CHAPTER FOUR – RESULTS

4.1 Introduction

Section 4 presents the results of the data generated from various sources, both from the research work of the author and from external sources. The origin and nature of the results will be discussed.

The test work and analyses were conducted in detail on the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca coals (as per Figure 63). The Free State Coalfield was not evaluated to the same degree as this is a coal of much poorer quality and unlikely to serve as an export source. It was included for comparative purposes. The Waterberg Upper Ecca and Witbank No. 4 Seam borehole data which included proximate analyses from the float-sink fractions were received from the mine geological services laboratory (Dr. Dorlant and Mr. Kevin McMillan). See Appendix E for the detailed size washability data.

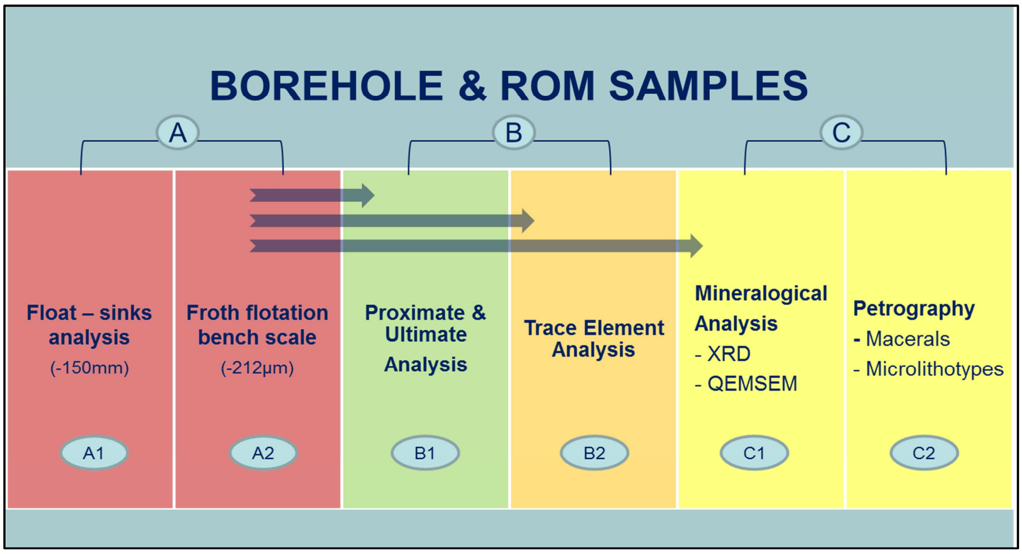

Figure 63: *Summary of samples, test work and analyses. A = Beneficiation test work, B1 = General analyses, B2 - C = Advanced additional analyses to identify maceral and mineral components in coal*

Portions of the same borehole samples were then utilised to generate the ultimate analysis, QEMSEM and petrographic analyses. The ROM, dense medium and froth flotation samples were taken through plant sampling schemes. The Free State ROM washability data results were provided by the mine at source. The Free State sample served to compare the characterisation of a high ash content Free State coal with that of the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca coal. The Free State ROM coal trace element analysis results, as seen in Table 13, were provided by Mr. Donovan Pretorius.

The particle size distribution analysis results in Figures 64 and 65 were generated by the author. This included size analysis (wet screening) of the ROM sample in the case of the Witbank Coalfield No. 4 Seam and size analysis (wet screening) of the Waterberg Upper Ecca large diameter borehole sample. The PSD (Particle Size Distribution) data is significant as it determines the process beneficiation route as will be discussed further in Section 8.1.

The raw composite (ROM) quality characteristics are given in Table 12. The full data sets are given in Section E in the Appendix, Tables X, XI, XII, and XIII.

Table 12: *Summary of Raw Coal Characteristics. * The petrographic data of Vereeniging ROM used is from Engelbrecht et al. (2008).*

		Witbank Coalfield No. 4 Seam (Combination of Borehole and ROM Data)	**Waterberg Upper Ecca (Combination of Large Diameter Borehole Data)**	**Free State (Vereeniging) (ROM Data)**
Rank Classification		Bituminous, Medium Rank C	Bituminous, Medium Rank C	Bituminous, Low Rank D
Inherent Moisture	%	2.8	2.2	5.6
Volatile Content	% (adb)	22.7	20.0	21.4
Ash	% (adb)	28.2	47.6	38.9
FC	% (adb)	46.3	15.0	34.1
CV	% (adb)	22.35	14.03	14.92
Carbon	% (daf)	81.5	87.8	76.7
Hydrogen	% (daf)	4.7	3.6	4.9
Nitrogen	% (daf)	1.9	4.4	1.9
Oxygen	% (daf)	10.4	3.7	11.5
Sulphur	% (adb)	1.5	1.2	0.53
Liptinite	(mmfb %)	5	6	3*
Vitrinite	(mmfb %)	25	44	23*
Inertinite content	(mmfb %)	70	50	74*
Vitrinite reflectance	%	0.75	0.63	0.53*
Sulphur Pyritic	% (adb)	1.0	1.1	-
Sulphur Organic	% (adb)	0.8	0.3	-
Sulphur Sulphatic	% (adb)	<0.010	0.014	-

The Witbank Coalfield No. 4 seam is of higher quality (lower percentage ash and higher calorific value) than the Waterberg Upper Ecca and Free State Coalfield (both of which have higher ash and lower calorific value). The Witbank Coalfield No. 4 and Waterberg Upper Ecca are classified as Medium Rank C Bituminous coals whereas the Free State coal is Low Rank D Bituminous coal.

The following section lists the four main categories of results:

1. Liberation Functions
    (a) QEMSCAN Analysis - Liberation was calculated in terms of the area percentage of mineral or maceral present in a particle through the identification of mineral and maceral proportions.
    (b) XRD Analysis – The XRD analysis revealed qualitative and quantitative information on the mineral matter composition. XRD analysis was done on each of the washability and froth flotation floatability fractions. The data from each of the washability density fractions were analysed to produce a liberation curve through curve fitting. The statistically optimum equation determined from the curve fitting can also be referred to as the liberation function.
    (c) Petrographic Analysis – The petrographic analysis revealed the liberation potential of the minerals and macerals. Petrographic analysis was also done on each of the washability density fractions to develop liberation functions, see Section 6.

2. The process modelling of various grade products (RB1, low grade thermal export and domestic thermal grade products).
    (a) Yield – The process modelling was used to determine the theoretical yields that could be expected by processing the respective coals to produce various product grades. The yield or expected recovery in turn influences the expected revenue and was therefore used to determine the financial impact.
    (b) Economics – A cost-benefit analysis was done on all the permutations namely various grade products and or using different processing equipment.

(c) Environmental risks – The environmental risks associated with the respective processing routes were also evaluated and expanded on.

3. Coal beneficiation involving the production of multiple products through real time online stream quality analysis and real time financial and marketing models.
   (a) As received quality optimisation - The associated moisture content of the coal produced influences the ‘as received’ calorific value of the coal. Different processing routes could result in different product surface moistures. The production of different products could entail optimisation of processing streams to produce an optimal ‘As received’ quality product.
   (b) Optimal roadmap for the South African coal industry – The processing and financial models produced are used to indicate which of the various combinations of product and processing route would produce the optimal financial and triple bottom line economic and sustainability benefit.

4. Advanced cleaning for strict environmental compliance.
   (a) Trace element removal – The distribution and partitioning of minerals, macerals and trace elements in various grades of washed products through the analysis of bulk samples was established. To aid in the analysis, statistical methods to enable multi-variable correlation and multi-optimisation between various grade coal product constituents were developed.
   (b) Total Carbon footprint reduction – Based upon the energy recovery concept, the environmental impact in relation to energy production has been calculated.

4.1.1 Sizing of Witbank No. 4 Seam

A typical sizing from ROM samples of Witbank Coalfield No. 4 seam is shown in Figure 64. In general, the Particle Size Distribution (PSD) of Witbank Coalfield No. 4

seam, 50 % of the particles by mass passes 7mm. In conjunction, 90 % of the particles reside in the 12 x 0.5 mm fraction, whereas the remainder, -0.5mm particles, accounts for approximately 10 % of the ROM Feed.

