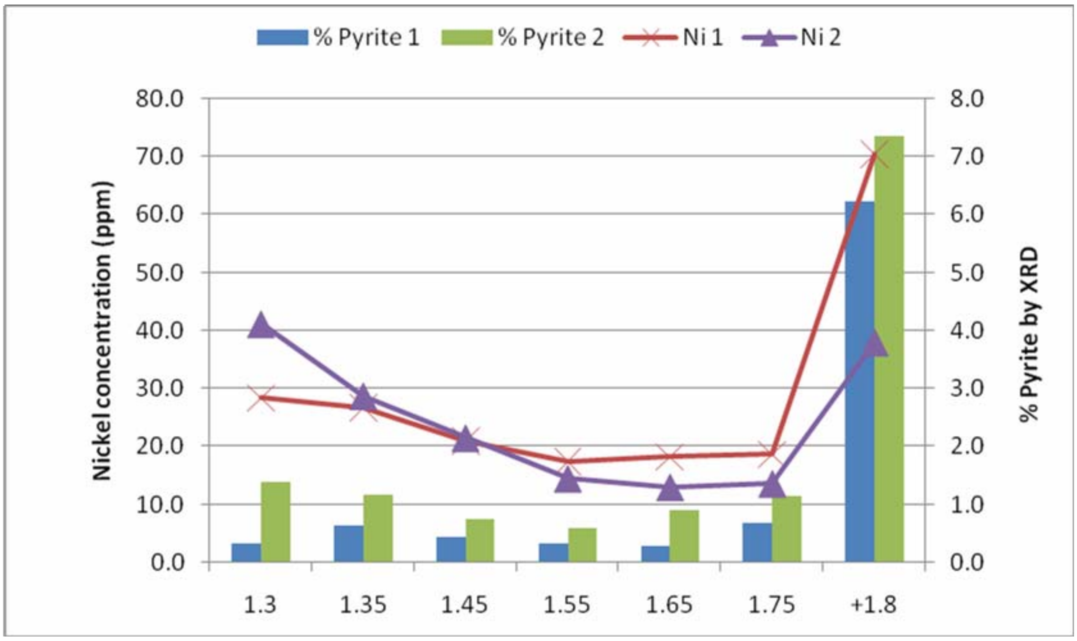


Figure 28: *Illustrating the relationship between the pyrite content and nickel concentration in the coal at various relative densities.*

4.3.3d) Vanadium

There is uncertainty about the occurrence of vanadium in bituminous coal. It is thought to be present in both the organic and mineral phases (clays, especially illite).

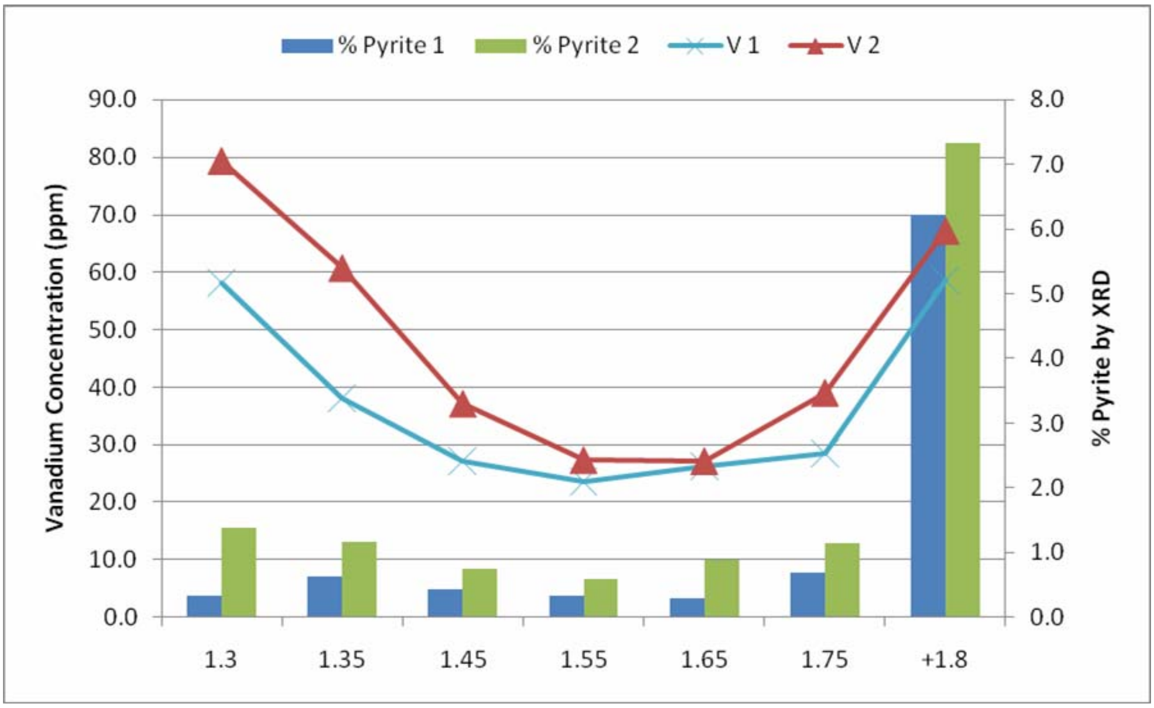


Figure 29: *Illustrating the relationship between the pyrite content and vanadium concentration in the coal at various relative densities.*

Previous test work by Dale (2003) illustrated that vanadium is associated with kaolinite. This is not observed according to the washability tables where the concentration of the vanadium is higher at lower densities, indicating a strong organic affinity. The source of this can be explained by the liberation characteristics of the clay minerals. Both the vanadium and chromium have local peaks at density of 1.30, 1.35 and 1.40 approximately. The vanadium and chromium probably occurs with the finer (down to 2 micrometers) clay minerals that are integrated in the coal matrix, at these low densities. These are syngenetic in nature. These clay forms are not liberated in the lower density fractions, but instead become part of those density fractions.

4.3.4 Trace elements of minor concern

In summary the trace elements of minor concern may be related to different mineral and organic contents. Antimony and cobalt prove to be associated to the pyrite content whereas the barium is associated the sulphates (gibbsite and organic sulphate). The manganese content has a good association with the carbonate minerals, mainly calcite and siderite. Figure 30 gives a summary of distributions according to relative density beneficiation.

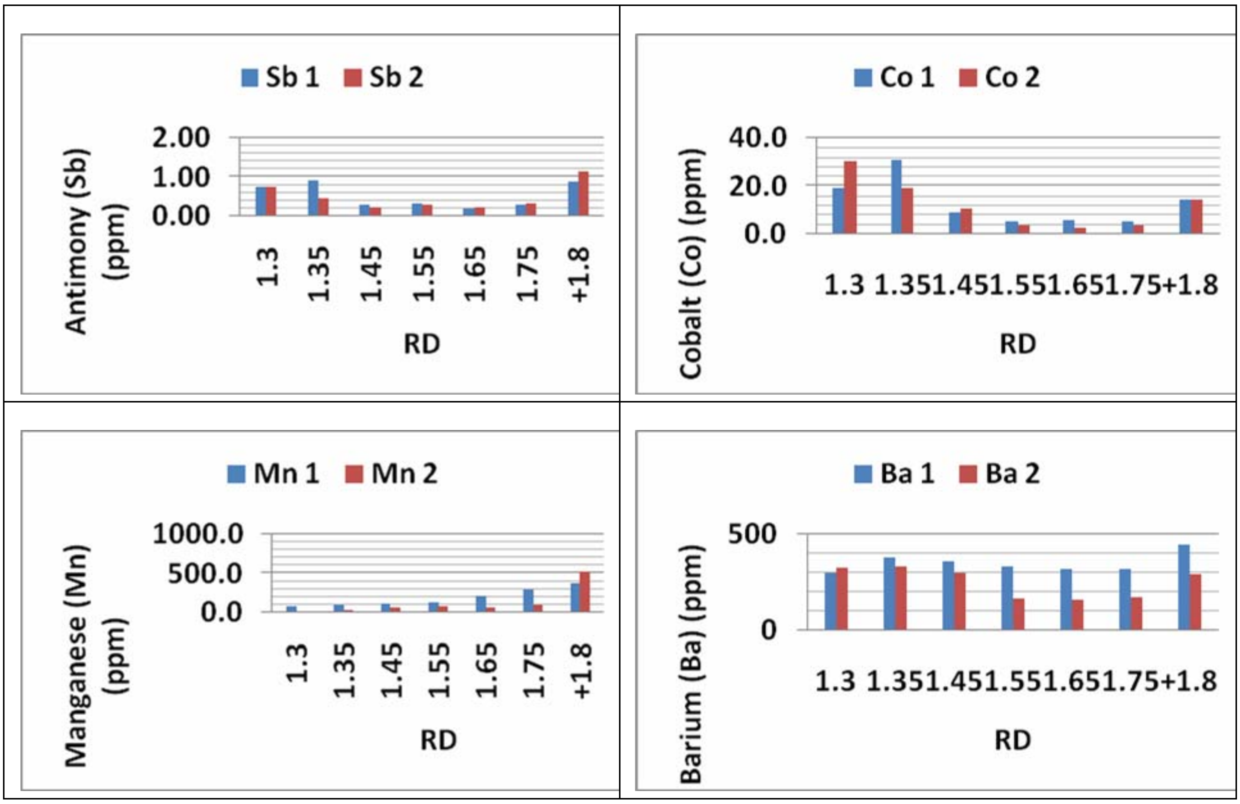


Figure 30: *Concentrations of trace elements of minor concern: Sb, Co, Mn and Ba at different washing densities.*

4.3.4a) Antimony

The partitioning of antimony has proven to be complex; the strongest correlation is with pyrite at 56. In previous work the relation is thought to be with sulphide minerals and with organic matter. The correlation to organic sulphur is at 48%.

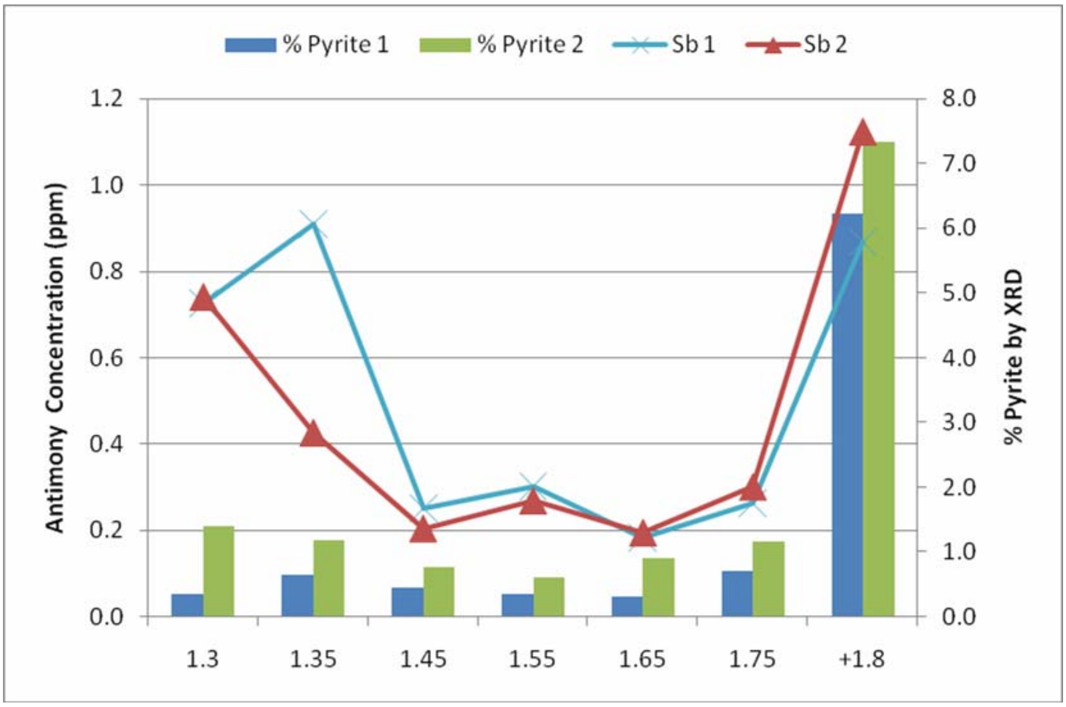


Figure 31: *Illustrating the relationship between the pyrite content and antimony concentration in the coal at various relative densities.*

4.3.4b) Cobalt

The partitioning of cobalt has proven to be complex as no fixed correlation can be verified. According to the observed trends, the closest correlation is with the mineral pyrite and organic sulphur bearing coal matter.

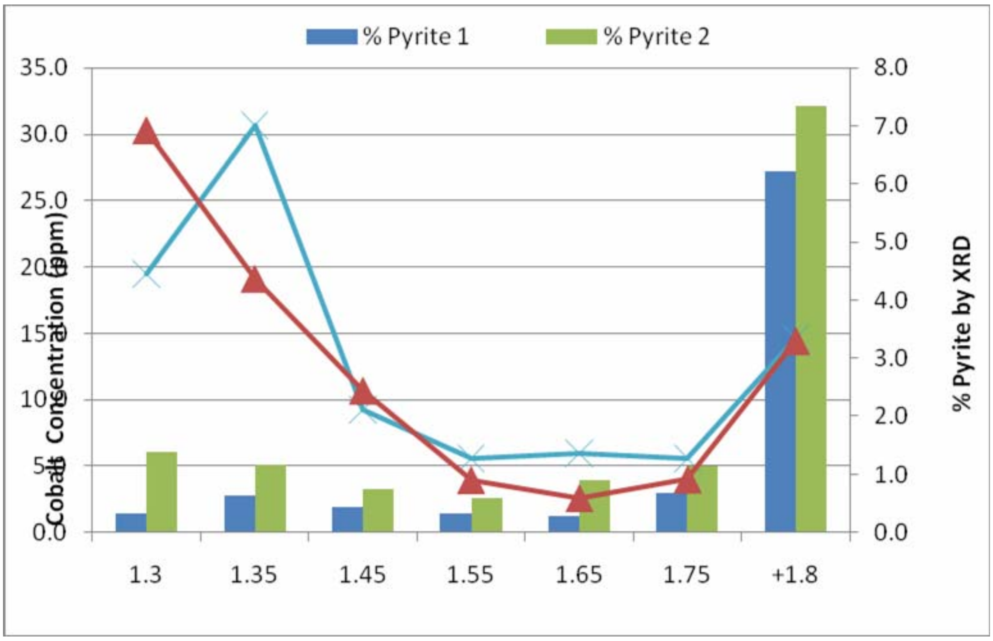


Figure 32: *Illustrating the relationship between the pyrite content and cobalt concentration in the coal at various relative densities.*

In figure 32, page 47 it can be seen that the major residual peak concentration is at a relative density of 1.3, similar to other sulphur-related trace elements.

4.3.4c) Manganese

Manganese appears to be associated mostly with the clay mineral kaolinite and secondly with the carbonate minerals siderite, dolomite and calcite. The correlation percentage is on average 98% with siderite and calcite and 93% with dolomite. The carbonate minerals occur as cleats and can therefore be liberated relatively easily.

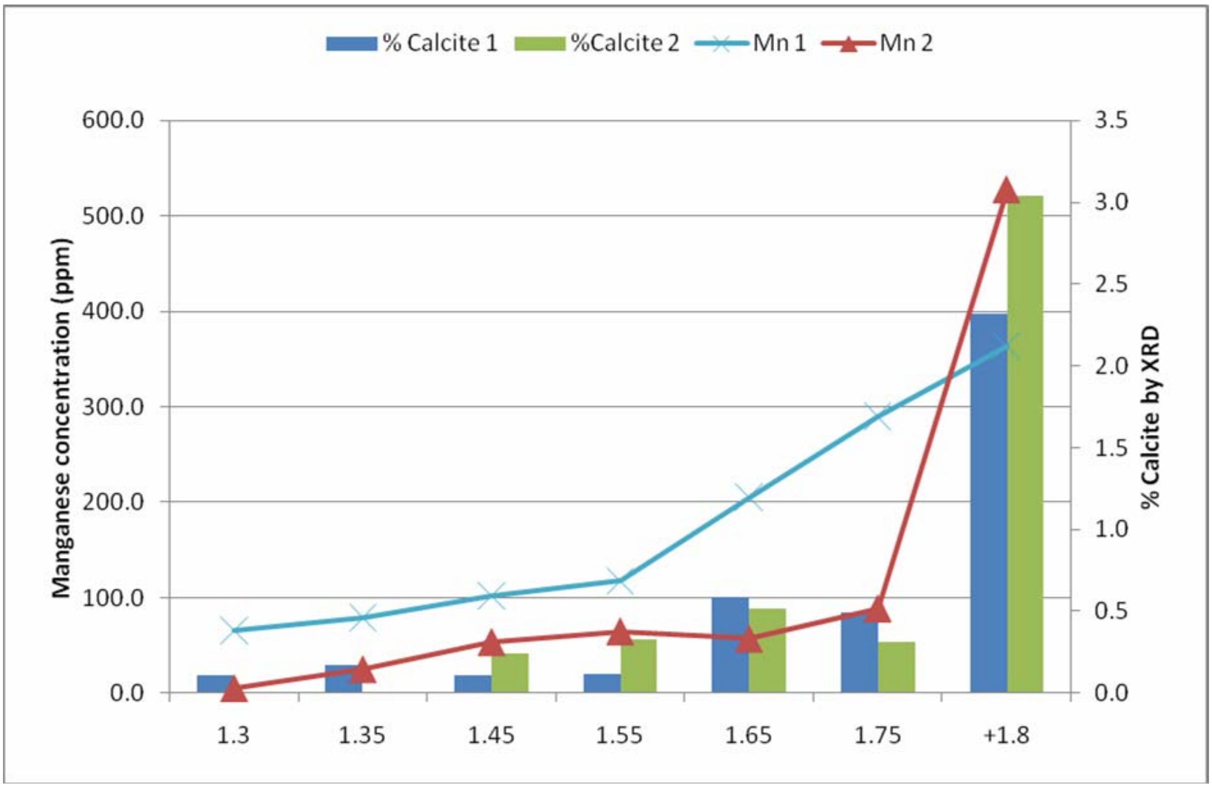


Figure 33: *Illustrating the relationship between the calcite content and manganese concentration in the coal at various relative densities.*

In figure 33 and 34 the comparative trends are illustrated for manganese with dolomite and calcite.