Figure 64: *Typical ROM Coal PSD of the Witbank Coalfield No. 4 Seam.*

4.1.2 Sizing of Waterberg Upper Ecca

A typical sizing from large borehole diameter samples of the Waterberg Upper Ecca Coalfield is given in Figure 65. In general, the PSD of Waterberg Upper Ecca Coalfield will yield 50 % of the particles by mass passing 16 mm. Although the large borehole diameter samples only indicated 1 % passing 0.5 mm it is anticipated that actual segregation during mining would increase the percentage minus 0.5 mm particles to more than 0.5 %.

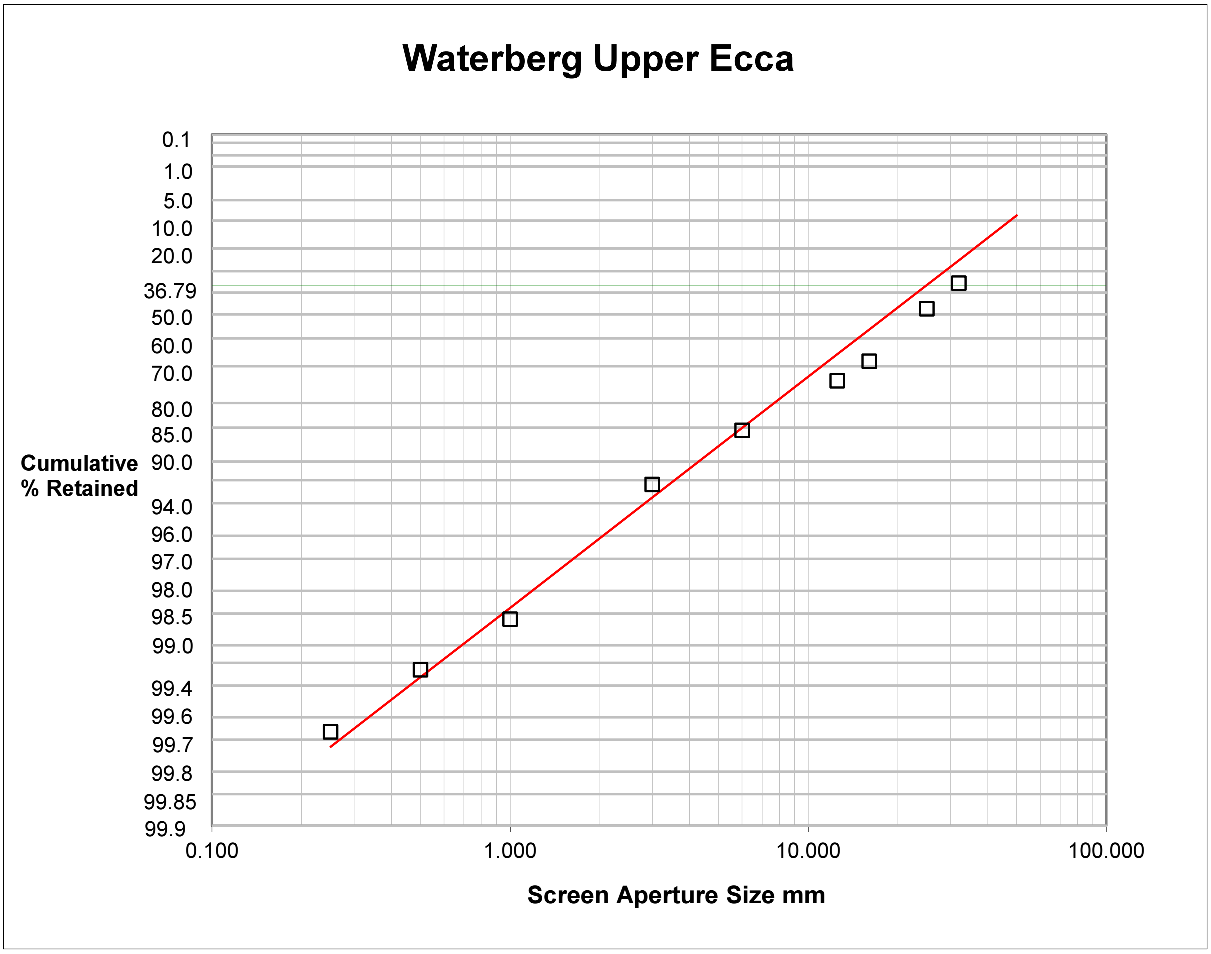

Figure 65: *Typical ROM Coal PSD of the Waterberg Upper Ecca.*

4.2 Composite trace elements sample

The feed composite or ROM samples 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 indicate a relatively good repeatability of the same order. There were, however, trace elements which had concentrations that were quite variable between tests of samples from the same origin, especially thorium. More importantly, the distribution trends of the trace elements during the washability tests were maintained for the majority of trace elements. The trace element results provided by Mr. Pretorius was done only on composite ROM samples.

Table 13: *Comparison of Trace Element content in raw composite coals from South Africa. * Mr. Donovan Pretorius*

				Witbank	Highveld	Witbank	Waterberg	Waterberg	Free State (Vereeniging)
				Coalfield	Coalfield	Coalfield	Coalfield	Grootegeluk Formation	
		Global Average	Global Average	2 Seam	4 Seam	4 Seam	Upper Ecca		
		Swaine et al., (1990)	Zhang et al., (2004)	Cairncross *et al.*, (1990)	Wagner *et al.*, (2004)	Bergh *et al.*, (2008)	Bergh *et al.*, (2011)	(Faure *et al.*, 1996b)	Pretorius, 2012*
Major concern									
Arsenic	mg/kg	0.5–80	5	4.6	3.14	4.7	11.3	6	3.3
Cadmium	mg/kg	0.1–3	0.6		0.44	0.3	0.2		0.1
Lead	mg/kg	2–80	25	10	7.51	15.03	76.8	89	24.1
Mercury	mg/kg	0.02–1	0.12		0.2	0.3	0.4		0.26
Molybdenum	mg/kg	0.1–10	5		1.18	2.1	3.6	2	2.2
Selenium	mg/kg	0.2–10	3	0.9	1.05	1.2	1.3	2	0.7
Moderate concern									
Chromium	mg/kg	0.5–60	10	28	70.5	41.4	10.7	64	106
Copper	mg/kg	0.5–50	15	9.7	13.2	16.8	138.3	27	10.4
Nickel	mg/kg	0.5–50	15	17	21.1	27.2	25.3	12	30.3
Vanadium	mg/kg	2–100	25	27	33.5	39.2	96.2	85	52.5
Minor concern									
Antimony	mg/kg	0.05–10	3	0.47	0.32	0.5	1.0		0.5
Cobalt	mg/kg	0.5–30	5	7.9	6.3	11	25	6	5.2
Manganese	mg/kg	5–300	50		19.6	135	192	89	84
Radio Active									
Uranium	mg/kg	0.02 – 5.5	3.1	4		2.6	4.9	12	4.3
Thorium	mg/kg	0.1 – 12.2	1.9	15		8.9	7.1	38	13.9

4.3 Distribution of trace elements at different densities

The partitioning of various trace elements are shown in both Figures 66 and 67 and Tables 14 and 15. Two trace elements (Hg and As) categorised under the HAP category will be discussed.

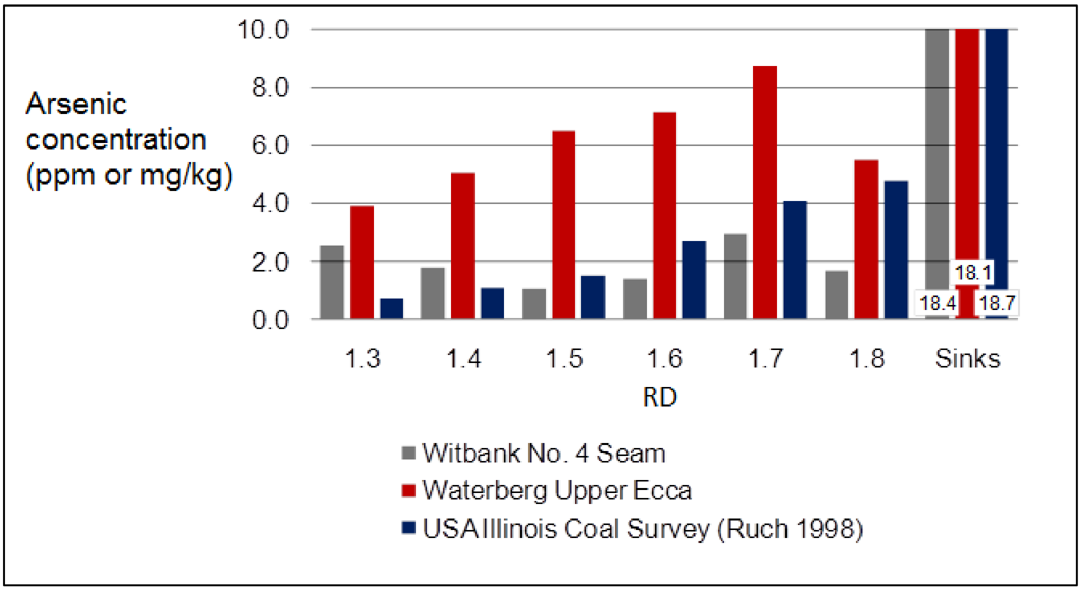

Figure 66: *Partitioning of arsenic content comparison*

It is shown in Figure 66 and 67 that the distribution of the trace elements from different coalfields, in this case Hg and As, differ considerably in terms of distribution at various density fractions. In Figures 66 and 67 the distribution of an Illinois Coal (Ruch, 1998) is illustrated. The distribution trends of the Waterberg Upper Ecca and Illinois Coal are similar, the Witbank Coalfield No. 4 Seam however has a unique trend where the concentration Hg and As decreases from RD 1.30 to RD 1.50.

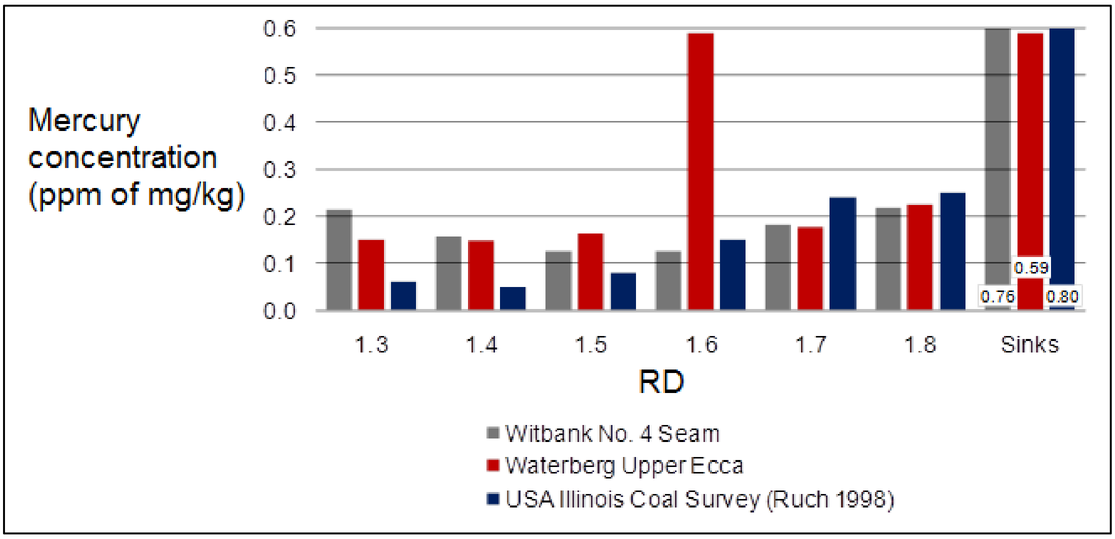

Figure 67: *Partitioning of Mercury content comparison*

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 3.

Equation 3: Trace element reduction equation

$$\%\,\mathrm{Reduction} = \frac{x_{\mathrm{Feed}} - x_{\mathrm{Product}}}{x_{\mathrm{Feed}}} \times 100\% \qquad (3)$$

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

The percentage maximum reduction potential of some of the trace elements at the optimum cut point densities are illustrated in Figure 68 and at the different densities in Table 14 & 15.

From the results it is clear that the trace elements of major concern tend to concentrate in finely disseminated minerals (especially pyrite and kaolinite) as will be described in more detail in Chapter 5. Such minerals are trapped in the lower densities or cleaner fractions of coal. These results and observations concur with findings made by Capes *et al.* (1996) through similar research on the distribution of certain elements in American coals.

Table 14: A *summary of historical and current results for feed (composite) and washed samples for Witbank Coalfield No. 4 Seam.*

		Global Average Swaine, (1990)	Global Average Zhang et al., (2004)	Highveld Coalfield 4 Seam Wagner et al., (2004)	Average Product Float Concentrations Witbank Coalfield 4 Seam								Steam Coal Product Export Data	Steam Coal Product Dale (2003)
					Feed	1.30	1.40	1.50	1.60	1.70	1.80	Sinks +1.8RD		
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	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	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	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	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	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	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	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	0.32	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	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		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		8.9	5.4	9.9	11.2	9.9	9.4	9.2	8.15	8.6	6.8

Table 15: A *summary of historical and current results for feed (composite) and washed samples for Waterberg Upper Ecca.*

		Global Average Swaine, (1990)	Global Average Zhang et al., (2004)	Highveld 4 Seam Wagner et al., (2004)	Average Product Float Concentrations Waterberg Upper Ecca Seams								Steam Coal Product Export Data	Steam Coal Product Dale (2003)
					Feed	1.30	1.40	1.50	1.60	1.70	1.80	Sinks +1.8RD		
Ash	%				47.6	13.2	14.1	19.0	24.1	31.9	35.1	47.6	15.2	
Major concern														
Arsenic	mg/kg	0.5–80	5	3.14	11.29	3.9	4.3	5.7	6.7	7.6	7.3	11.3	3.4	8.7
Cadmium	mg/kg	0.1–3	0.6	0.44	0.25	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.1	0.1
Lead	mg/kg	2–80	25	7.51	76.80	20.4	20.4	16.7	16.1	47.9	51.0	60.5	17.7	2.9
Mercury	mg/kg	0.02–1	0.12	0.2	0.37	0.2	0.2	0.2	0.4	0.4	0.3	0.4	0.1	0.1
Molybdenum	mg/kg	0.1–10	5	1.18	3.57	5.4	5.2	4.2	4.8	4.5	4.5	4.1	11.2	6.9
Selenium	mg/kg	0.2–10	3	1.05	1.27	0.6	0.6	0.8	1.6	1.6	1.6	1.5	2.2	1
Moderate														
Chromium	mg/kg	0.5–60	10	70.5	10.7	9.9	10.6	11.5	14.7	14.3	14.1	12.8	30.1	29
Copper	mg/kg	0.5–50	15	13.2	138.3	29.3	27.7	20.0	17.6	58.0	68.6	94.4	12.8	10
Nickel	mg/kg	0.5–50	15	21.1	25.3	16.6	17.3	24.9	24.9	25.0	25.0	25.1	58.3	18
Vanadium	mg/kg	2–100	25	33.5	96.2	125.8	121.4	104.6	122.1	116.7	115.5	108.3	14.8	18
Zinc					305	196.4	213.2	298.3	312.9	322.1	321.2	315.2		
Minor concern														
Antimony	mg/kg	0.05–10	3	0.32	1.04	1.7	1.6	1.3	1.4	1.4	1.3	1.2	0.5	0.8
Cobalt	mg/kg	0.5–30	5	6.3	24.5	18.4	18.3	18.8	22.9	23.2	23.2	23.7	9.3	8
Manganese	mg/kg	5–300	50	19.6	191.9	89.8	97.0	157.3	220.0	232.0	236.5	220.0	33.1	300
Radio Active														
Uranium	mg/kg	0.02 – 5.5	3.1		4.65	3.3	3.3	3.6	4.7	4.7	4.7	4.7	3.0	21
Thorium	mg/kg	0.1 – 12.2	1.9		9.31	2.3	2.5	5.1	11.5	10.9	10.6	9.3	8.6	6.8

The reduction potential of the various trace elements in the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca respectively, is given in Figure 68 & 69. It can be seen that in the case of the Witbank Coalfield No. 4 Seam Mn, Zn, As and Th can be easily reduced. For the Witbank Coalfield No. 4 Seam the cut point densities or RDs where optimal trace element reduction can take place can be deduced from Table 14. It should be noted that optimal cut point densities vary due to the difference in liberation of the associated mineral matter.