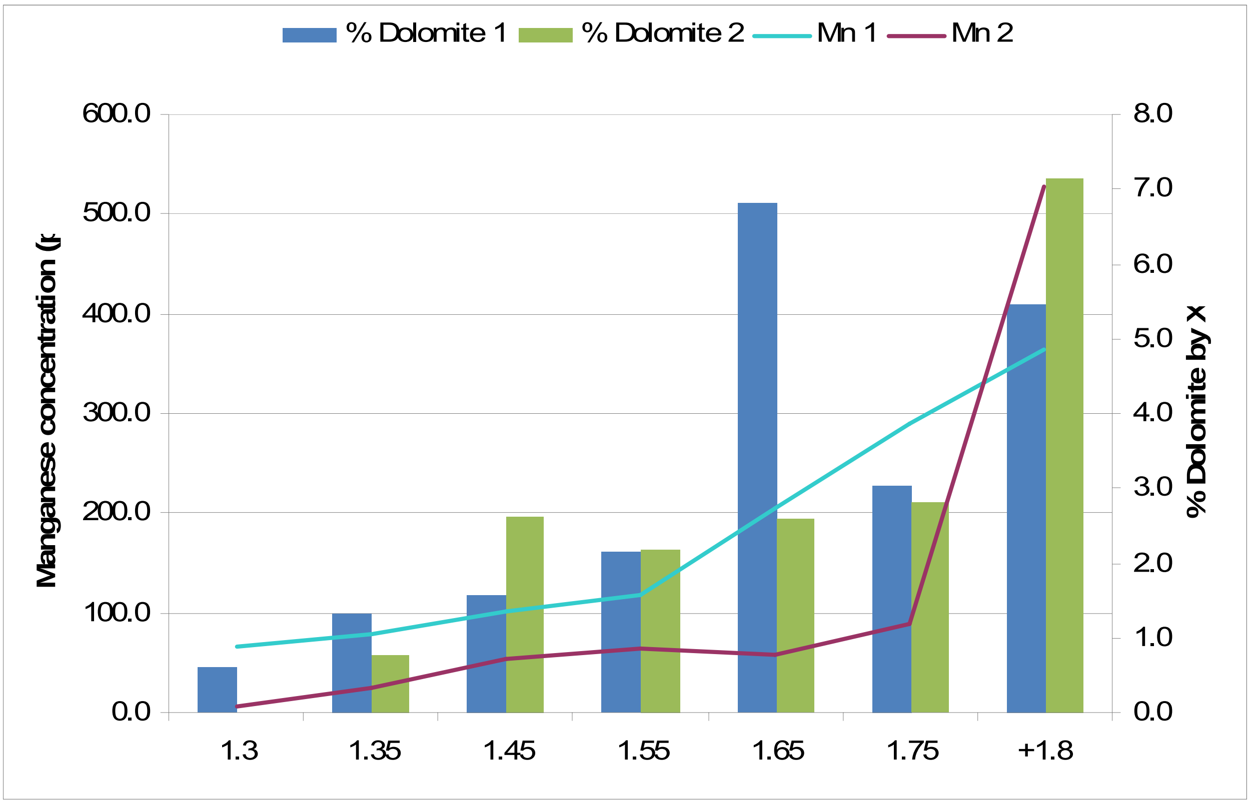


Figure 34: *Illustrating the relationship between dolomite content and manganese concentration in the coal at various relative densities.*

The partitioning of manganese to kaolinite illustrates similar trends and has a correlation coefficient of 93% in the first and 76% in the second test. Kaolinite occurs mainly as included mineral matter and is not well liberated.

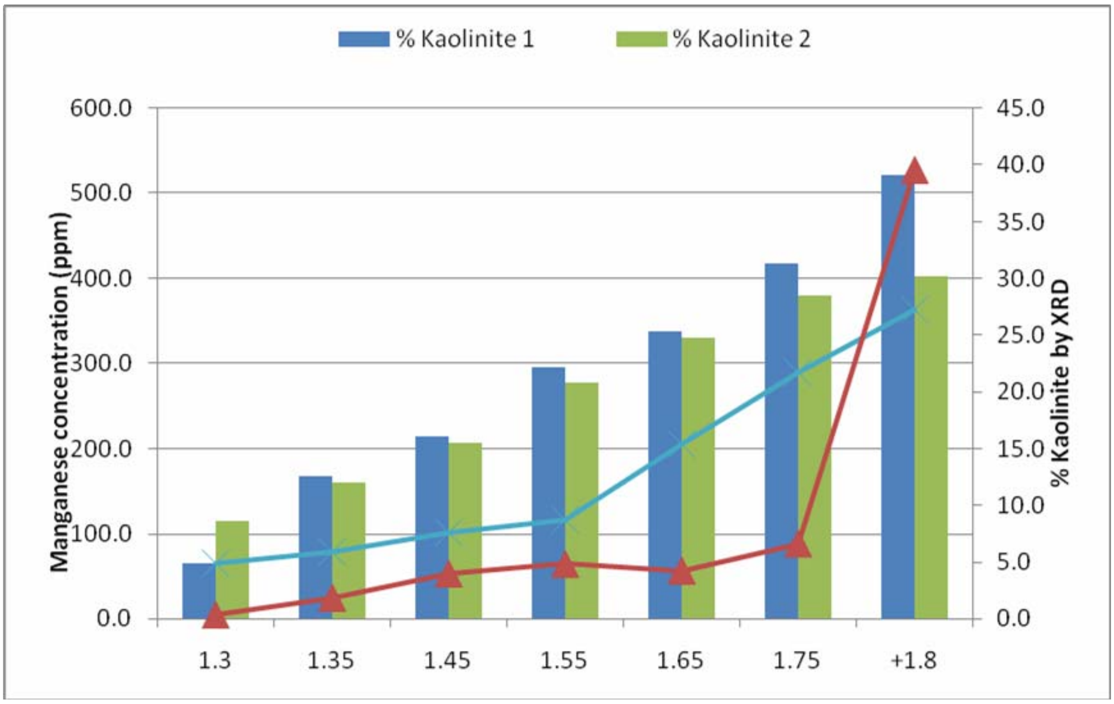


Figure 35: *Illustrating the relationship between the kaolinite content and manganese concentration in the coal at various relative densities.*

4.3.4d) Barium

The most likely occurrences of barium in coal in the No. 4 seam is with the sulphate content, mainly organically originated and to a lesser extent sulphate minerals i.e. Gibbsite. Figure 36 illustrated the relationship with barium and the sulphate content in the coal.

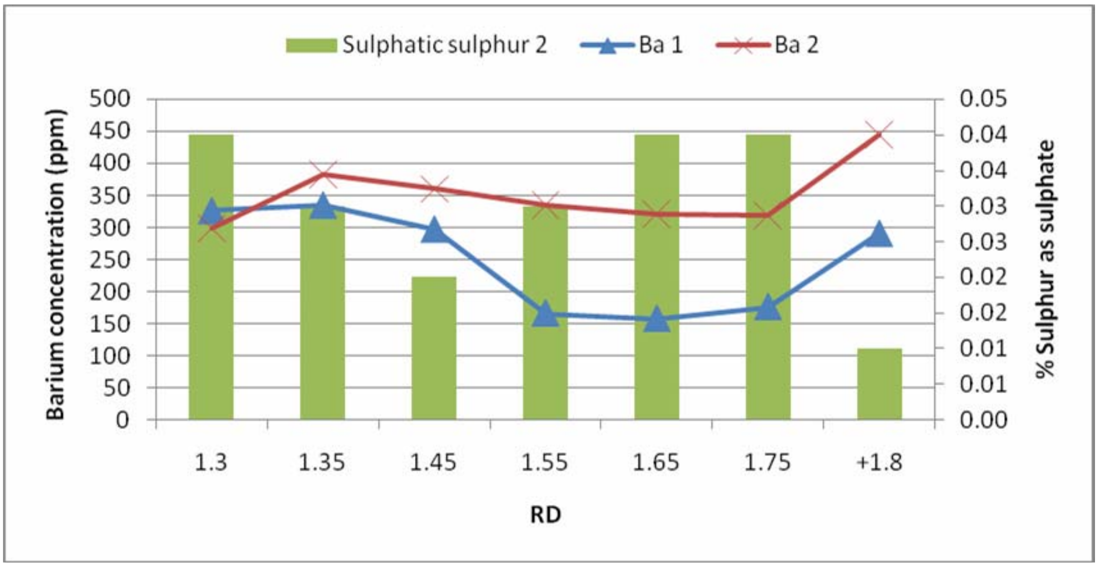


Figure 36: *Illustrating the relationship between the sulphate content and barium concentration in the coal at various relative densities.*

4.3.5 Radio active trace elements

The partitioning of radioactive trace elements in coal has been shown in previous work to be complex. In this research the main correlations were found with the minerals monazite and pyrite respectively. Although monazite (a phosphate mineral) wasn't minerologically identified, its densimetric identification is explained in section 4.3.2 with the evaluation of the phosphoric species. Uranium can best be associated with the minerals zircon and pyrite, whereas thorium is expected to have the strongest association with monazite. In terms of repeatability the second sample's results especially with thorium have proven to be different.

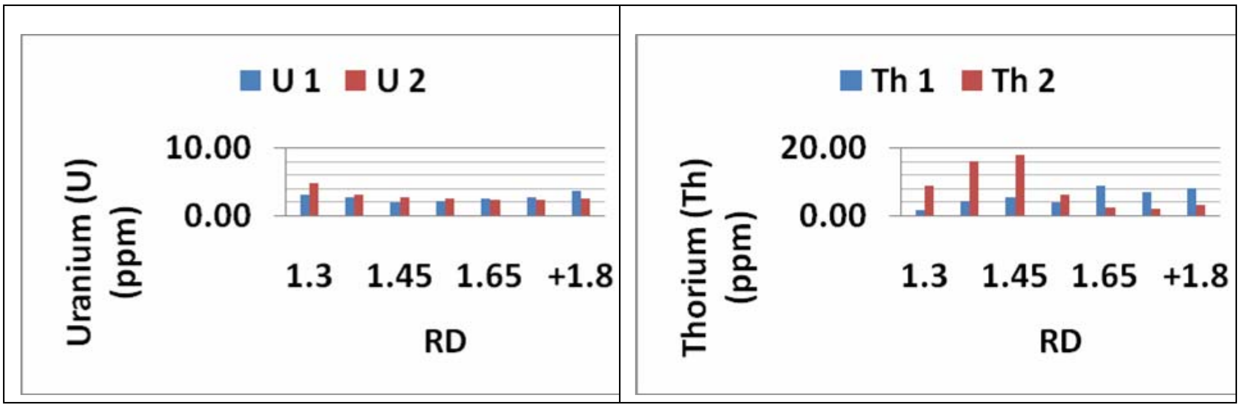


Figure 37: *Concentrations of the Radioactive trace elements of concern: U and Th at different washing densities.*

4.3.5a) Uranium

In the current test work, uranium is associated mainly with zircon with a correlation of 98%. It has also proven to be associated with sulphur bearing organic matter in the coal.

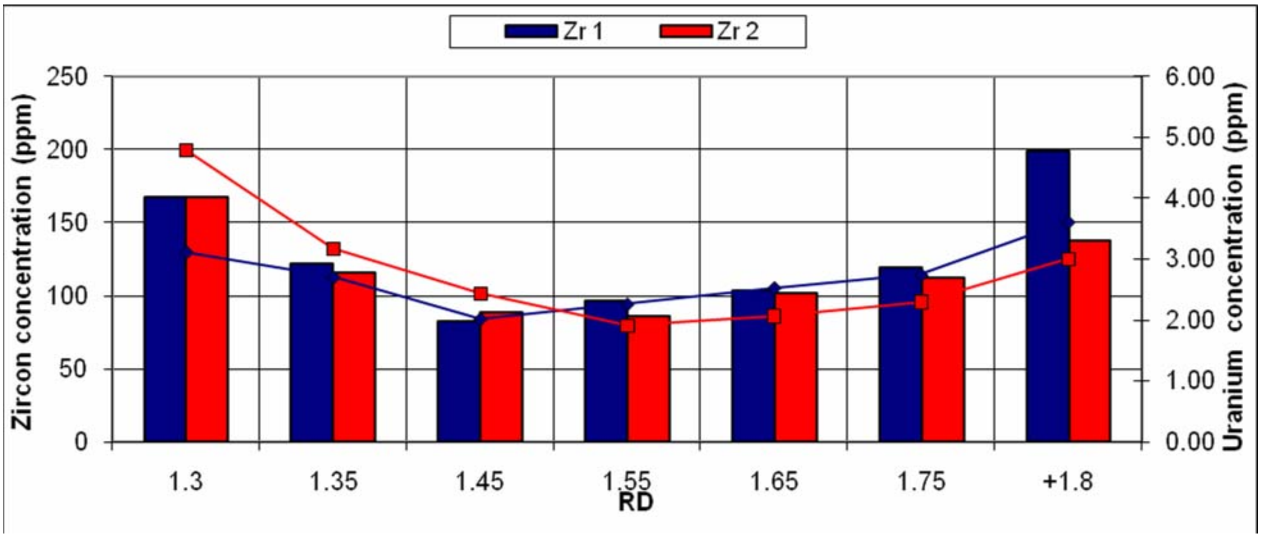


Figure 38: *Illustrating the relationship between the zircon element concentration and uranium concentration in the coal at various relative densities.*

4.3.5b) Thorium

Thorium has a good correlation with the carbonate dolomite at 91% and kaolinite 85%. From the associated elements of monazite namely La, Ce and Y strong association is expected. The verification is explained in section 5.3.2 on the partitioning of phosphorous and its related species.

4.3.6 Other trace elements of concern

4.3.6a) Germanium

From previous test work, germanium has been found to have a high organic affinity. This association has been verified by the test work on the Witbank coalfield No. 4 seam. The concentration is the highest in the lowest densities. This then decreases in relative density and increases slightly towards the sinks fraction. Correlation to maceral content, probably vitrinite, is the strongest relationship.

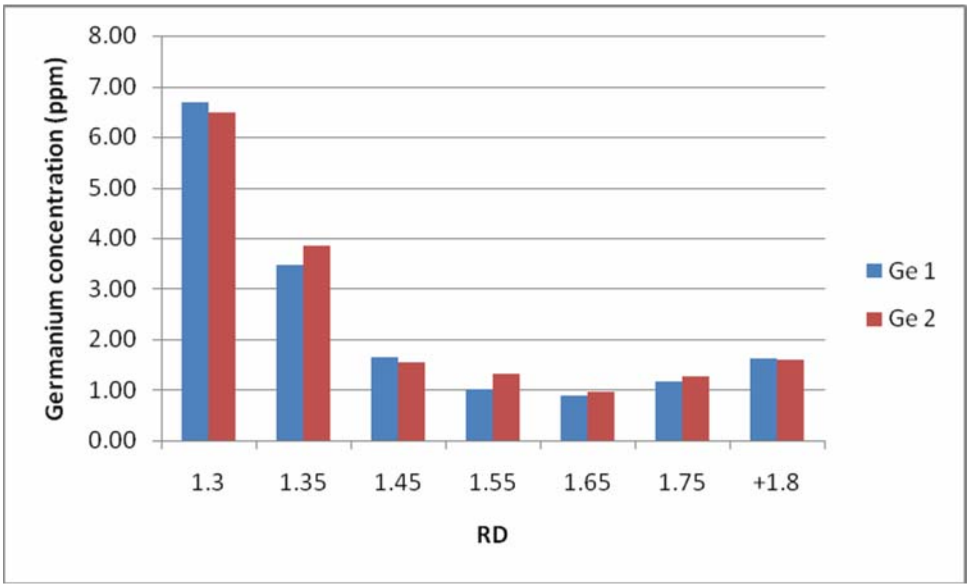


Figure 39: *Partitioning of germanium at different relative densities.*

3.3.6b) Boron

Boron theoretically should have a high organic affinity (Ruch et al (1974)). The Boron unfortunately has proven to give a low repeatability when comparing the first and second test. In figure 40 the partitioning of the boron at different relative densities is illustrated. There does seem to be residual peaks at the lowest density fractions. An increase is observed again towards the higher density and sink fraction.