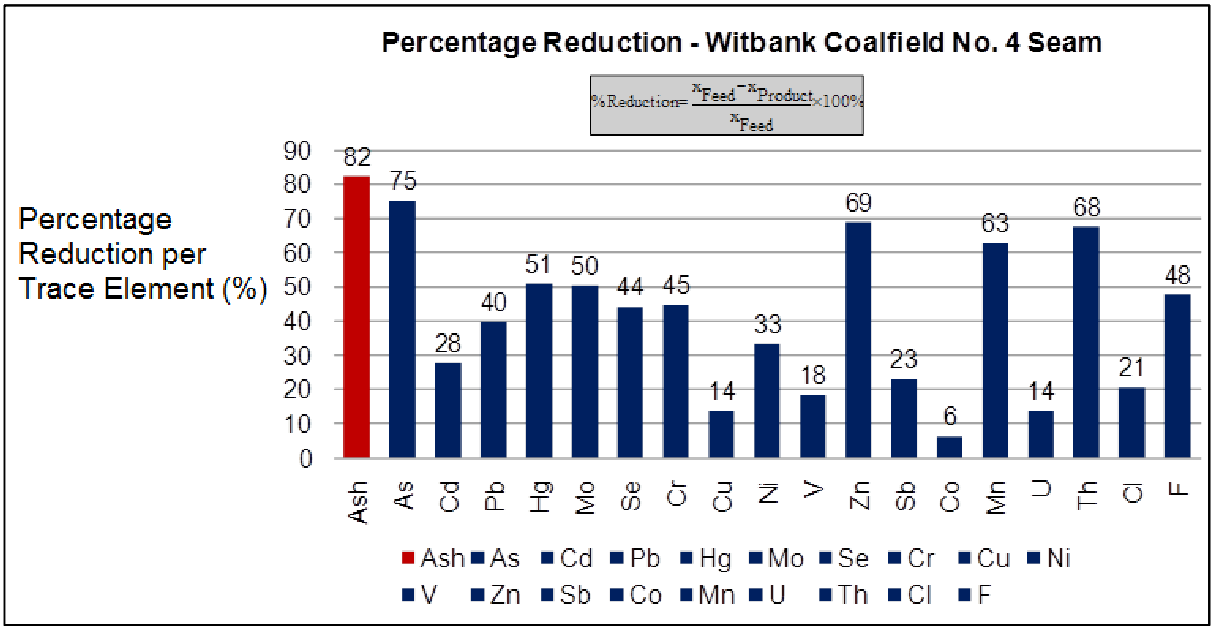

Figure 68: *Reduction potential of various trace elements though beneficiation - Witbank Coalfield No. 4 Seam*

In the case of the Waterberg Upper Ecca, the reduction potential of most trace elements compared to the Witbank Coalfield No. 4 Seam is lower; this could be due to the higher percentage ash in the feed and in the Waterberg Upper Ecca product coals generally. The cut point densities or RDs where optimal trace element reduction can take place can be deduced from Table 15 in the case of the Waterberg Upper Ecca.

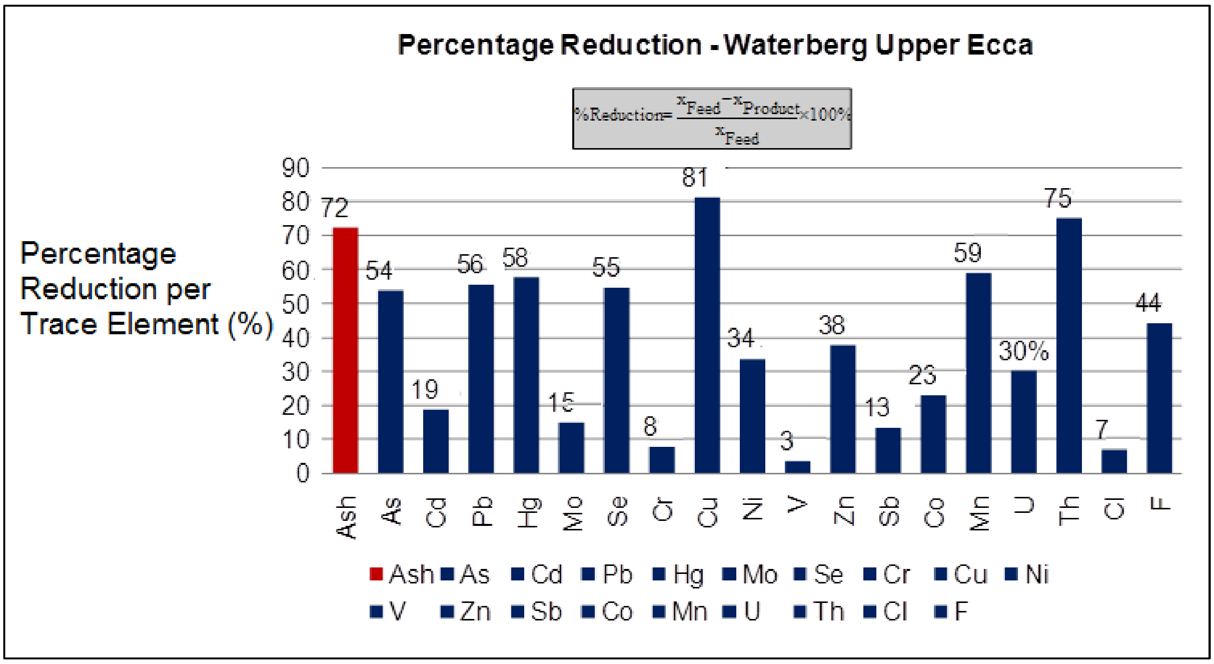

Figure 69: *Reduction potential of various trace elements - Waterberg Upper Ecca*

4.5 Washability analysis – dense medium beneficiation

The basic washability curves of the composite ROM samples are given below.

Witbank Coalfield No. 4 Seam

The Witbank Coalfield No. 4 Seam has a low ash content profile per density fraction compared to the Waterberg Upper Ecca and Free State coals. The Witbank Coalfield No. 4 Seam has the potential for high grade export, low grade export and a domestic power station middling product. The washability curve is given in Figure 70.

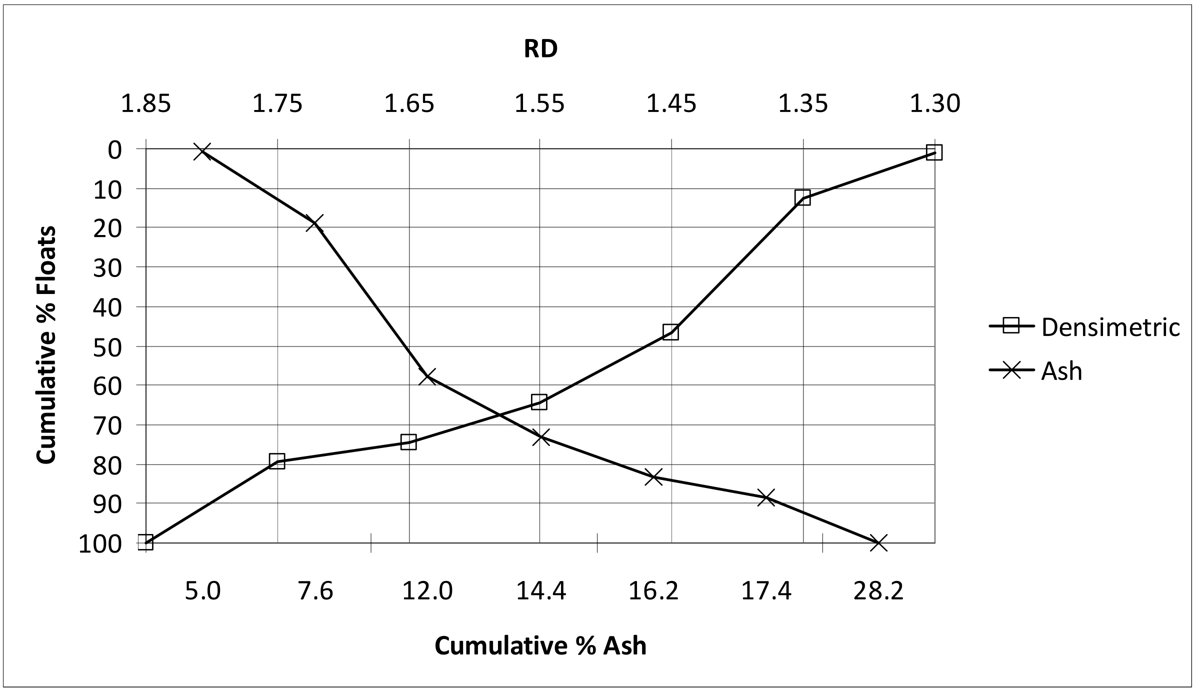

Figure 70: *Composite washability of Witbank Coalfield No. 4 Seam*

Waterberg Upper Ecca

The Waterberg Upper Ecca coal has a high ash content profile per density fraction (see Figure 71) and has the potential for low grade export and domestic power station product use only.

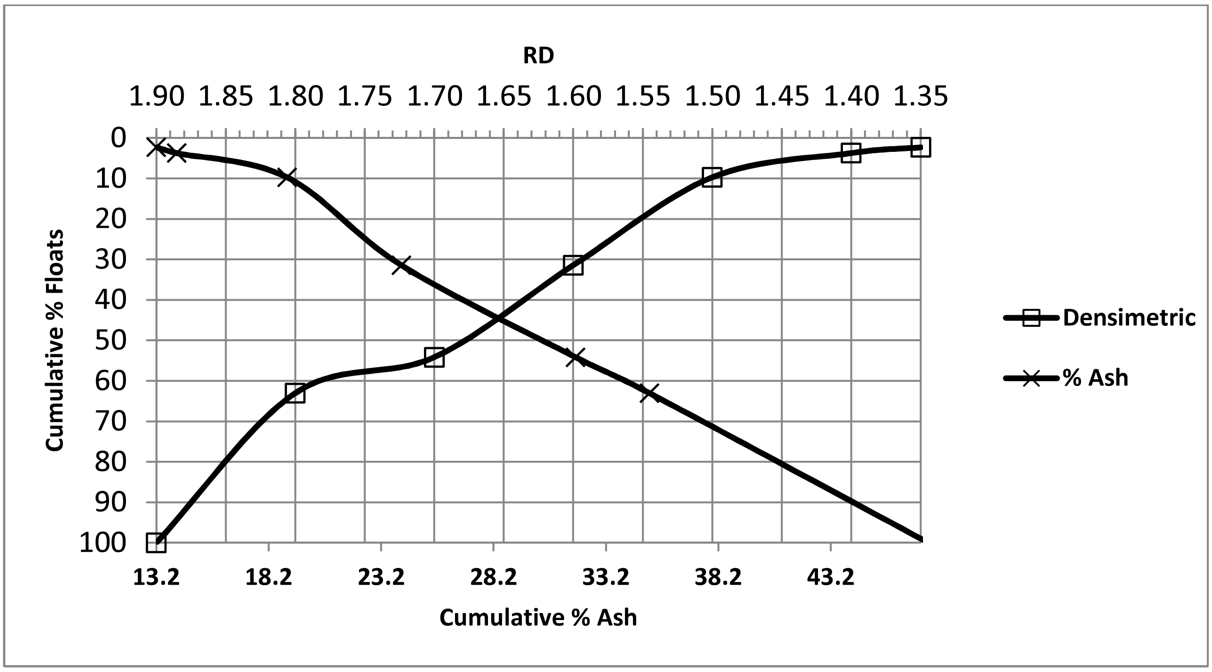

Figure 71: *Composite washability of Waterberg Upper Ecca*

Vereeniging (Free State)

The Free State coal (top, middle and bottom seam) has the highest ash content and profile per density fraction. The seams were mined in the following proportions Top seam (50 %), Middle seam (30 %) and Bottom seam (20 %). The Free State coal is only suitable for domestic power station use. The Free State coal will be used to illustrate the potential of utilising a high ash content product for sustainable value. The top seam is not considered to be upgradeable through coal beneficiation and the bottom seam is conventionally beneficiated to remove the parting minerals. The Free State ROM coal cannot be beneficiated to produce an export quality coal (see Figure 72).

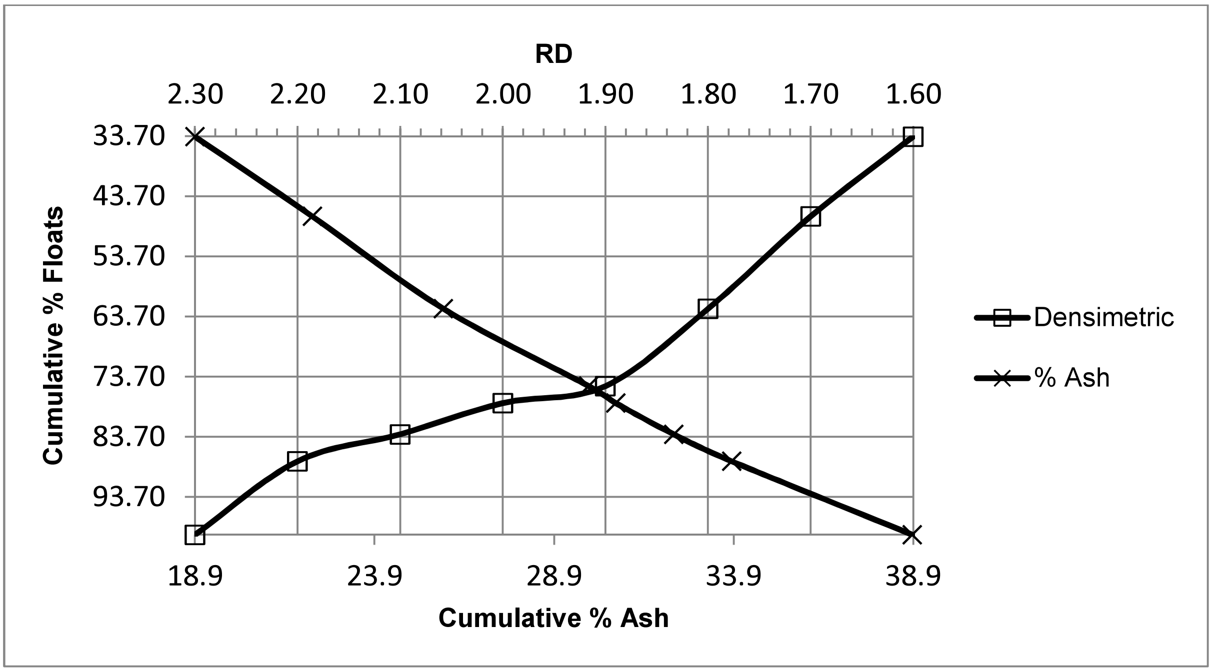

Figure 72: *Composite washability of Free State (Vereeniging) ROM*

4.6 Froth Flotation

Release analysis was carried out on the Witbank Coalfield No. 4 Seam to identify the optimum upgrading potential of the ultra-fine material and to derive the grade recovery curve. The ultra-fine samples were taken from in-stream samplers in the operating froth flotation plant. The feed qualities were as follows:

- CV = 22.91 MJ/kg,
- Ash = 24.7 %
- Sulphur 1.0 %

From Figure 73, the optimum ash achievable is 27.50 % ash at a 33 % recovery, between feed 1 & 2.