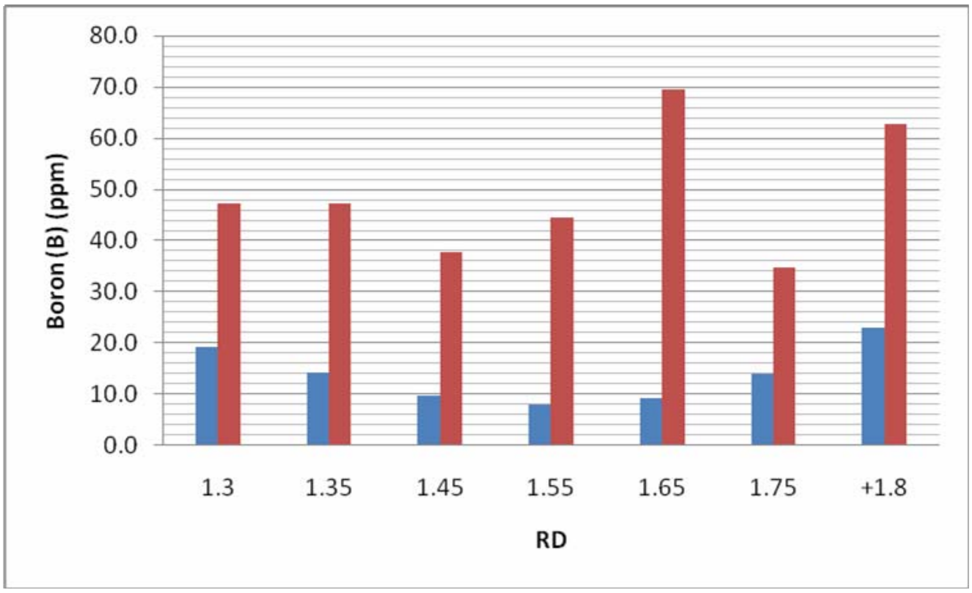


Figure 40: *Partitioning of boron at different relative densities.*

4.3.6c) Fluorine

Fluorine in previous test work has proven to be associated to greater extent to the organic matter. However in the Witbank coalfield No. 4 seam fluorine has shown a greater inorganic affinity with appetite in the first set of results and an organic affinity in the second set. The apatite concentrations however are very low. See section 5.3.2 for the phosphorous distribution. The two sets of samples having shown different results prove that the distribution of the fluorine is complex.

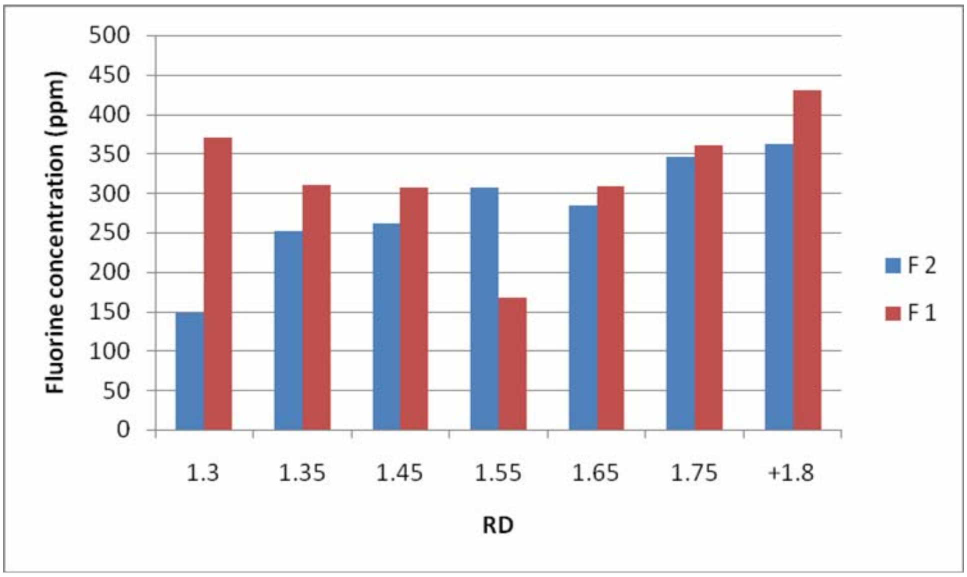


Figure 41: *Partitioning of fluorine at different relative densities.*

4.4 Percentage Reduction of certain trace elements

The reduction potential of the trace elements by beneficiation was measured by calculating the percentage reduction in concentration. The formula used in the calculation is given by equation 1.

$$\%\,\text{Reduction} = \frac{x_{\text{Feed}} - x_{\text{Product}}}{x_{\text{Feed}}} \times 100\% \qquad \textbf{Equation 1}$$

Where x_n = Trace Element Concentration (ppm) and n = Feed & Product

The percentage maximum reduction of some of the trace elements at the optimum cut point densities are illustrated in figure 42, page 57 and at the different densities in table 4, page 56.

From the results it is clear that the trace elements of major concern, which indicate lower reduction proportions, tend to concentrate in finely disseminated minerals (especially pyrite and kaolinite). Such minerals are trapped in the lower densities or cleaner fractions of coal. These results and observations concur with findings made by Capes (1994) on distribution of certain elements in American coals.

Table 4: A *summary of historical and current results for feed (composite) and washed samples.*

		Global Swaine, (1990)	Global Zhang et al., (2004)	Witbank Coalfield 2 Seam Cairncross et al., (1990)	Highveld Coalfield 4 Seam Wagner et al., (2004)	Average Product Float Concentrations Witbank Coalfield 4 Seam								Steam Export Data	Steam L. S. Dale (2003)
						Feed	1.30	1.40	1.50	1.60	1.70	1.80	Sinks (+1.8 RD)		
Ash	%					25.0	4.5	7.8	11.7	14.0	15.8	16.9	28.2	15.2	
Major concern															
Arsenic	mg/kg	0.5–80	5	4.6	3.14	4.7	3.8	3.4	2.2	2.0	2.0	2.0	18.8	3.4	8.7
Cadmium	mg/kg	0.1–3	0.6		0.44	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.36	0.1	0.1
Lead	mg/kg	2–80	25	10	7.51	15.03	13.09	9.83	9.51	9.55	10.07	10.39	29.3	17.7	2.9
Mercury	mg/kg	0.02–1	0.12		0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.76	0.1	0.1
Molybdenum	mg/kg	0.1–10	5		1.18	2.1	3.3	2.1	1.5	1.4	1.3	1.3	6.78	11.2	6.9
Selenium	mg/kg	0.2–10	3	0.9	1.05	1.2	0.9	0.6	0.8	0.6	0.6	0.7	1.39	2.2	1
Moderate															
Chromium	mg/kg	0.5–60	10	28	70.5	41.4	38.7	31.2	31.2	29.6	29.5	29.7	112	30.1	29
Copper	mg/kg	0.5–50	15	9.7	13.2	16.8	17.6	20.3	17.3	16.6	15.9	15.8	25.3	12.8	10
Nickel	mg/kg	0.5–50	15	17	21.1	27.2	34.7	28.2	23.1	21.1	20.4	20.1	70.3	58.3	18
Vanadium	mg/kg	2–100	25	27	33.5	39.2	68.7	50.9	37.2	33.9	32.9	33.0	58.6	14.8	18
Minor concern															
Antimony	mg/kg	0.05–10	3	0.47	0.32	0.5	0.7	0.7	0.3	0.3	0.3	0.3	0.87	0.5	0.8
Cobalt	mg/kg	0.5–30	5	7.9	6.3	11.0	24.9	24.9	14.0	11.4	10.5	10.1	14.6	9.3	8
Manganese	mg/kg	5–300	50		19.6	163.4	35.2	50.6	70.2	75.9	83.4	89.7	151.9	33.1	300
Radio Active															
Uranium	mg/kg	0.02 –	3.1	4.0		2.6	4.0	3.0	2.5	2.4	2.4	2.4	3.61	3.0	21
Thorium	mg/kg	0.1 –	1.9	15.0		8.9	5.4	9.9	11.2	9.9	9.4	9.2	8.15	8.6	6.8

4.5 Washability analysis – dense medium beneficiation

From the washability analysis done on the Witbank coalfield No. 4 seam ROM samples, the cleanability of the trace elements can be divided into (I) the trace elements that indicate high levels of inorganic and organic affinities and (II) the more complex systems which can only be evaluated by mineralogy and liberation characteristics of species related to the trace elements.

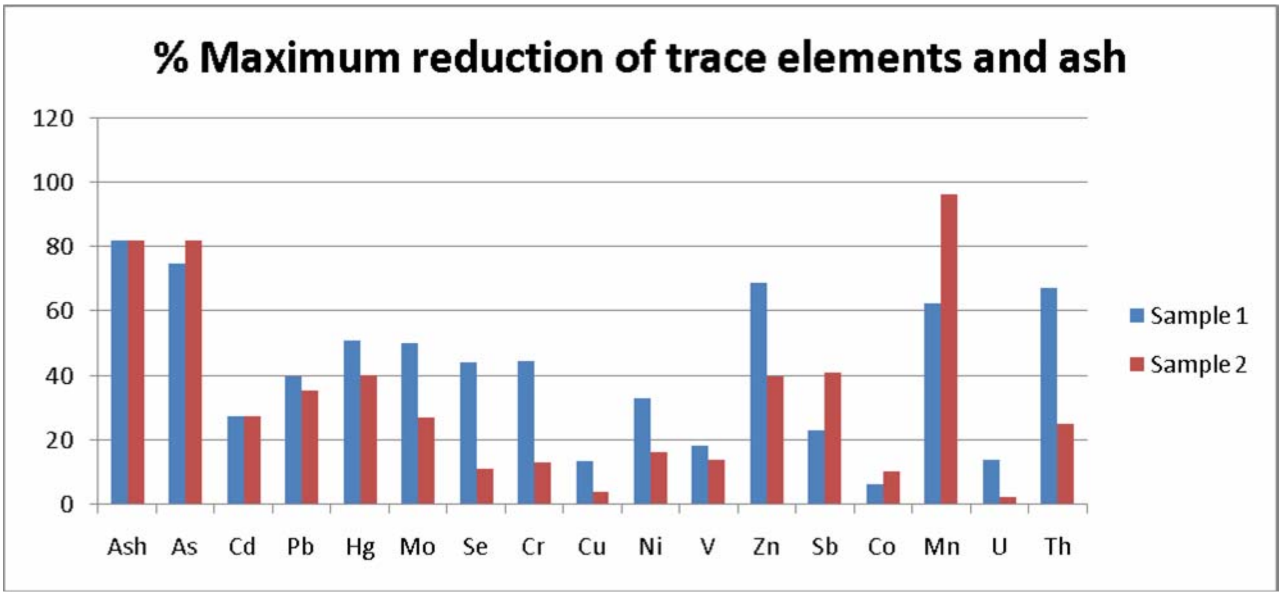


Figure 42: *Indicating the maximum reduction obtainable for various trace elements and ash on taken samples 1 and 2.*

The relation of mineral matter to the trace elements is critical in establishing the partitioning of the trace elements. In figure 42 the maximum reducibility of various trace elements is illustrated at different respective densities. Figure 43, page 58 illustrates the reduction of minerals down to a density of 1.30. If the reduction is low, an indication of poorer liberation can be established. If the reducibility is negative it indicates that the matter is either organically bound or that it occurs as finely disseminated mineral matter with a low level of liberation or that it is locked in the organic coal matrix.

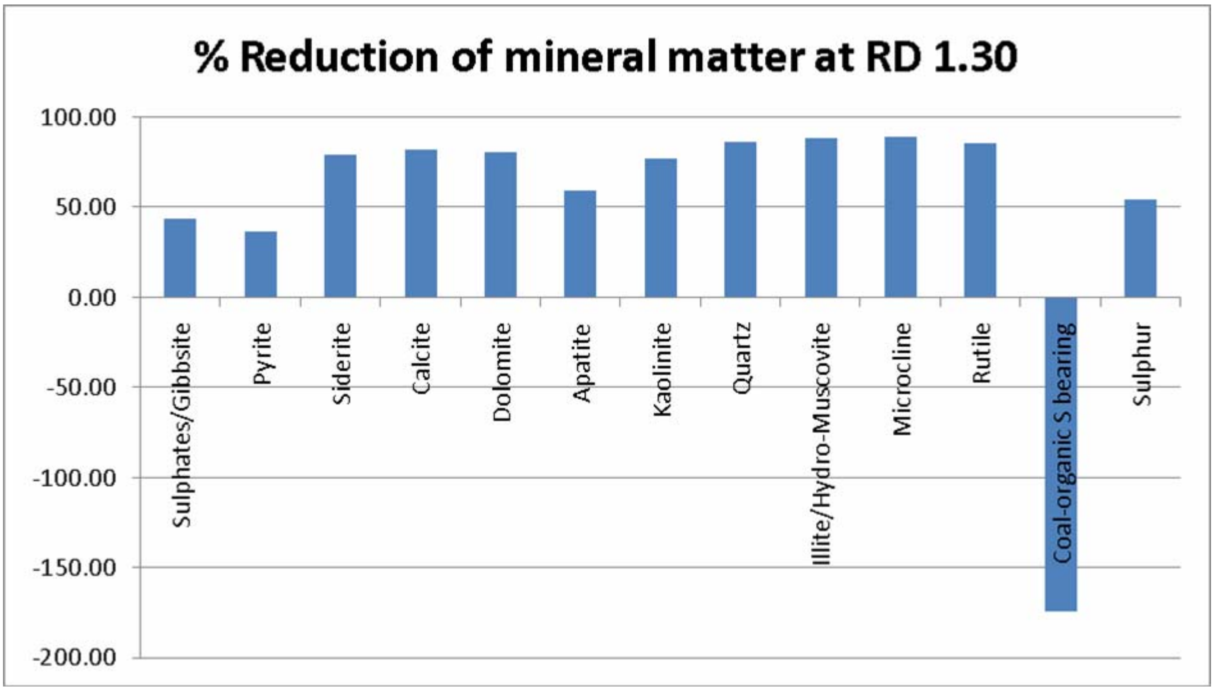


Figure 43: *Reduction of various minerals in the Witbank Coalfield No. 4 seam by dense medium beneficiation at a relative density of 1.30*

Upon higher liberation of the organic fraction, more of the organic matter can be recovered. In general in beneficiation plants improved trace element cleanability is obtained when beneficiating larger particles due to the process separation efficiency (Wenfeng, 2006). In comparison, improved cleanability is obtained in the floats/sinks analysis compared to the trace element reduction obtained by flotation. The No. 4 seam coal in the Witbank coalfield as mentioned are difficult to wash and contains a high percentage of near gravity material.

4.6 Froth Flotation

The washability data on the trace elements of the No. 4 seam may not be applicable to separation based on the flotation processes. The separation produced by a heavy media washability analysis is based on the mass bulk property of the collective particles (relative density), while the separation resulting from a froth flotation process is based on surface properties. There is therefore a substantial difference between the two types of separation processes. Data on the cleanability of trace elements by the use of froth flotation will give an indication of its relative efficiency as an alternative method of beneficiation. In recent history the ultrafine coal from the Witbank coalfield was considered difficult to beneficiate and indicated low sulphur reduction. Pyrite has high froth flotation floatability and if pyrite is present in the liberated and even locked form it froth floats very easily. Another significant factor is that the presence of finely disseminated mineral matter for instance clays and pyrite nodules in the coal matrix in conventional froth flotation will float with the coal and therefore cause inefficiency. More selective flotation mechanisms should therefore be considered.

One further important aspect is that organic sulphur in the high sulphur-bearing fraction or vitrinite fraction is not reduced in froth flotation, but indicates a negative reduction. This is illustrated in figure 43, page 58. There is however a positive reduction in percentage pyrite which would constitute the floating of the liberated pyrite fraction.