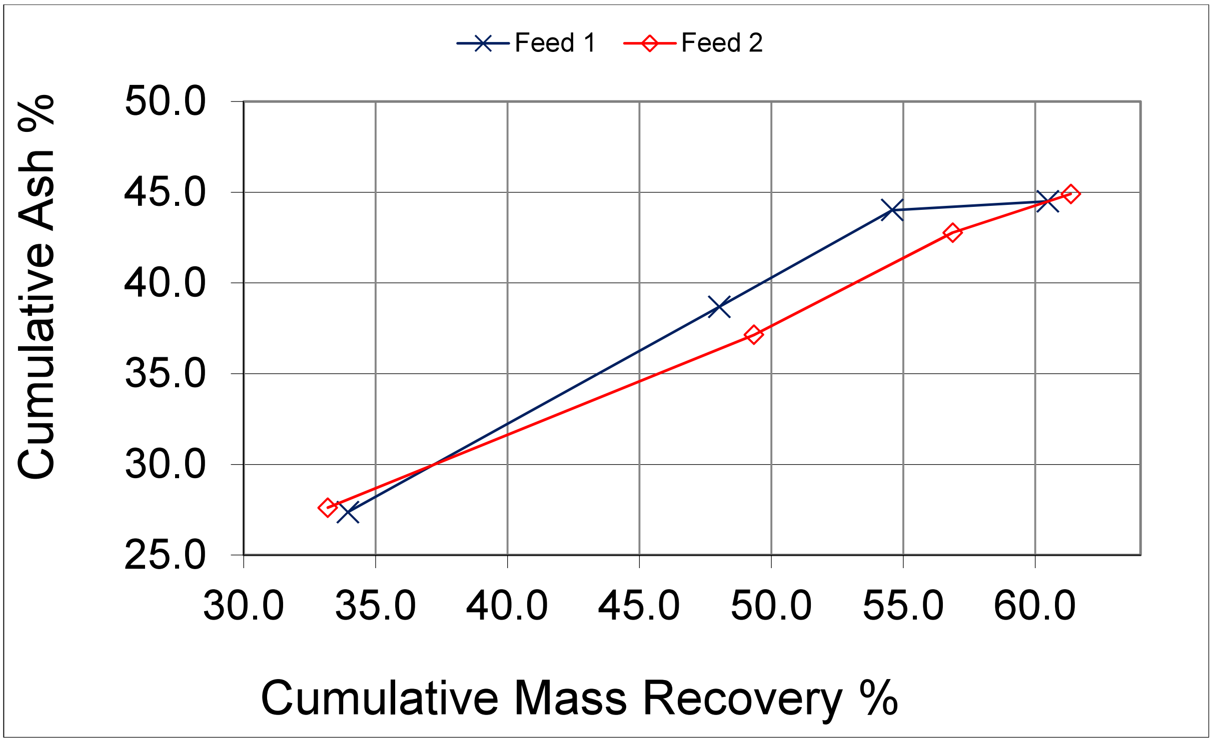

Figure 73: *Witbank Coalfield No. 4 Seam ash grade-recovery curve from release analysis*

In Figure 74, the optimum 28.40 MJ/kg at a recovery of 33 %, between feed 1 & 2.

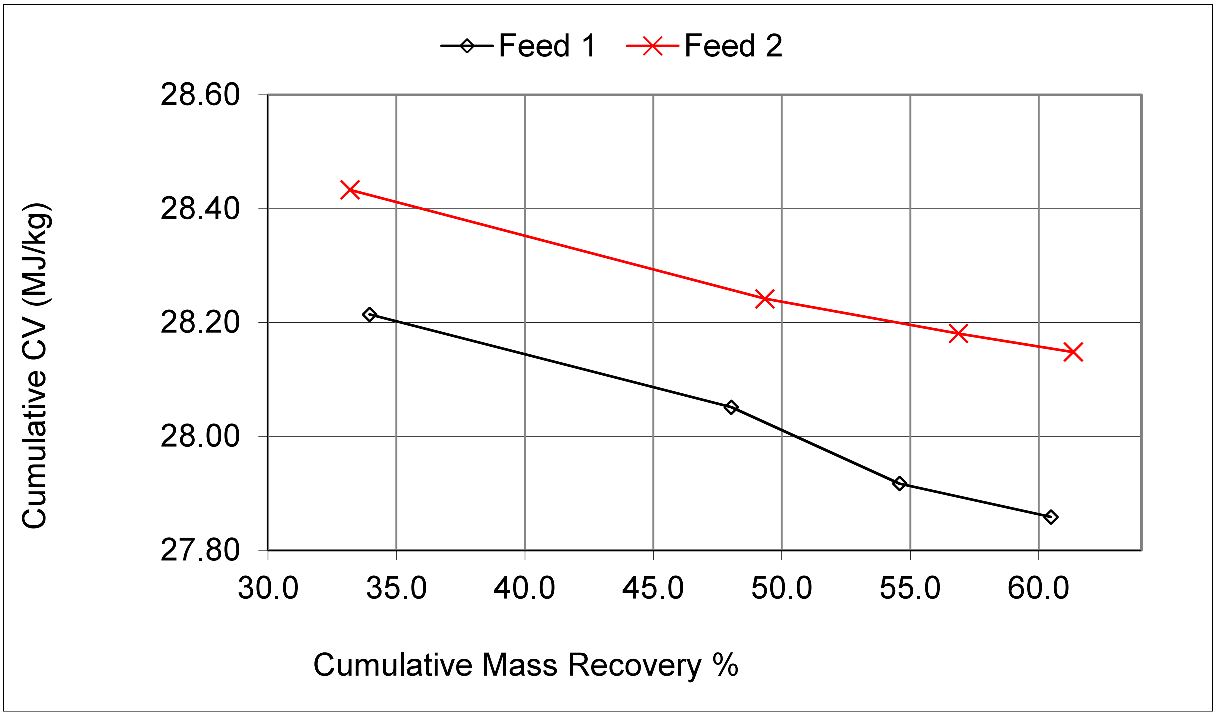

Figure 74: *Witbank Coalfield No. 4 Seam CV grade-recovery curve from release analysis*

From a trace element reduction perspective froth flotation proved to be highly effective in the removal of Mn, see Figure 75. Manganese is usually associated with the carbonate minerals or to some extent the clays (Dale, 2003). From the results obtained from froth floatability characterisation, the manganese does follow the dolomite and calcite and to a greater extent the kaolinite. From the results in Figure 74, a 28 % reduction in kaolinite, 47 % reduction in calcite and 20 % reduction in dolomite are obtained, with a 52 % reduction in the manganese concentration.

A negative reduction illustrated in Figure 75 is due to enrichment of the particular trace element in the froth flotation product. This was identified in the case of Cr and Cd.

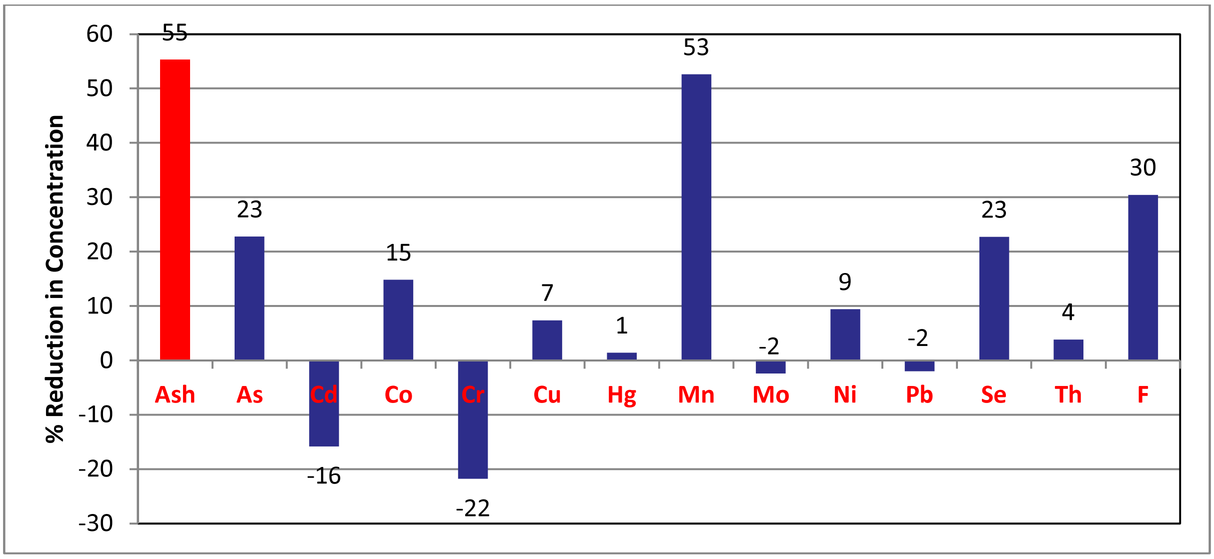

Figure 75: *Trace element reduction through froth flotation of Witbank Coalfield No. 4 Seam ultra-fine material.*

4.7 Liberation Analysis Results

4.7.1 Liberation prediction from XRD Data and Wash Curves

XRD data is primarily used as a method to quantify the amount of respective mineral matter phases in coal, but this analysis cannot account for the mineral liberation directly. However, in washability form and through curve trend analysis, a liberation trend can be established which provides an indication of the liberation potential of specific minerals. The XRD data can be seen in Appendix E, Tables IV and V.

The liberation data is discussed in detail Chapter 6.2 where the relevant minerals are plotted on M-curves to illustrate the liberation factors and parameters of the respective minerals together with macerals.

4.7.2 Liberation illustrated through QEMSEM Analysis

Pascoe *et al.* (2007) illustrated that QEMSCAN analysis can be utilised to develop particle size, density and concentration data to more accurately predict gravity separator performance. In the data so derived, apparent SGs could be determined and correlated to fractionated samples and their analysis respectively. Consequently as a result of an acceptable error with a high ash content sample, the variance between the reconciled ash content and ash analysis was deemed as being in the range of acceptable.

The QEMSCAN assisted with the analysis of the characteristics of the minerals and coal in the Witbank No. 4 seam and Waterberg Upper Ecca. The QEMSCAN analyses were conducted on the float -and sink fractions of the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca samples, as well as Witbank Coalfield No. 4 Seam froth flotation samples. For the liberation analysis, the QEMSCAN characterises the particles into different groups, see Table 16. The results are summarised in Appendix E, Tables I and VI. 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.

Witbank Coalfield No. 4 Seam

In the QEMSCAN results it was observed that fine pyrite nodules (syngenetic to authigenic) occur in the lower density fractions.

Table 16: *Mass percentage mineral distribution. Witbank Coalfield No. 4 Seam and float fractions*

Mineral	Ideal Composition	Witbank Coalfield No. 4 Seam Feed	F1.3	F1.6
Sulphates/Gibbsite	Ca- and Al-bearing sulphates	0.1	0.0	0.1
Pyrite	FeS_2	1.1	1.2	1.1
Siderite	$FeCO_3$	0.4	0.1	0.3
Calcite	$CaCO_3$	0.4	0.1	0.5
Dolomite	$CaMg(CO_3)_2$	1.6	0.3	7.4
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$	0.9	0.4	0.8
Kaolinite	$Al_2Si_2O_5(OH)_4$ (clay)	10.0	2.3	14.3
Quartz	SiO_2 (sand)	4.0	0.5	7.5
Illite/Hydro-Muscovite	$K_2Al_6Si_6O_{20}(OH)_4$/ $KAl_5Si_7O_{20}(OH)_4$	1.0	0.1	0.2
Microcline	$(K,Na)AlSi_3O_8$	0.6	0.1	0.4
Rutile	TiO_2	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

The ash correlation between the QEMSEM analysis and the proximate analysis was determined to be different, and a 15 % variance was observed.

Based on the QEMSEM analysis in Table 17, it has been determined that the pyrite content in the feed was 1.1 %. The pyrite QEMSEM data correlate well with the XRD composite pyrite content result. From Table 17 and Figure 76 it can be observed that the pyrite in the Witbank Coalfield No. 4 Seam does occur as fine cleats and very fine nodules (less than 15 micron in size).

Table 17: *Particle characteristics (Mass percentage)*

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

In Table 17 it can be seen that the pyrite content reduction does not occur readily in the washed 1.30 RD (F1.3) and 1.60 RD (F1.6) fractions. This is due to the locked liberation of the pyrite particles. From Figure 75 it can also be seen that the pyrite is largely associated with the vitrinite content in the coal, and can be seen distributed in the organic vitrinite matrix.

From the data shown in Table 17 it can be seen that the calcite content in the 1.60 RD washed fraction is higher than in the feed fraction. From Figure 76, it can be seen that the dolomite and calcite particles are associated largely with the inertinite maceral (note the blue locked particles in the dark grey matrix).

Kaolinite is also intimately mixed with the organic matrix, but in particular the inertinite maceral.

Note that the very low density liptinite maceral could not be identified with QEMSEM analysis, but based on the petrographic analysis the concentration is low (below 4 %) which could entail a lower level of significance in this study.

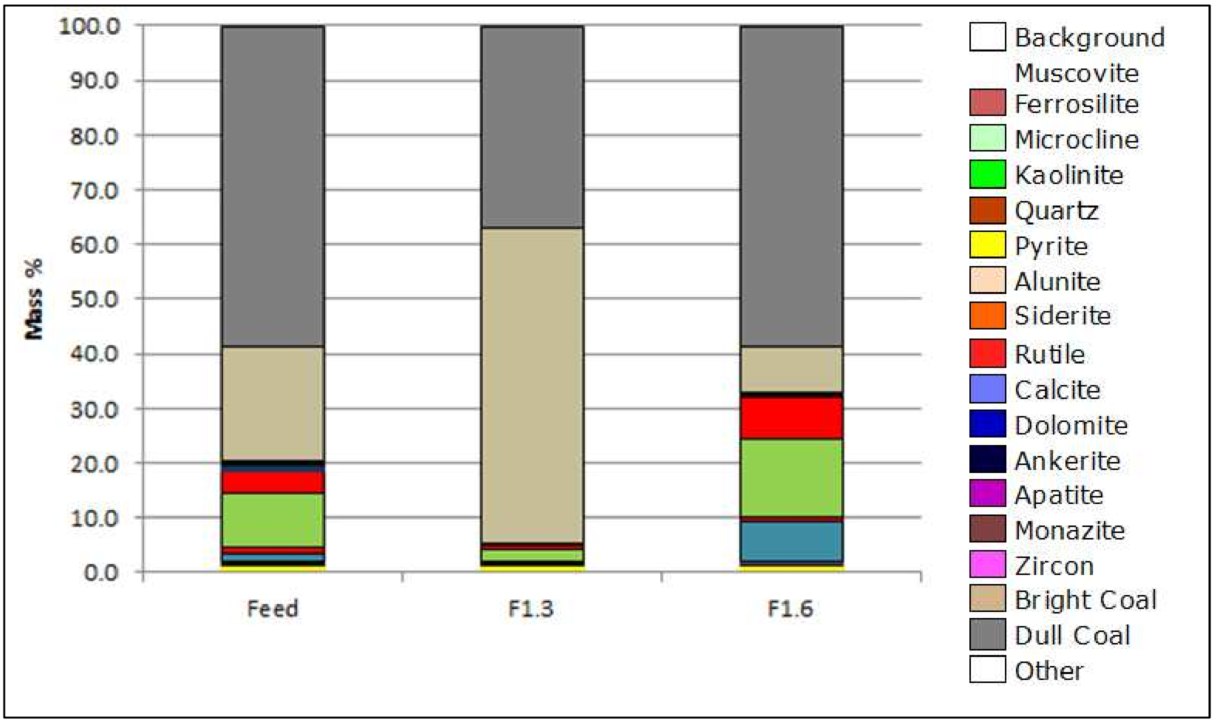

Figure 76: *Bulk mineralogy of the Witbank Coalfield No. 4 Seam samples through QEMSCAN.*

The diagram in Figure 76 shows the mass percentage mineral proportions relative to the maceral proportions for the Witbank Coalfield No. 4 Seam. In Figure 76 it is shown that Bright (organic sulphur rich coal) which can be identified as the vitrinite maceral is dominant in the F1.3 (1.30 RD) washability fraction. The Dull coal is dominant in the F1.6 (1.60 RD) washability fraction, the Dull coal could be a combination of reactive and non-reactive inertinite .