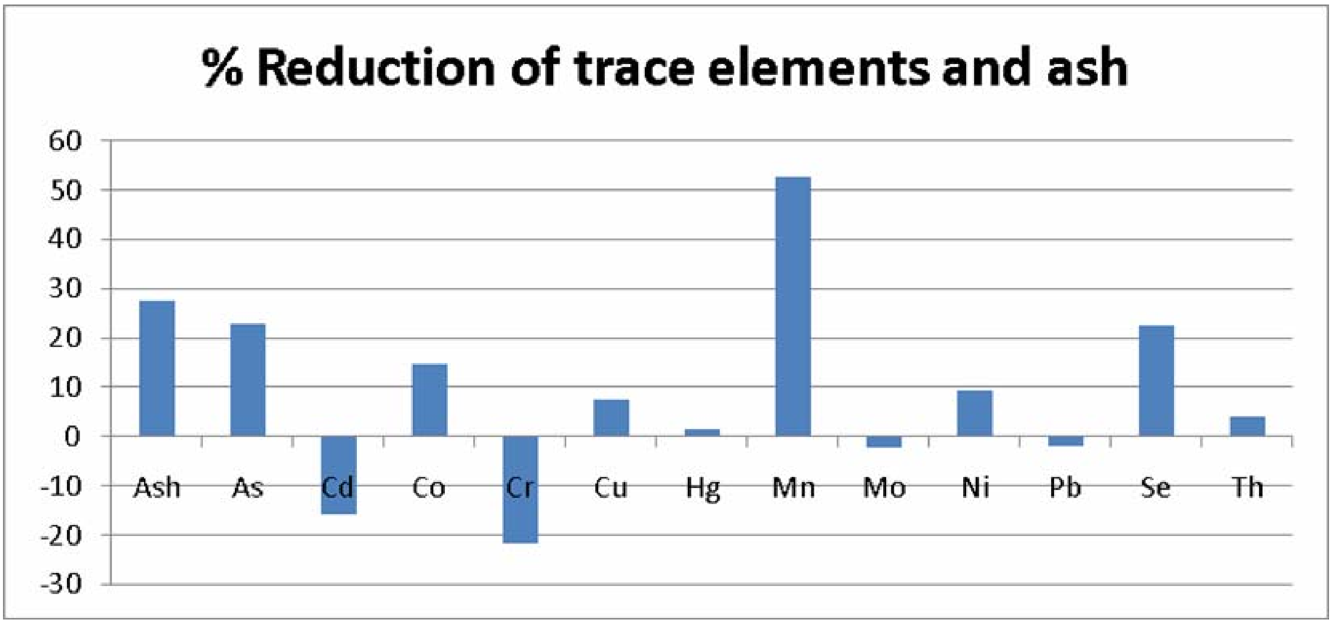


Figure 44: *Reduction of Witbank coalfield No. 4 seam trace elements by flotation*

Froth flotation proved to be highly effective in the removal of manganese, see figure 44. Manganese is usually associated with the carbonate minerals or to some extent the clays. From the results obtained from dense media washability characterisation, the manganese does follow the dolomite and calcite and to a greater extent the kaolinite. From the results in figure 43, page 58 a 28 percent reduction in kaolinite, 47 per cent reduction in calcite and 20 percent reduction in dolomite are obtained with a 52 percent reduction in the manganese concentration.

4.7 Liberation Analysis Results

QEMSCAN assisted with the analysis of the characteristics of the minerals and coal in the 4 seam. The QEMSCAN analyses were done on the floats-sinks fractions as well as the No. 4 seam froth flotation samples. For the liberation analysis the QEMSCAN characterises the particles into different groups, see table 5.

Table 5: *Summary of particle liberation as coal and mineral species.*

Mineral	**4 Seam Feed (% by mass)**	**Floats at RD 1.3 (% by mass)**	**Floats at RD 1.6 (% by mass)**
Pyrite/Siderite Cleat	0.76	0.11	0.59
Carbonate Cleat	0.78	0.08	2.75
Sandstone	1.12	0.03	0.47
Mudstone	3.42	0.56	2.73
Siltstone	0.25	0.01	3.57
Middling	20.22	2.84	48.55
Included	60.30	68.04	35.30
Free Coal	13.14	28.33	6.03
Total	100.00	100.00	100.00

The characterisation is based on the mineral proportion relative to the coal proportion and the mineral composition (van Alphen 2008). The five generic or main groups are described as cleats, stone, middling, included and free particles, see table VI in appendix for the group definitions.

Illustrations of the QEMSEM micrographs is given in figure 45 and 46 for pyrite and sulphur bearing coal and kaolinite respectively.

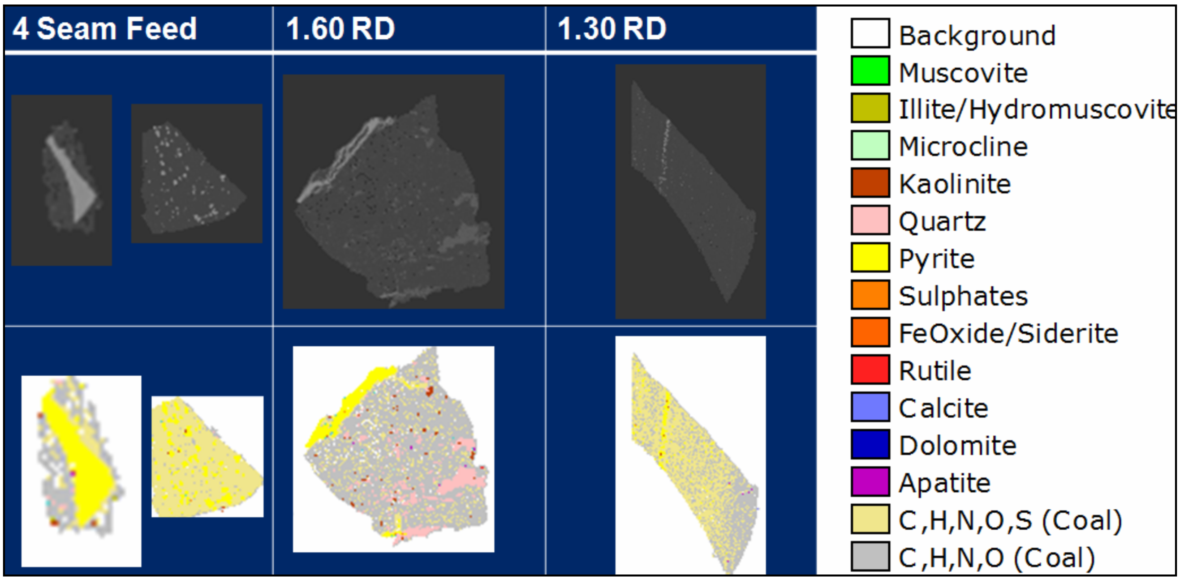


Figure 45: *Comparative QEMSEM micrographs of particles in the feed, RD 1.30 floats and RD 1.60 floats. Focus on pyrite and sulphur bearing coal fractions.*

In figure 45 the particles are -150 micron in size and the focus is on pyrite and sulphur bearing coal (organic sulphur). It can be seen that in the feed fraction of the 4 seam the pyrite occurs in the cleat and syngenetic nodule form. Even in the low density 1.3 RD fraction the pyrite occurs in the cleat and included syngenetic mineral matter form. The organic sulphur occurs widely disseminated over the matrix.

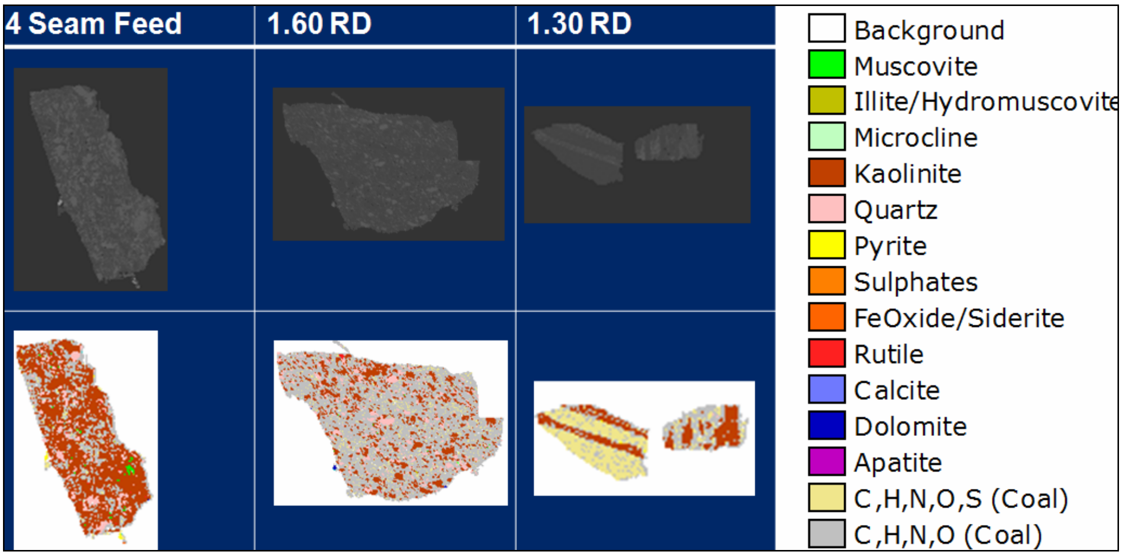


Figure 46: *Comparative QEMSEM micrographs of particles in the feed, RD 1.30 floats and RD 1.60 floats. Focus on clay mineral, specifically kaolinite bearing coal fractions.*

In figure 46, the distribution of the kaolinite is illustrated. It can be seen that the kaolinite occurs mainly as finely disseminated matter in the coal matrix. There are also instances of lenses or layers. The kaolinite occurrence can be described as mainly syngenetic. In froth flotation where good liberation may be expected it can be seen that the reduction of kaolinite is only at approximately 28% whereas a 70% reduction was achieved with the dense media beneficiation.

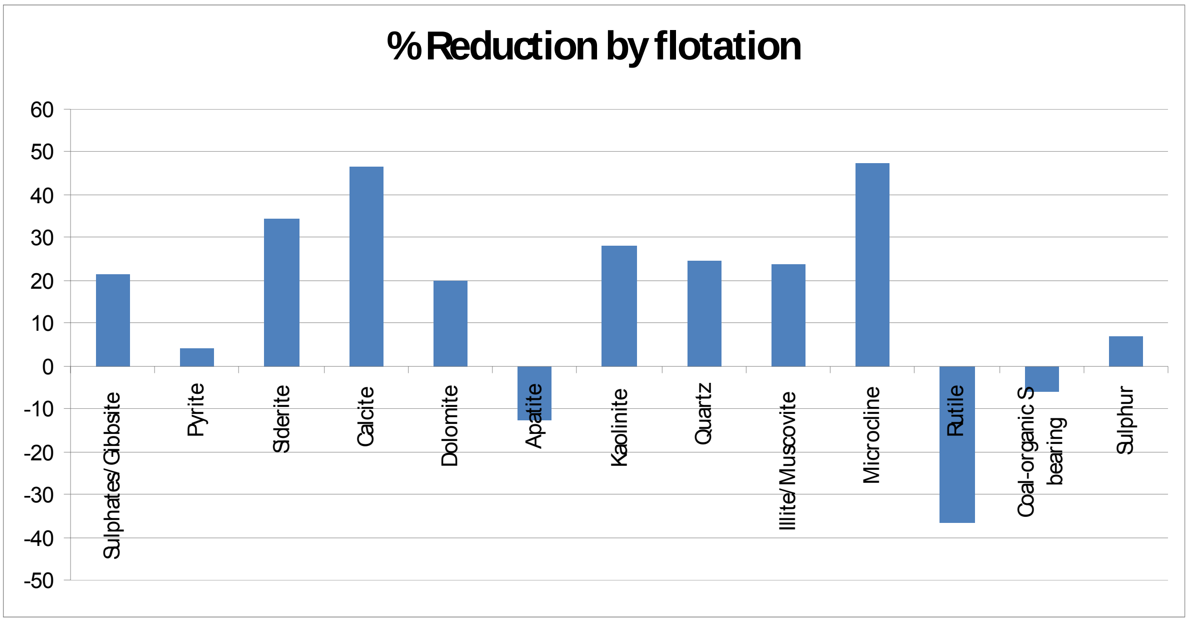


Figure 47: *Reduction of various minerals in the Witbank Coalfield No. 4 seam by froth flotation.*

In the less liberated float fraction at RD 1.60, it was found that the sample had significantly higher ash and dolomite content than expected. The high dolomite content can be confirmed with the XRD results where a peak of 6.81 per cent dolomite was analysed. The high percentage dolomite can best be explained by liberation. At RD 1.60, 2.75 per cent of the carbonates occur as cleats. Dolomite being a carbonate could be part of this cleat fraction as it usually occurs as an epigenetic mineral precipitate, filling cleats.

The total analysis of the mass distribution and liberation of the particles in the ultra-fine fraction is summarised in table 6 and 7. The results are reported for the froth flotation feed, product and tailings.

Table 6: *% Mineral distribution in froth flotation feed, product and tailings by mass as determined by QEMSEM.*

Minerals	Feed	Product	Tail	%Recovery
Sulphates	0.1	0.1	0.1	38.0
Pyrite	3.0	1.7	5.1	28.7
FeOxide/Siderite	0.7	0.3	1.5	16.7
Calcite	1.0	0.4	4.3	10.3
Dolomite	2.4	1.7	7.6	21.0
Apatite	0.7	0.7	0.6	57.7
Kaolinite	14.6	9.2	15.5	41.3
Quartz	5.7	3.9	6.4	42.2
Illite/Hydromuscovite	0.7	0.3	0.3	51.2
Muscovite	0.9	0.2	2.1	12.6
Microcline	1.5	0.5	5.9	9.0
Rutile	0.2	0.1	0.4	22.5
C,H,N,O,S (Coal)	14.6	23.8	8.1	77.6
C,H,N,O (Coal)	53.5	56.8	41.0	62.2
Other	0.4	0.2	1.0	21.2
Total	100.0	100.0	100.0	54.3
Mineral Matter	31.9	19.4	50.9	31.1
Mineral Volatiles	5.7	3.4	11.2	26.4
Ash-% Calc	26.2	16.0	39.7	32.4
Ash-% Measured(DB)	27.2	18.6	38.7	36.3

In table 6 it can be seen that the percentage apatite in the ultra-fine feed fraction is slightly higher than the courser fraction. The pyrite content is reduced from 0.55 to 0.28 percent in the product, most of the pyrite in the feed is liberated and included in the ultra-fine coal feed fraction, see table 7.

Table 7: *Particle recoveries. Fine particle agglomerates will mainly report as "middling 50-60".*

Stone Report - Mass%	Feed	Product	Tail	%Recovery
Pyrite Cleat	0.55	0.28	3.60	8.54
Calcite Cleat	0.22	0.12	3.32	4.12
Dolomite Cleat	0.60	0.28	5.12	6.06
Carbonate Cleat	0.17	0.09	0.60	15.14
Sandstone	1.42	0.44	5.97	7.98
Mudstone	2.81	1.28	11.78	11.44
Siltstone	1.48	0.85	2.41	29.66
Middling50	8.30	4.69	17.32	24.35
Middling60	7.84	3.11	7.88	31.92
Middling70	18.04	5.91	7.84	47.25
Included80	22.58	20.98	6.99	78.10
Included90	20.63	47.51	9.57	85.51
Mineral FreeCoal	15.35	14.45	17.61	49.37

The kaolinite shows an increased reduction of 42%, almost no kaolinite bands are observed at -150 µm. The difference between calculated and measured feed is attributed to the fine particle agglomerates.

CHAPTER FIVE - DISCUSSION

5. 1 Relationship between Trace elements, sulphur and mineral matter associations

The association of the trace elements with the mineral and organic species was found to be quite indicative. Tthe partitioning of a majority of the trace elements within the seam was found to be clearly related to the distribution of the sulphide minerals and organic matter (vitrinite maceral).

In figure 48, page 65, it can be seen that the arsenic follows the trend of the pyrite well. Statistically the data indicates a correlation of 98.09 per cent. The same statistical correlation of 96.01 per cent is obtained for the organic sulphur and arsenic relationship, see figure 10. In essence the higher concentrations observed in the lower density fractions can be attributed to the increased sulphur in the high vitrinite fractions (Roberts, 1998). From a geological perspective this particular situation can be explained partially by the environmental conditions during geological deposition. When peat accumulates in marine or brackish water, the organic matter is converted to vitrinite. Under these same conditions the S^- and Fe^+ ions, when saturated in the acidic and/or anaerobic waters, precipitate out as sulphide minerals whilst elemental sulphur is absorbed into the organic matrix of the peat fragments. As vitrinite has a relative density of 1.3-1.35, this maceral with its organic sulphur and fine syngenetic pyritic minerals reports to the low density floats fraction. This is the reason for the high sulphur in the low density fractions and its association with vitrinite.

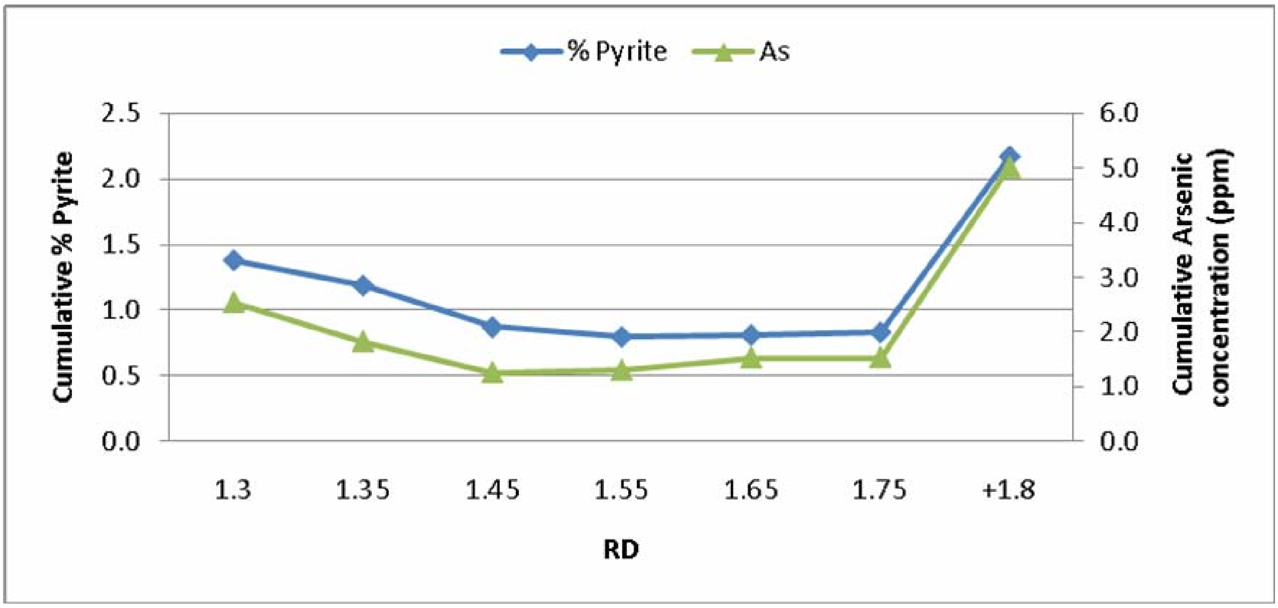


Figure 48: *Illustrating the relationship between % Pyrite by XRD and Arsenic concentration at various densities.*

In the current research, figure 49 proves that there is an increase in organic sulphur towards the lower density fractions.

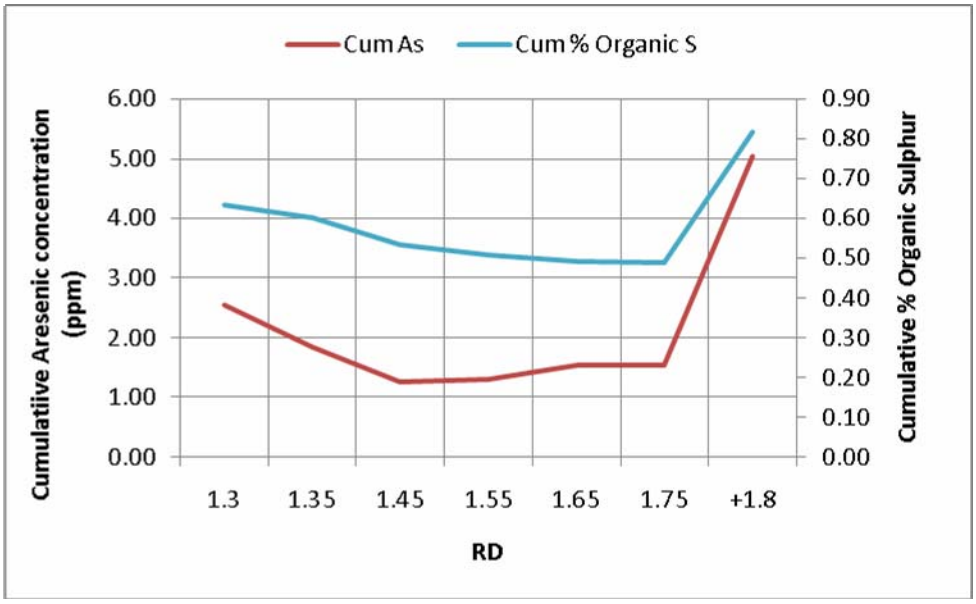


Figure 49: *Relationship between organic sulphur and arsenic content.*

From figure 48 and 49 it can be seen that the optimum density range for As and other sulphur related trace elements, beneficiation lies between RD 1.45 and RD 1.65. It is also within this density range where the product specification in terms of heating value at optimum yield is situated, namely at RD 1.60, also known as the cut-point density. This situation is potentially of great significance in terms of coal marketability.

5.2 Modelling of trace element reduction by dense medium beneficiation

The efficiency of removal of the trace element content by means of beneficiation would depend not only on the organic efficiency of the equipment, but also on the proportion of near gravity material and the liberation characteristics of the mineral species containing specific trace elements.

In table 8 a dense medium beneficiation wash at a density of 1.60 is modelled and it can be seen that the comparative trace element concentrations, especially with regard to the trace elements of major concern, are generally lower than the published concentrations of other typical South African export thermal coal.

Table 8: *Comparative product trace element content of more especially thermal coals with a simulated wash at a 1.60 relative density.*

Elements	Australian Export	South African Export	Guide to trace elements in coal	Actual concentration	Model
	Thermal Coals	Thermal Coals Export Data (Aug 2007-2008)	South African Export Thermal Coals	RD 1.60 Wash	RD 1.60 Wash
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Major concern					
Arsenic	1.26	4.5	8.7	1.3	1.53
Cadmium	0.067	0.2	0.1	0.25	0.16
Lead	6.8	12.4	2.9	8.75	9.73
Mercury	0.042	0.2	0.1	0.13	0.14
Molybdenum	1.71	2.7	6.9	1.19	1.17
Selenium	0.5	1.7	1	0.86	0.86
Moderate concern					
Chromium	15.9	22.9	29	23.5	35.5
Copper	9.8	14.6	10	18.3	17.7
Nickel	11.5	23.1	18	21.2	20.8
Vanadium	11.5	23.1	18	21.2	28.1
Minor concern					
Antimony	0.47	0.6	0.8	0.3	0.3
Cobalt	4.48	7.6	8	12.2	10.4
Manganese	51.4	92.6	300	101	75.5

5.3 Beneficiation techniques for optimum trace element reduction

5.3.1 The case of sulphuric related species and its associated trace elements

In the case of trace element and ash removal, for individual trace elements the percentage removal is specific to the coal and to the cleaning process used. From the washability data obtained, a low RD (relative density) indicates a high reduction in ash content, but not a high reduction in all other trace elements. The optimum RD for minimum values of As, Hg, Mo, Pb, Se and Cd removal lies within RD range 1.45 to RD 1.65, the average indicating a RD of 1.60.

One possible method of trace element removal would be to undertake a low density wash at approximately 1.35 and remove the high vitrinite fraction followed by conventional washing to remove the bulk of the mineral matter at a higher density. The low density fraction then has to be crushed down typically to -100µm to induce sufficient liberation of the mineral matter. Such fine sizes however will have their own detrimental processing aspects. In general the cleanability of trace elements will depend on the liberation characteristics of the mineral species in which they occur, so crushing to liberate these minerals and consequent beneficiation will prove effective. To achieve this very fine grinding has to take place. In most instances the cleavage is between the coal and the impure mineral particles, so breakage should take part easily and cleanly.

The concern is with the syngenetic mineral matter that forms part of the coal matrix. At times the impure particles may be bound to the coal so strongly and intimately that when crushing occurs, they become locked in with the coal (Capes 1994).

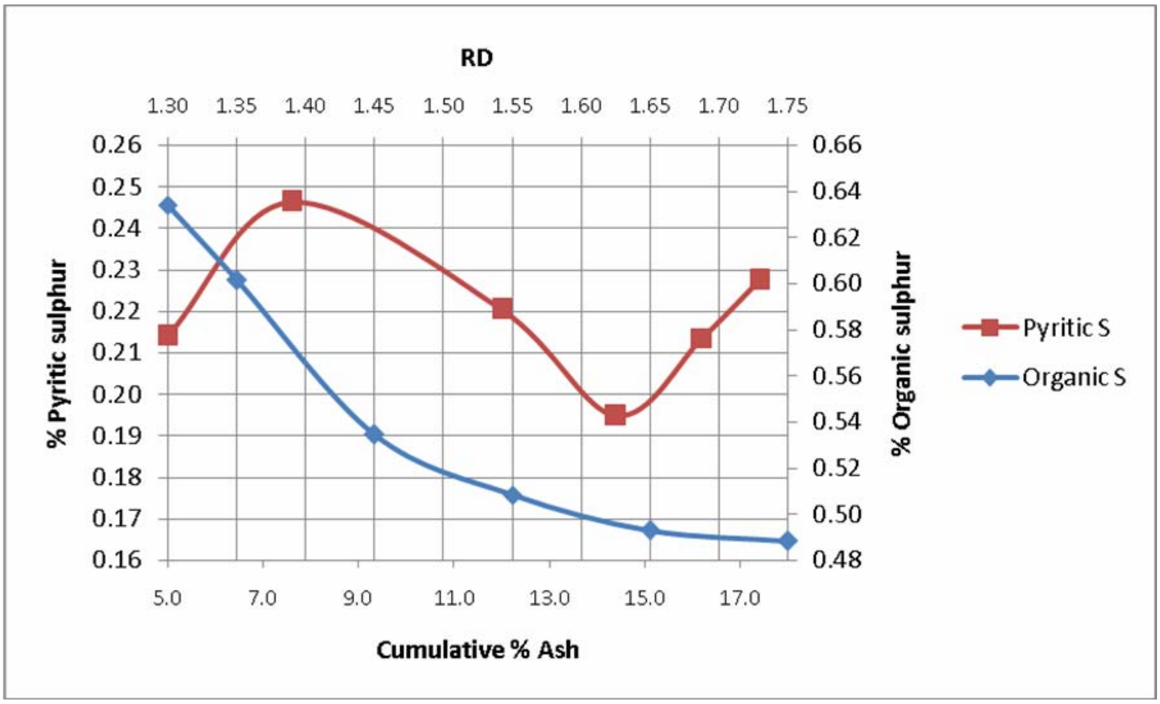


Figure 50: *Illustrating the concentrations of pyretic and organic forms of sulphur in relation to proportions by percentage ash and relative density.*

The size of pyrite nodules as inherent syngenetic minerals is often very fine. After grinding and liberation a froth flotation process can be used to recover the coal. One proposal is that reverse flotation be employed to depress the coal in a first stage float and then in a second stage float the coal. Conventionally, because pyrite floats relatively easily, its concentration reduction is relatively poor. The organic sulphur is more difficult and is likely to be removed only by chemical means. Chemical removal of organic sulphur is however uneconomical and has a higher inherent risk than coal preparation.

In the No. 4 seam the RD 1.30 to RD 1.40 fraction constitutes approximately only 12-14 percent of the feed material. Depending on the organic efficiency of the beneficiation process during the RD 1.30 removal and subsequent processing, a yield loss of minimal effect would be observed. Figure 51 illustrates that above a RD of 1.55 a consistent low level of both organic and pyretic sulphur occurs at a cumulative ash of 11.2 percent, which still constitutes a yield of above 65% above quality specifications.

The handling and dewatering of such a fine flotation product however would be difficult and entail many logistical and management issues. There are new technologies in filtration and other dewatering equipment which could aid the dewatering and handling of such material in future, should such proposed steps be followed.

In summary, the trace element washability data indicates not only the beneficiating capacity of the trace elements, but also implied environmental data for noxious emissions at power generation plants. In the case of the Witbank coalfield No. 4 seam, when removing the lowest density fraction thereby leaving a consequent higher density wash, a reduction in overall sulphur and associated trace element contents occurs. The low density fraction can be added if necessary as a sweetener to reduce the overall ash content of the final product, but only after a separate sulphur removal step has taken place. This approach may also be used in the development of a new low-sulphur product for sulphur and SO_x sensitive markets. The modelling of maximum reduction, or reduction capacity factor, will also permit matching specific coals for specific markets. Products with specific trace element and sulphur contents could also be modelled for use in advanced gasification processes and in the production of synthetic organic chemicals.

5.3.2 The case of phosphoric species and its associated trace elements

The distribution of phosphorous in coal can be divided mainly into two sources (a) matrix associated with maceral and (b) as well as in mineral matter as phosphates or ash components. The main phosphate mineral that occurs in coal is apatite associated with fluorine and chlorine. In the research undertaken the presence of monazite however, which is associated with thorium and uranium is also evident. In figure 52, page 71 the organic and inorganic phosphorus distribution is illustrated. The organic phosporus reaches maximum peaks at the higher densities possibly as a result of a strong relation to the specific maceral inertinite. The inorganic phospherous distribution is unusual with a peak at the lower relative density fraction 1.3 and 1.4.

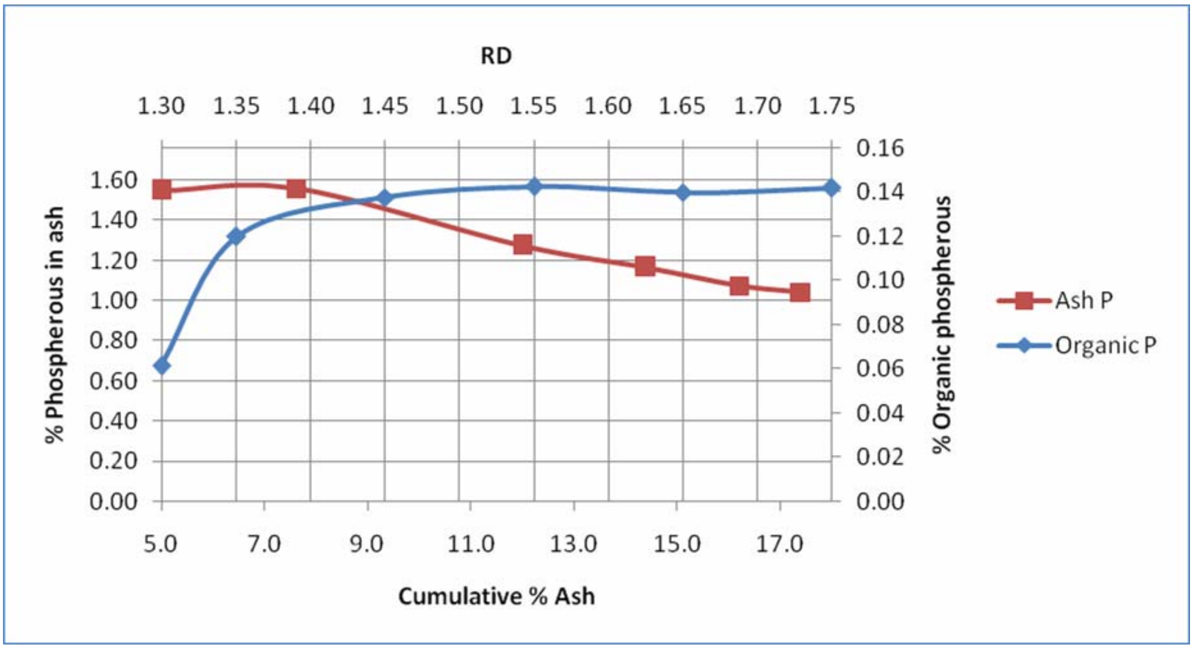


Figure 51: *Densimetric curve illustrating the concentrations of phosphorous in the ash and organic matter in relation to the % ash.*

The best explanantion for the high phosphoros concentration in the lower density fraction can be attributed mainly to its inclusion as very small mineral forms (1-5 μm) in the maceral vitrinite which floats at relative densities of 1.30 – 1.35. However in other sources of phosphorus, monazite, the distribution of trace elements cerium, lanthanum, yttrium, thorium and neodymium as illustrated in figure 52 follow the same trend in the density distribution. Monazite was not identified in the QEMSEM or XRD analysis. Monazite is a radioactive heavy phosphate mineral with a specific gravity of 5.5 t/m^3.

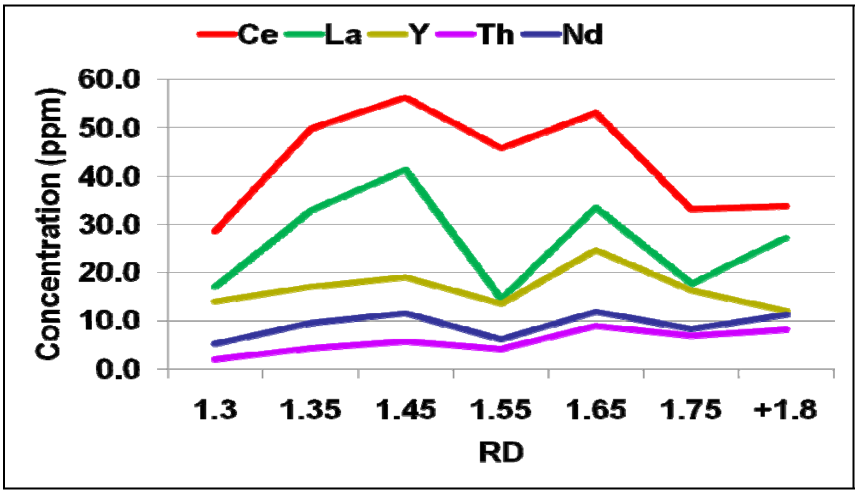


Figure 52: *The trace elements in monazite, an evidence of distribution.*

Monazite from figure 53 peaks at different relative densities namely 1.45 and 1.65 respectively.

Apatite's distribution is critical; it is related to the critical highly volatile elements F and Cl. The quantity of apatite (mainly hydroxy-apatite) is less than 0.5%, as confirmed by both the XRD and QEMSEM analysis. This should be the main reason why the F and Cl content in the No. 4 seam coal is lower than the global average, Wagner (2005).

The distribution of the total phosphorous in the coal in the Witbank coalfield No. 4 seam is illustrated in figure 53. The drop in concentration at RD 1.65 is likely due to the phosphorus relationship with the inertinite maceral and not to that of apatite.

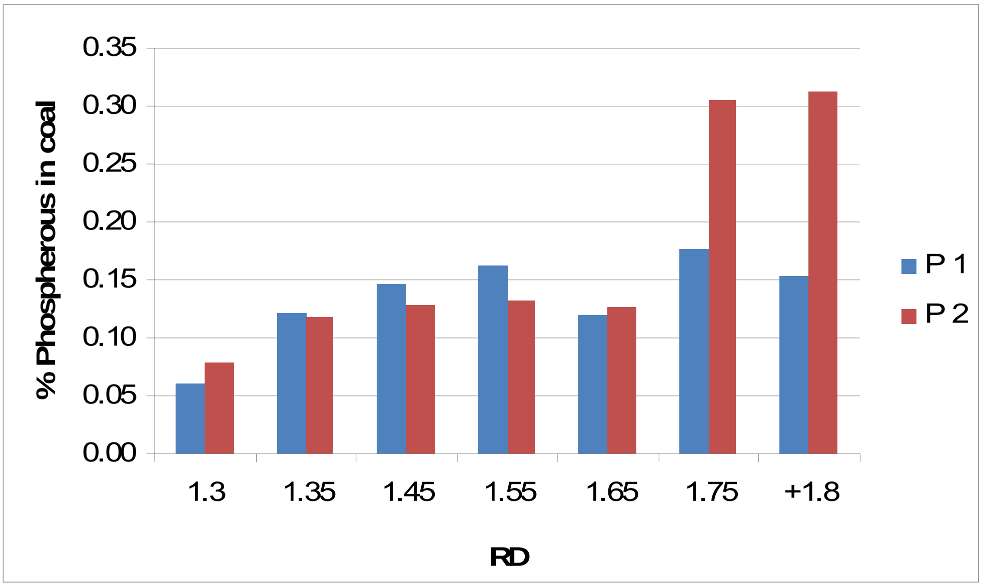


Figure 53: *Washability curve of phosphorus for Witbank Coalfield No. 4 seam coal.*

In figure 54, page 73 which illustrates the distribution of phosphorus at different densities for USA coal from the Illinois basin, it can be seen that a very similar distribution is observed.

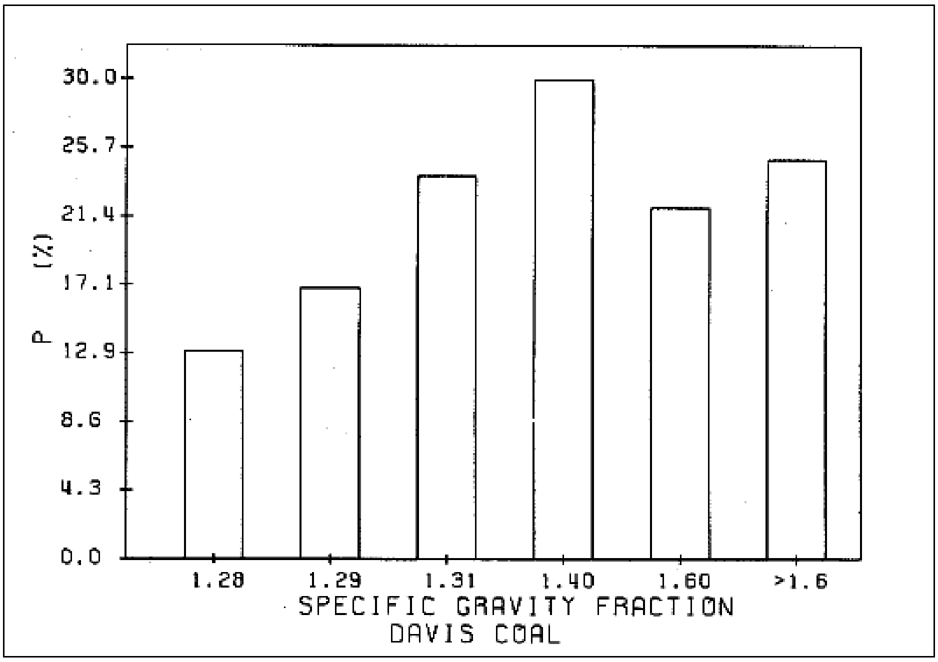


Figure 54: *Phosphorus in specific density fractions of a sample from the Illinois Coal Basin - Davis.coal member. Ruch, Gluskoter Et al. (1974).*

In both the Witbank coalfield No. 4 seam and the Illinois coal basin samples there is a decrease in concentration at a density of approximately 1.60, although a difference may be expected due to the different depositional characteristics of the coals. In concentration however, the difference is clear, with the USA coal being much higher than the Witbank coalfield No. 4 seam. This is likely to be due mainly to the fact that the Illinois basin coal was deposited in marine conditions with high sulphur and phosphorus elements in that environment.

6. CONCLUSIONS

- There exists a clear relationship between the trace elements and the organic (maceral) and inorganic (mineral) components in the No. 4 seam coal.
- The concentrations of most trace elements in the final marketable coal product can be manipulated by beneficiation. A low operating density to obtain as low as possible ash coal does not necessarily constitute a product with a low specific trace element concentration.
- The volatile trace elements of major concern which have a higher concentration than the global average in the run of mine coal include mercury, arsenic and molybdenum, whilst those that occur in proportions lower than the global average include selenium, cadmium and lead.
- Arsenic and mercury are not only associated with the mineral pyrite, but are also linked to the organic sulphur components in coal. The No. 4 seam organic sulphur in turn has been proven to be related to the vitrinite maceral in the coal.
- The radioactive trace elements in the No.4 seam coal, namely uranium and thorium, both occur in concentrations within the global average range. Uranium is associated with the element zircon, and shares association to monazite with thorium.
- The phosphorous distribution illustrates a close relation to fluorine and radioactive trace element contents.

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APPENDIX

Table I: No. 4 Seam QEM SEM flotation test work

Mineral	**Ideal Composition**	**S4-Feed**	**S4-Calc. Fd.**	**S4-Product**	**S4-Tailings**	**%Recovery**
Sulphates/Gibbsite	Ca- and Al-bearing sulphates	0.1	0.1	0.0	0.1	42.3
Pyrite	FeS2	2.3	2.5	2.2	2.7	46.8
Siderite	FeCO3	0.7	0.8	0.5	1.1	31.0
Calcite	CaCO3	0.9	0.6	0.5	0.8	39.3
Dolomite	CaMg(CO3)2	2.0	1.9	1.6	2.2	43.8
Apatite	Ca5(PO4)3(OH,F,Cl)	0.2	0.3	0.3	0.4	44.2
Kaolinite	Al2Si2O5(OH)4 (clay)	13.1	14.8	9.4	20.6	33.1
Quartz	SiO2 (sand)	6.7	6.1	5.1	7.3	43.0
Illite/Muscovite	K2Al6Si6O20(OH)4/ KAl5Si7O20(OH)4	0.9	1.5	0.7	2.4	23.4
Microcline	(K,Na)AlSi3O8	1.4	2.2	0.8	3.7	18.1
Rutile	TiO2	0.2	0.2	0.2	0.2	49.7
Coal-organic S bearing	C,H,O,N,S	16.7	15.7	17.7	13.5	58.8
Coal	C,H,O,N	54.4	53.0	60.8	44.4	59.7
Other	Unidentified Phases	0.4	0.4	0.3	0.6	32.9
Total		100.0	100.0	100.0	100.0	
Mineral Matter/Ash reconciliation						
Total Mineral Matter	100-Total("Coal")	28.9	31.4	21.5	42.1	35.6
Mineral-derived volatiles	Calculated	4.8	5.0	3.7	6.4	38.7
Calculated Ash-%	MM-MV	24.1	26.4	17.7	35.7	35.0
Measured ash-%	Proximate	28.5	25.5	13.7	38.2	28.0

Table II: No. 4 seam batch flotation test work proximate results - 1

				TEF1D	**TEF1F**	**TEF1P**	**Ash yield%**
Proximate Analysis	Moisture as analysed (Inherent Moisture)	IM	%	2.4	2.5	2.6	57.4%
	Volatile Matter	VOL	%	21.4	22.5	22.8	
	Ash content	ASH	%	35.9	26.2	19	
	Fixed Carbon	FC	%	40.3	48.9	55.7	
							CV Yield to product
Other	Calorific Value	CV	MJ/kg	18.89	22.71	25.46	58.1%
	Sulphur	S	%	0.74	0.88	0.82	

Table III: No. 4 seam batch flotation test work proximate results - 1

FLOTATION TEST SAMPLES	**DATE**	2009/02/03	**ASH YIELD%**	57.8%	**%RECOVERY**	54.3%	
FEED	**MASS IN GRAMS**	**ASH 1**	**ASH 2**	**CV**	**VOLS**	**%IM**	**FC %**
	400.00	26.78	26.90	23.33	24.3	1.2	47.7
PRODUCT	**MASS**	**ASH 1**	**ASH 2**	**CV**	**VOLS**	**%IM**	**FC %**
	234.80	18.61	18.22	26.56	25.1	1.0	55.5
TAIL	**MASS**	**ASH 1**	**ASH 2**	**CV**	**VOLS**	**%IM**	**FC %**
	198.00	37.95	37.64	18.36	23.9	2.3	36.0

Table IV: XRD results first sample set % mass distribution per density fraction

	Calcite	**Dolomite**	**Graphite**	**Muscovite**	**Kaolinite**	**Pyrite**	**Quartz**	**Siderite**	**Rutile**
RD	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
1.3	0	0	94.16		4.83	0.34	0.62	0.05	
1.35	0	0.76	83.87		12.53	0.64	1.93	0.27	
1.45	0.24	2.62	76.78		16.06	0.43	3.53	0.33	
1.55	0.33	2.19	67.85		22.2	0.33	6.58	0.52	
1.65	0.52	2.58	60.07	1.690	25.29	0.29	8.26	1.31	
1.75	0.31	2.82	52.6		31.33	0.69	10.29	1.69	0.29
+1.8	3.04	7.15	17.7	7.020	39.1	6.22	11.23	7.58	0.95

Table V: XRD results second sample set % mass distribution per density fraction

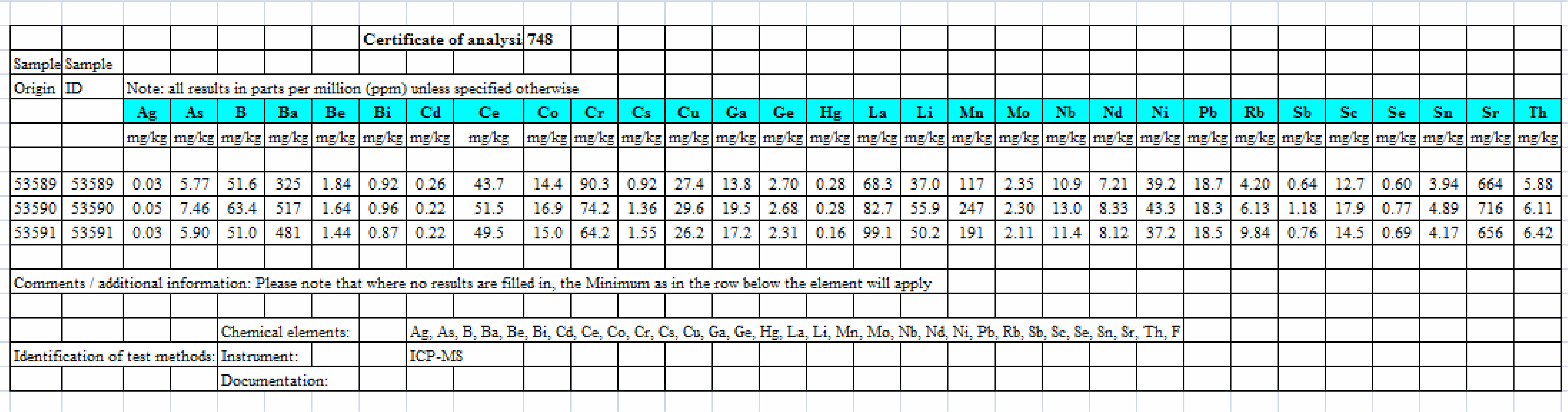
	Calcite	Dolomite	Graphite	Hydroxyapatite	Kaolinite	Pyrite	Quartz	Siderite
RD	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
1.3	0.11	0.61	87.38	0.160	8.59	1.38	1.72	0.04
1.35	0.17	1.33	82.13	0.410	11.93	1.17	2.7	0.15
1.45	0.11	1.56	75.69	0.330	15.51	0.75	5.85	0.21
1.55	0.12	2.15	65.19	0.000	20.8	0.6	10.34	0.8
1.65	0.59	6.81	53.99	0.000	24.77	0.9	11.92	1.02
1.75	0.49	3.04	46.6	0.000	28.52	1.15	15.2	5.03
+1.8	2.32	5.46	28.1	0.000	30.2	7.33	20.96	5.56

Table VI: QEMSEM mineral composition % mass distribution per Feed and 1.3., 1.6 density fractions

Mineral	**Ideal Composition**	**S4-Feed**	**F1.3**	**F1.6**
Sulphates/Gibbsite	Ca- and Al-bearing sulphates	0.1	0.0	0.1
Pyrite	FeS2	1.1	1.2	1.1
Siderite	FeCO3	0.4	0.1	0.3
Calcite	CaCO3	0.4	0.1	0.5
Dolomite	CaMg(CO3)2	1.6	0.3	7.4
Apatite	Ca5(PO4)3(OH,F,Cl)	0.9	0.4	0.8
Kaolinite	Al2Si2O5(OH)4 (clay)	10.0	2.3	14.3
Quartz	SiO2 (sand)	4.0	0.5	7.5
Illite/Hydro-Muscovite	K2Al6Si6O20(OH)4/ KAl5Si7O20(OH)4	1.0	0.1	0.2
Microcline	(K,Na)AlSi3O8	0.6	0.1	0.4
Rutile	TiO2	0.2	0.0	0.2
Coal-organic S bearing	C,H,O,N,S	21.1	58.0	8.7
Coal	C,H,O,N	58.4	36.8	58.2
Other	Unidentified Phases	0.2	0.1	0.3
Total		100.0	100.0	100.0
Mineral Matter/Ash Reconciliation				
Total Mineral Matter	100-Total("Coal")	20.48	5.21	33.11
Mineral-derived volatiles	Calculated	3.19	1.18	6.51
Calculated Ash-%	MM-MV	17.29	4.03	26.60
Measured ash-%	Proximate	28.28	5.12	16.70
Mineral	**Classification Specifications**	**S4-Feed**	**F1.3**	**F1.6**
Pyrite/Siderite Cleat	Pyrite/Siderite>60 Area%	0.76	0.11	0.59
Carbonate Cleat	Calcite+Dolomite>60 Area%	0.78	0.08	2.75

Sandstone	Quartz+Microcline>60 Area%	1.12	0.03	0.47
Mudstone	Kaolinite+Illite/Hydro-Muscovite>60 Area%	3.42	0.56	2.73
Siltstone	Kaolinite+Quartz>60 Area%	0.25	0.01	3.57
Middling	Mineral Matter 30-60 Area-%	20.22	2.84	48.55
Included	Mineral Matter 0.1-30 Area-%	60.30	68.04	35.30
Free Coal	No included mineral matter	13.14	28.33	6.03
Total		100.00	100.00	100.00

Table VII: Trace element analysis of flotation samples (Feed, product and tailings)



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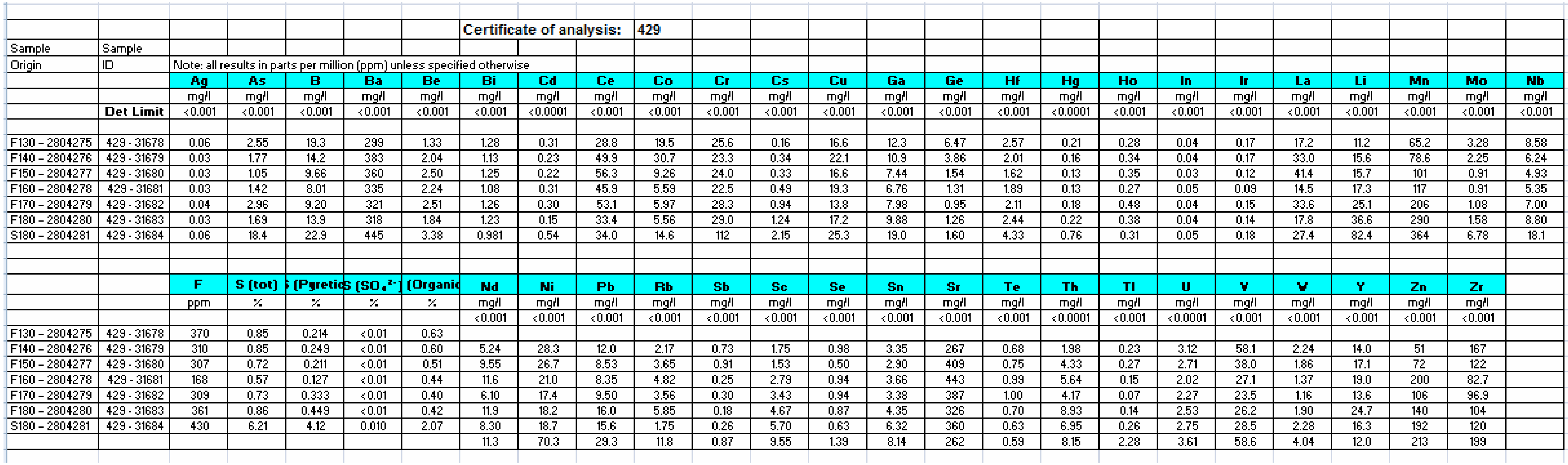
Note: all results in parts per million (ppm) unless specified otherwise

Sample Origin	Sample ID	Ag	As	B	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Ga	Ge	Hg	La	Li	Mn	Mo	Nb	Nd	Ni	Pb	Rb	Sb	Sc	Se	Sn	Sr	Th
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
53589	53589	0.03	5.77	51.6	325	1.84	0.92	0.26	43.7	14.4	90.3	0.92	27.4	13.8	2.70	0.28	68.3	37.0	117	2.35	10.9	7.21	39.2	18.7	4.20	0.64	12.7	0.60	3.94	664	5.88
53590	53590	0.05	7.46	63.4	517	1.64	0.96	0.22	51.5	16.9	74.2	1.36	29.6	19.5	2.68	0.28	82.7	55.9	247	2.30	13.0	8.33	43.3	18.3	6.13	1.18	17.9	0.77	4.89	716	6.11
53591	53591	0.03	5.90	51.0	481	1.44	0.87	0.22	49.5	15.0	64.2	1.55	26.2	17.2	2.31	0.16	99.1	50.2	191	2.11	11.4	8.12	37.2	18.5	9.84	0.76	14.5	0.69	4.17	656	6.42

Comments / additional information: Please note that where no results are filled in, the Minimum as in the row below the element will apply

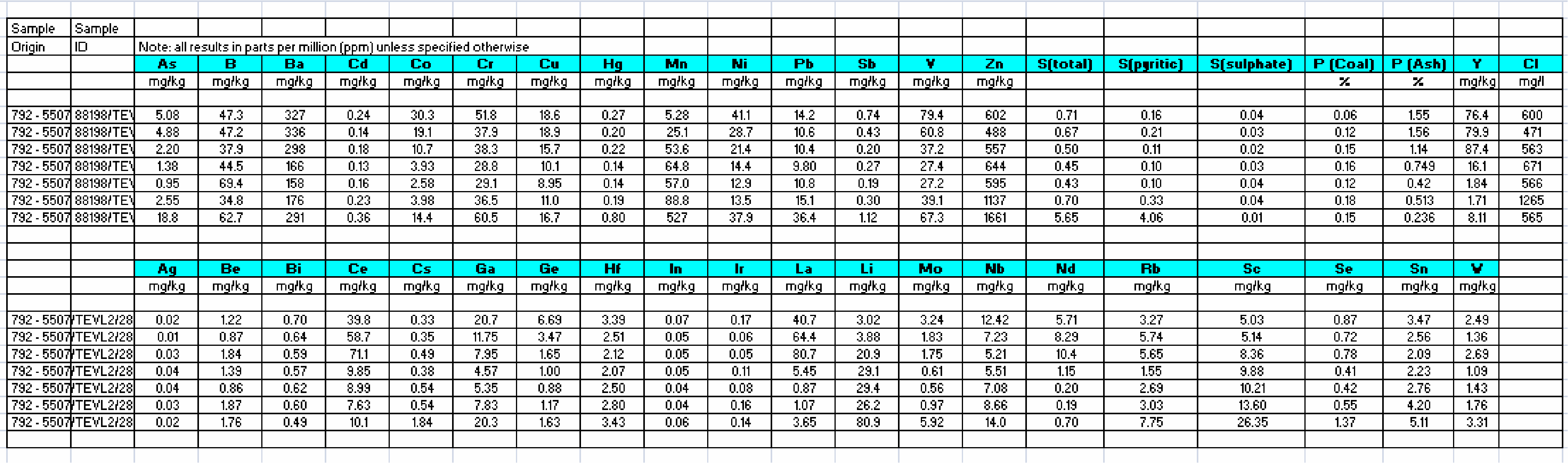
Chemical elements:	Ag, As, B, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Ga, Ge, Hg, La, Li, Mn, Mo, Nb, Nd, Ni, Pb, Rb, Sb, Sc, Se, Sn, Sr, Th, F
Identification of test methods: Instrument:	ICP-MS
Documentation:	

Table VIII: Trace element analysis of washability samples at seven relative density fractions – first sample set



							Certificate of analysis:			429														
Sample	Sample																							
Origin	ID	Note: all results in parts per million (ppm) unless specified otherwise																						
		Ag	**As**	**B**	**Ba**	**Be**	**Bi**	**Cd**	**Ce**	**Co**	**Cr**	**Cs**	**Cu**	**Ga**	**Ge**	**Hf**	**Hg**	**Ho**	**In**	**Ir**	**La**	**Li**	**Mn**	**Mo**	**Nb**
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	Det Limit	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F130 – 2804275	429 - 31678	0.06	2.55	19.3	299	1.33	1.28	0.31	28.8	19.5	25.6	0.16	16.6	12.3	6.47	2.57	0.21	0.28	0.04	0.17	17.2	11.2	65.2	3.28	8.58
F140 – 2804276	429 - 31679	0.03	1.77	14.2	383	2.04	1.13	0.23	49.9	30.7	23.3	0.34	22.1	10.9	3.86	2.01	0.16	0.34	0.04	0.17	33.0	15.6	78.6	2.25	6.24
F150 – 2804277	429 - 31680	0.03	1.05	9.66	360	2.50	1.25	0.22	56.3	9.26	24.0	0.33	16.6	7.44	1.54	1.62	0.13	0.35	0.03	0.12	41.4	15.7	101	0.91	4.93
F160 – 2804278	429 - 31681	0.03	1.42	8.01	335	2.24	1.08	0.31	45.9	5.59	22.5	0.49	19.3	6.76	1.31	1.89	0.13	0.27	0.05	0.09	14.5	17.3	117	0.91	5.35
F170 – 2804279	429 - 31682	0.04	2.96	9.20	321	2.51	1.26	0.30	53.1	5.97	28.3	0.94	13.8	7.98	0.95	2.11	0.18	0.48	0.04	0.15	33.6	25.1	206	1.08	7.00
F180 – 2804280	429 - 31683	0.03	1.69	13.9	318	1.84	1.23	0.15	33.4	5.56	29.0	1.24	17.2	9.88	1.26	2.44	0.22	0.38	0.04	0.14	17.8	36.6	290	1.58	8.80
S180 – 2804281	429 - 31684	0.06	18.4	22.9	445	3.38	0.981	0.54	34.0	14.6	112	2.15	25.3	19.0	1.60	4.33	0.76	0.31	0.05	0.18	27.4	82.4	364	6.78	18.1
		F	**S (tot)**	**(Pyretic**	**S (SO$_4^{2-}$**	**(Organic**	**Nd**	**Ni**	**Pb**	**Rb**	**Sb**	**Sc**	**Se**	**Sn**	**Sr**	**Te**	**Th**	**Tl**	**U**	**V**	**W**	**Y**	**Zn**	**Zr**	
		ppm	%	%	%	%	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	
							<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.001	
F130 – 2804275	429 - 31678	370	0.85	0.214	<0.01	0.63																			
F140 – 2804276	429 - 31679	310	0.85	0.249	<0.01	0.60	5.24	28.3	12.0	2.17	0.73	1.75	0.98	3.35	267	0.68	1.98	0.23	3.12	58.1	2.24	14.0	51	167	
F150 – 2804277	429 - 31680	307	0.72	0.211	<0.01	0.51	9.55	26.7	8.53	3.65	0.91	1.53	0.50	2.90	409	0.75	4.33	0.27	2.71	38.0	1.86	17.1	72	122	
F160 – 2804278	429 - 31681	168	0.57	0.127	<0.01	0.44	11.6	21.0	8.35	4.82	0.25	2.79	0.94	3.66	443	0.99	5.64	0.15	2.02	27.1	1.37	19.0	200	82.7	
F170 – 2804279	429 - 31682	309	0.73	0.333	<0.01	0.40	6.10	17.4	9.50	3.56	0.30	3.43	0.94	3.38	387	1.00	4.17	0.07	2.27	23.5	1.16	13.6	106	96.9	
F180 – 2804280	429 - 31683	361	0.86	0.449	<0.01	0.42	11.9	18.2	16.0	5.85	0.18	4.67	0.87	4.35	326	0.70	8.93	0.14	2.53	26.2	1.90	24.7	140	104	
S180 – 2804281	429 - 31684	430	6.21	4.12	0.010	2.07	8.30	18.7	15.6	1.75	0.26	5.70	0.63	6.32	360	0.63	6.95	0.26	2.75	28.5	2.28	16.3	192	120	
							11.3	70.3	29.3	11.8	0.87	9.55	1.39	8.14	262	0.59	8.15	2.28	3.61	58.6	4.04	12.0	213	199	

Table IX: Trace element analysis of washability samples at seven relative density fractions – second sample set



Sample	Sample																					
Origin	ID	Note: all results in parts per million (ppm) unless specified otherwise																				
		As	**B**	**Ba**	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Mn**	**Ni**	**Pb**	**Sb**	**V**	**Zn**	**S(total)**	**S(pyritic)**	**S(sulphate)**	**P (Coal)**	**P (Ash)**	**Y**	**Cl**
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg				%	%	mg/kg	mg/l
792 - 5507	88198/TEV	5.08	47.3	327	0.24	30.3	51.8	18.6	0.27	5.28	41.1	14.2	0.74	79.4	602	0.71	0.16	0.04	0.06	1.55	76.4	600
792 - 5507	88198/TEV	4.88	47.2	336	0.14	19.1	37.9	18.9	0.20	25.1	28.7	10.6	0.43	60.8	488	0.67	0.21	0.03	0.12	1.56	79.9	471
792 - 5507	88198/TEV	2.20	37.9	298	0.18	10.7	38.3	15.7	0.22	53.6	21.4	10.4	0.20	37.2	557	0.50	0.11	0.02	0.15	1.14	87.4	563
792 - 5507	88198/TEV	1.38	44.5	166	0.13	3.93	28.8	10.1	0.14	64.8	14.4	9.80	0.27	27.4	644	0.45	0.10	0.03	0.16	0.749	16.1	671
792 - 5507	88198/TEV	0.95	69.4	158	0.16	2.58	29.1	8.95	0.14	57.0	12.9	10.8	0.19	27.2	595	0.43	0.10	0.04	0.12	0.42	1.84	566
792 - 5507	88198/TEV	2.55	34.8	176	0.23	3.98	36.5	11.0	0.19	88.8	13.5	15.1	0.30	39.1	1137	0.70	0.33	0.04	0.18	0.513	1.71	1265
792 - 5507	88198/TEV	18.8	62.7	291	0.36	14.4	60.5	16.7	0.80	527	37.9	36.4	1.12	67.3	1661	5.65	4.06	0.01	0.15	0.236	8.11	565
		Ag	**Be**	**Bi**	**Ce**	**Cs**	**Ga**	**Ge**	**Hf**	**In**	**Ir**	**La**	**Li**	**Mo**	**Nb**	**Nd**	**Rb**	**Sc**	**Se**	**Sn**	**W**	
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	
792 - 5507	/TEVL2/28	0.02	1.22	0.70	39.8	0.33	20.7	6.69	3.39	0.07	0.17	40.7	3.02	3.24	12.42	5.71	3.27	5.03	0.87	3.47	2.49	
792 - 5507	/TEVL2/28	0.01	0.87	0.64	58.7	0.35	11.75	3.47	2.51	0.05	0.06	64.4	3.88	1.83	7.23	8.29	5.74	5.14	0.72	2.56	1.36	
792 - 5507	/TEVL2/28	0.03	1.84	0.59	71.1	0.49	7.95	1.65	2.12	0.05	0.05	80.7	20.9	1.75	5.21	10.4	5.65	8.36	0.78	2.09	2.69	
792 - 5507	/TEVL2/28	0.04	1.39	0.57	9.85	0.38	4.57	1.00	2.07	0.05	0.11	5.45	29.1	0.61	5.51	1.15	1.55	9.88	0.41	2.23	1.09	
792 - 5507	/TEVL2/28	0.04	0.86	0.62	8.99	0.54	5.35	0.88	2.50	0.04	0.08	0.87	29.4	0.56	7.08	0.20	2.69	10.21	0.42	2.76	1.43	
792 - 5507	/TEVL2/28	0.03	1.87	0.60	7.63	0.54	7.83	1.17	2.80	0.04	0.16	1.07	26.2	0.97	8.66	0.19	3.03	13.60	0.55	4.20	1.76	
792 - 5507	/TEVL2/28	0.02	1.76	0.49	10.1	1.84	20.3	1.63	3.43	0.06	0.14	3.65	80.9	5.92	14.0	0.70	7.75	26.35	1.37	5.11	3.31	

Table X: Proximate, phosphorous and calorific value analysis of washability samples at seven relative density fractions – first sample set

Anglo Coal Central Laboratory			Date: 10/11/2008											
Report on Completed Samples			Time: 17:50:49											
Density	Kg	%	%	%	%	%	%	%	%	%	%	MJ/kg	MJ/kg	%
			Cum		**Cum**		**Cum**		**Cum**		**Cum**		**Cum**	
	Mass	**Yield**	**Yield**	**IM**	**IM**	**VOL**	**VOL**	**ASH**	**ASH**	**FC**	**FC**	**CV**	**CV**	**P**
F @-1.30	3.31	0.962	0.962	2.3	2.3	36.2	36.2	5	5	56.5	56.5	32	32	0.079
1.30-1.40	39.796	11.561	12.522	2.2	2.2	32.1	32.4	7.8	7.6	57.9	57.8	30.13	30.27	0.117
1.40-1.50	117.812	34.224	46.746	2.3	2.3	24.1	26.4	13.6	12	59.9	59.4	28.26	28.8	0.128
1.50-1.60	61.012	17.724	64.47	2.1	2.3	21.2	24.9	20.6	14.4	56.1	58.4	25.35	27.85	0.133
1.60-1.70	34.86	10.127	74.597	2	2.2	21.6	24.5	27.9	16.2	48.4	57.1	21.85	27.04	0.127
1.70-1.80	16.2	4.706	79.303	2	2.2	19.6	24.2	35.7	17.4	42.7	56.2	19.25	26.58	0.306
S @-1.80	71.246	20.697	100	0.9	1.9	16.9	22.7	70	28.2	12.2	47.1	6.14	22.35	0.313

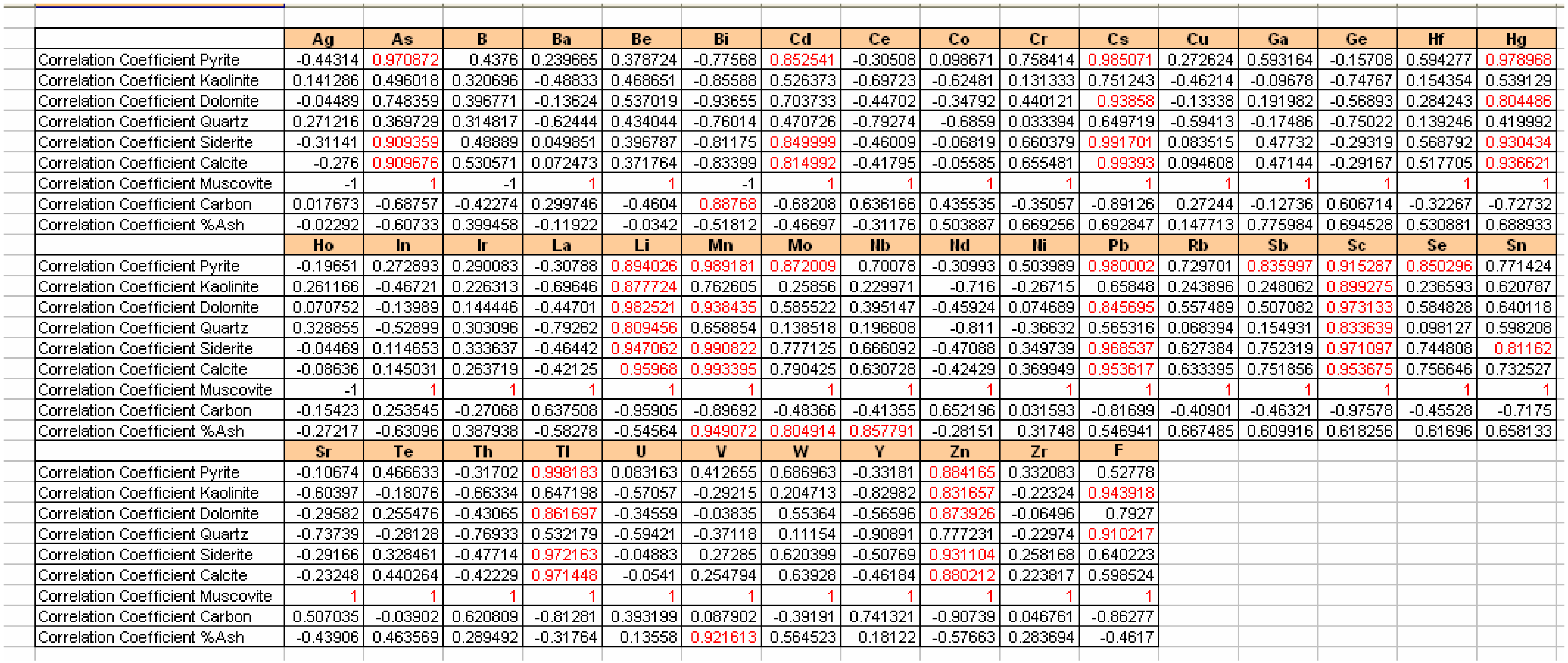
Table XI: Proximate, phosphorous and calorific value analysis of washability samples at seven relative density fractions – second sample set

Anglo Coal Central Laboratory			Date: 29/01/2009											
Report on Completed Samples			Time: 13:44:35											
	Kg	%	%	%	%	%	%	%	%	%	%	MJ/kg	MJ/kg	%
			Cum		**Cum**		**Cum**		**Cum**		**Cum**		**Cum**	
Density	**Mass**	**Yield**	**Yield**	**IM**	**IM**	**VOL**	**VOL**	**ASH**	**ASH**	**FC**	**FC**	**CV**	**CV**	**P**
F @-1.30	0.926	0.668	0.668	2.9	2.9	36.6	36.6	3.9	3.9	56.5	56.5	32.17	32.17	1.55
1.30-1.40	25.136	18.137	18.805	3.1	3.1	29.9	30.2	8.1	7.9	58.9	58.8	30.4	30.47	1.56
1.40-1.50	54.228	39.128	57.933	2.9	3	24.8	26.5	12.9	11.3	59.4	59.2	28.16	28.91	1.14
1.50-1.60	21.276	15.352	73.284	3	3	20.1	25.2	21.7	13.5	55.1	58.4	24.61	28.01	0.749
1.60-1.70	14.054	10.141	83.425	2.6	2.9	18.5	24.4	28.6	15.3	50.3	57.4	21.75	27.25	0.42
1.70-1.80	7.042	5.081	88.506	2.5	2.9	18.3	24	34.7	16.4	44.5	56.6	19.69	26.81	0.513
S @-1.80	15.93	11.494	100	1.5	2.8	18.8	23.4	62.2	21.7	17.5	52.1	8.5	24.71	0.236

Table XII: Correlation between mineral species and trace elements – first sample set.

	Ag	As	B	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Ga	Ge	Hf	Hg
Correlation Coefficient Pyrite	0.692019	0.993849	0.785524	0.804397	0.706908	-0.71691	0.859433	-0.4368	0.140673	0.994238	0.83255	0.74884	0.928048	-0.09689	0.960585	0.995068
Correlation Coefficient Kaolinite	-0.01571	0.536763	0.072082	0.331981	0.636263	-0.42025	0.31363	-0.14163	-0.6087	0.575069	0.883533	0.192026	0.26998	-0.7907	0.510638	0.552189
Correlation Coefficient Dolomite	0.143003	0.519637	0.025607	0.271861	0.671037	-0.2217	0.4485	0.109866	-0.43326	0.51157	0.729749	-0.01579	0.240308	-0.62593	0.436968	0.487823
Correlation Coefficient Quartz	0.165257	0.703536	0.252854	0.463701	0.707784	-0.54942	0.498311	-0.25687	-0.51979	0.736731	0.949219	0.347997	0.451304	-0.69347	0.675647	0.716851
Correlation Coefficient Siderite	0.289568	0.675802	0.503348	0.437161	0.46762	-0.46726	0.350522	-0.53226	-0.2927	0.721485	0.920857	0.440906	0.607915	-0.43479	0.749524	0.738938
Correlation Coefficient Calcite	0.588613	0.977548	0.661341	0.755415	0.784021	-0.6737	0.814574	-0.35389	-0.03711	0.982563	0.935028	0.634176	0.842454	-0.29887	0.932985	0.976482
Correlation Coefficient Hydroxyappetite	-0.18339	-0.35524	-0.06914	0.134557	-0.2411	0.210454	-0.36771	0.425053	0.705756	-0.35838	-0.60632	0.089082	-0.14522	0.438126	-0.43262	-0.37358
Correlation Coefficient Carbon	-0.19686	-0.72298	-0.28584	-0.48387	-0.71696	0.528611	-0.50198	0.248115	0.468806	-0.75337	-0.9678	-0.34876	-0.48648	0.673801	-0.6967	-0.73698
Correlation Coefficient %Ash	0.375262	0.678927	0.736196	0.463402	0.811515	-0.66681	-0.69611	-0.30171	-0.09033	0.045266	0.871145	0.496098	0.731192	0.234954	0.015108	0.977472
	Ho	**In**	**Ir**	**La**	**Li**	**Mn**	**Mo**	**Nb**	**Nd**	**Ni**	**Pb**	**Rb**	**Sb**	**Sc**	**Se**	**Sn**
Correlation Coefficient Pyrite	-0.20306	0.509376	0.531388	0.017502	0.936013	0.717423	0.948738	0.96788	0.316832	0.986922	0.911849	0.875688	0.567595	0.824509	0.741254	0.814052
Correlation Coefficient Kaolinite	0.359159	0.718388	-0.09085	-0.10574	0.764437	0.931107	0.265849	0.550903	0.411328	0.355378	0.726575	0.523084	-0.2951	0.894753	0.328146	0.837847
Correlation Coefficient Dolomite	0.659504	0.423178	0.157086	0.206856	0.611158	0.729826	0.248503	0.469512	0.625146	0.332934	0.69759	0.647012	-0.22819	0.72485	0.366157	0.600374
Correlation Coefficient Quartz	0.19832	0.764008	0.007081	-0.13736	0.878409	0.960951	0.461414	0.708473	0.376528	0.546032	0.839781	0.65357	-0.12803	0.967639	0.502968	0.912465
Correlation Coefficient Siderite	0.063711	0.719989	0.23148	-0.24887	0.876275	0.953932	0.572416	0.780123	0.218838	0.588351	0.820139	0.477969	0.083559	0.903656	0.344005	0.96374
Correlation Coefficient Calcite	0.015779	0.578553	0.464959	0.052241	0.981156	0.84911	0.856935	0.95182	0.441786	0.915277	0.970649	0.90192	0.386137	0.926375	0.704362	0.89227
Correlation Coefficient Hydroxyappetite	-0.12148	-0.78956	0.201079	0.571813	-0.48665	-0.66234	-0.1831	-0.42459	0.128252	-0.16926	-0.58761	-0.24625	0.360904	-0.66066	-0.43339	-0.58377
Correlation Coefficient Carbon	-0.26108	-0.73403	-0.09042	0.083412	-0.89458	-0.97702	-0.48771	-0.73186	-0.43196	-0.56832	-0.86612	-0.67722	0.090037	-0.97406	-0.48105	-0.92494
Correlation Coefficient %Ash	-0.16094	-0.21963	-0.08524	0.195572	-0.01852	0.911661	0.551842	0.946341	0.213991	0.277768	0.84569	0.807012	0.329197	0.059906	0.625334	0.536817
	Sr	**Te**	**Th**	**Tl**	**U**	**V**	**W**	**Y**	**Zn**	**Zr**	**F**					
Correlation Coefficient Pyrite	-0.61522	-0.53925	0.398396	0.998678	0.809922	0.691147	0.936229	-0.49984	0.457257	0.822051	0.655187					
Correlation Coefficient Kaolinite	-0.24466	-0.35419	0.846382	0.519444	0.253914	-0.15671	0.49471	0.008888	0.755966	0.15248	0.212235					
Correlation Coefficient Dolomite	-0.39002	-0.42726	0.913152	0.445147	0.263753	-0.07043	0.456764	0.407017	0.501009	0.156486	0.244025					
Correlation Coefficient Quartz	-0.37277	-0.39844	0.783986	0.688482	0.40984	0.041909	0.64059	-0.16484	0.75312	0.3373	0.312219					
Correlation Coefficient Siderite	-0.41693	-0.6052	0.599667	0.705161	0.58512	0.241325	0.758569	-0.35112	0.694145	0.507623	0.55911					
Correlation Coefficient Calcite	-0.60084	-0.57761	0.61327	0.967613	0.746083	0.531619	0.920165	-0.32373	0.574921	0.720494	0.624479					
Correlation Coefficient Hydroxyappetite	0.561321	0.314055	-0.46584	-0.2879	-0.29687	0.024393	-0.33662	0.114713	-0.31051	-0.2396	-0.0258					
Correlation Coefficient Carbon	0.396875	0.465885	-0.82164	-0.70717	-0.44803	-0.07188	-0.67959	0.114882	-0.74833	-0.36492	-0.3742					
Correlation Coefficient %Ash	-0.51976	0.740521	-0.34543	0.418455	0.786334	0.882405	0.758286	-0.41431	0.059274	-0.00048	0.745442					

Table XIII: Correlation between mineral species and trace elements – second sample set.



	Ag	As	B	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Ga	Ge	Hf	Hg
Correlation Coefficient Pyrite	-0.44314	0.970872	0.4376	0.239665	0.378724	-0.77568	0.852541	-0.30508	0.098671	0.758414	0.985071	0.272624	0.593164	-0.15708	0.594277	0.978968
Correlation Coefficient Kaolinite	0.141286	0.496018	0.320696	-0.48833	0.468651	-0.85588	0.526373	-0.69723	-0.62481	0.131333	0.751243	-0.46214	-0.09678	-0.74767	0.154354	0.539129
Correlation Coefficient Dolomite	-0.04489	0.748359	0.396771	-0.13624	0.537019	-0.93655	0.703733	-0.44702	-0.34792	0.440121	0.93858	-0.13338	0.191982	-0.56893	0.284243	0.804486
Correlation Coefficient Quartz	0.271216	0.369729	0.314817	-0.62444	0.434044	-0.76014	0.470726	-0.79274	-0.6859	0.033394	0.649719	-0.59413	-0.17486	-0.75022	0.139246	0.419992
Correlation Coefficient Siderite	-0.31141	0.909359	0.48889	0.049851	0.396787	-0.81175	0.849999	-0.46009	-0.06819	0.660379	0.991701	0.083515	0.47732	-0.29319	0.568792	0.930434
Correlation Coefficient Calcite	-0.276	0.909676	0.530571	0.072473	0.371764	-0.83399	0.814992	-0.41795	-0.05585	0.655481	0.99393	0.094608	0.47144	-0.29167	0.517705	0.936621
Correlation Coefficient Muscovite	-1	1	-1	1	1	-1	1	1	1	1	1	1	1	1	1	1
Correlation Coefficient Carbon	0.017673	-0.68757	-0.42274	0.299746	-0.4604	0.88768	-0.68208	0.636166	0.435535	-0.35057	-0.89126	0.27244	-0.12736	0.606714	-0.32267	-0.72732
Correlation Coefficient %Ash	-0.02292	-0.60733	0.399458	-0.11922	-0.0342	-0.51812	-0.46697	-0.31176	0.503887	0.669256	0.692847	0.147713	0.775984	0.694528	0.530881	0.688933

	Ho	In	Ir	La	Li	Mn	Mo	Nb	Nd	Ni	Pb	Rb	Sb	Sc	Se	Sn
Correlation Coefficient Pyrite	-0.19651	0.272893	0.290083	-0.30788	0.894026	0.989181	0.872009	0.70078	-0.30993	0.503989	0.980002	0.729701	0.835997	0.915287	0.850296	0.771424
Correlation Coefficient Kaolinite	0.261166	-0.46721	0.226313	-0.69646	0.877724	0.762605	0.25856	0.229971	-0.716	-0.26715	0.65848	0.243896	0.248062	0.899275	0.236593	0.620787
Correlation Coefficient Dolomite	0.070752	-0.13989	0.144446	-0.44701	0.982521	0.938435	0.585522	0.395147	-0.45924	0.074689	0.845695	0.557489	0.507082	0.973133	0.584828	0.640118
Correlation Coefficient Quartz	0.328855	-0.52899	0.303096	-0.79262	0.809456	0.658854	0.138518	0.196608	-0.811	-0.36632	0.565316	0.068394	0.154931	0.833639	0.098127	0.598208
Correlation Coefficient Siderite	-0.04469	0.114653	0.333637	-0.46442	0.947062	0.990822	0.777125	0.666092	-0.47088	0.349739	0.968537	0.627384	0.752319	0.971097	0.744808	0.81162
Correlation Coefficient Calcite	-0.08636	0.145031	0.263719	-0.42125	0.95968	0.993395	0.790425	0.630728	-0.42429	0.369949	0.953617	0.633395	0.751856	0.953675	0.756646	0.732527
Correlation Coefficient Muscovite	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Correlation Coefficient Carbon	-0.15423	0.253545	-0.27068	0.637508	-0.95905	-0.89692	-0.48366	-0.41355	0.652196	0.031593	-0.81699	-0.40901	-0.46321	-0.97578	-0.45528	-0.7175
Correlation Coefficient %Ash	-0.27217	-0.63096	0.387938	-0.58278	-0.54564	0.949072	0.804914	0.857791	-0.28151	0.31748	0.546941	0.667485	0.609916	0.618256	0.61696	0.658133

	Sr	Te	Th	Tl	U	V	W	Y	Zn	Zr	F
Correlation Coefficient Pyrite	-0.10674	0.466633	-0.31702	0.998183	0.083163	0.412655	0.686963	-0.33181	0.884165	0.332083	0.52778
Correlation Coefficient Kaolinite	-0.60397	-0.18076	-0.66334	0.647198	-0.57057	-0.29215	0.204713	-0.82982	0.831657	-0.22324	0.943918
Correlation Coefficient Dolomite	-0.29582	0.255476	-0.43065	0.861697	-0.34559	-0.03835	0.55364	-0.56596	0.873926	-0.06496	0.7927
Correlation Coefficient Quartz	-0.73739	-0.28128	-0.76933	0.532179	-0.59421	-0.37118	0.11154	-0.90891	0.777231	-0.22974	0.910217
Correlation Coefficient Siderite	-0.29166	0.328461	-0.47714	0.972163	-0.04883	0.27285	0.620399	-0.50769	0.931104	0.258168	0.640223
Correlation Coefficient Calcite	-0.23248	0.440264	-0.42229	0.971448	-0.0541	0.254794	0.63928	-0.46184	0.880212	0.223817	0.598524
Correlation Coefficient Muscovite	1	1	1	1	1	1	1	1	1	1	1
Correlation Coefficient Carbon	0.507035	-0.03902	0.620809	-0.81281	0.393199	0.087902	-0.39191	0.741321	-0.90739	0.046761	-0.86277
Correlation Coefficient %Ash	-0.43906	0.463569	0.289492	-0.31764	0.13558	0.921613	0.564523	0.18122	-0.57663	0.283694	-0.4617