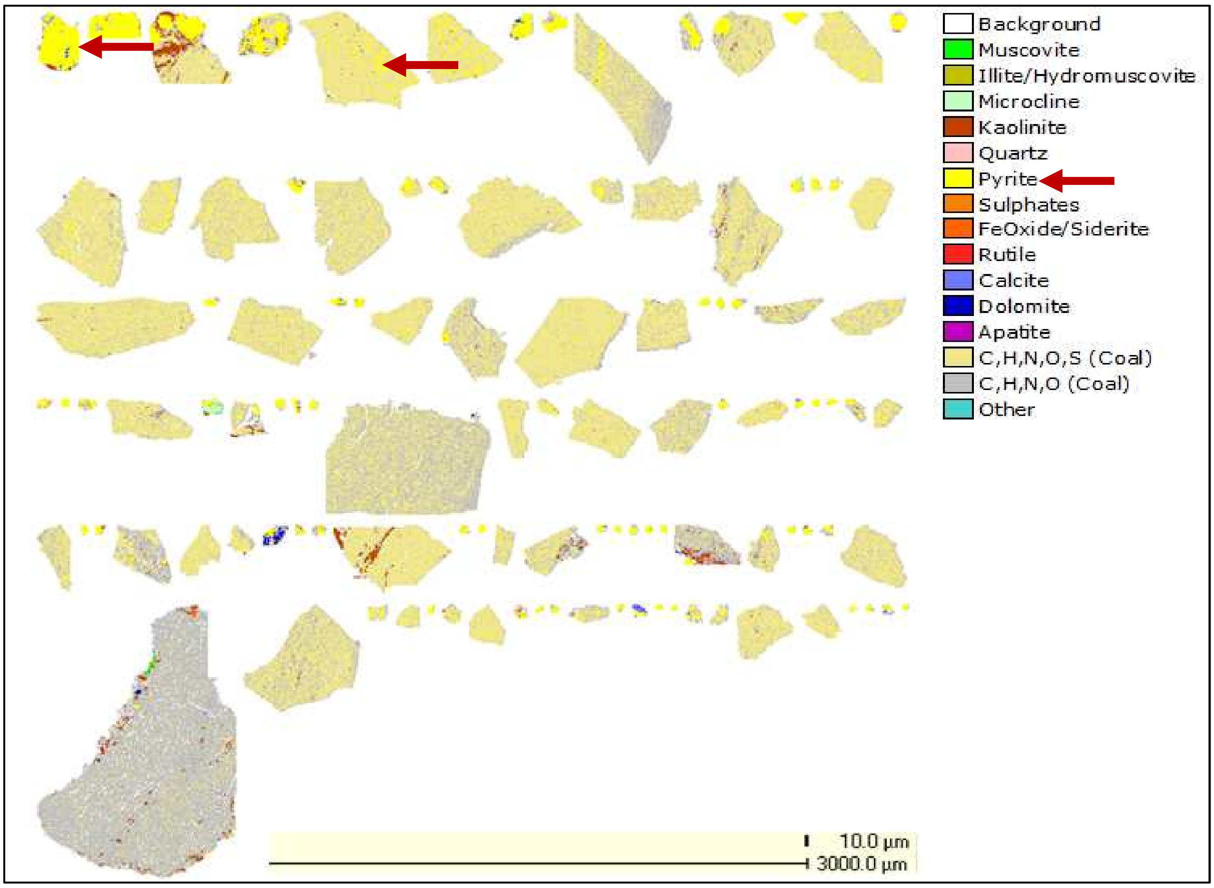

Figure 77: *QEMSEM images of pyrite in Witbank Coalfield No. 4 Seam*

In Figure 76 the distribution and occurrence of the mineral matter is illustrated. It is shown that the pyrite is associated mainly with the sulphur rich coal or vitrinite. The pyrite occur as very fine nodules, smaller than 15 µm. This distribution of pyrite nodules was confirmed with the petrographic analysis.

The size of the particles enriched with pyrite is in the order 50 µm, which will typically be processed in a froth flotation circuit (Figure 77). Pyrite has a natural high hydrophobicity which results in a high floatability potential in the case of froth flotation. The occurrence of the pyrite enriched particles in the froth flotation product would result in a higher ash, higher pyritic sulphur and associated trace element content.

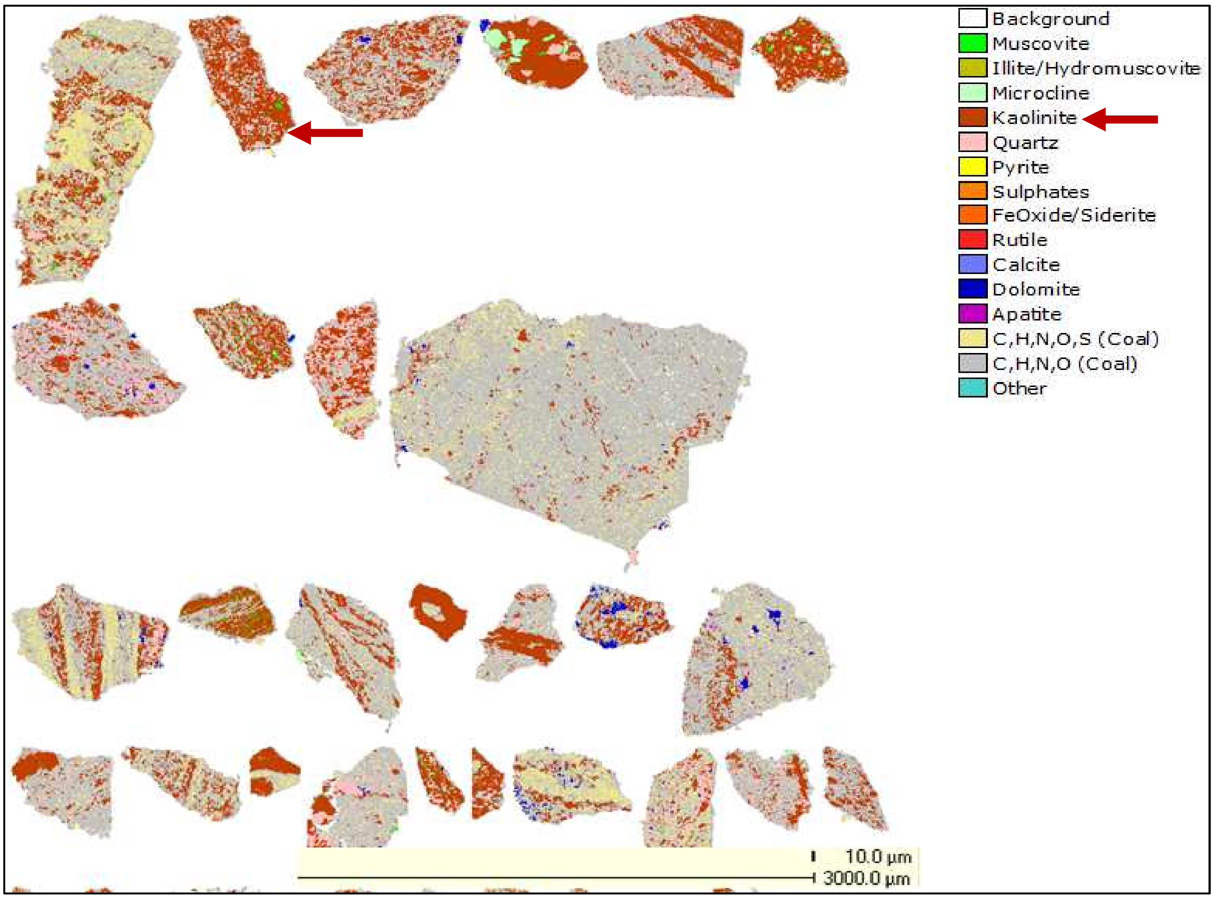

Figure 78: *QEMSEM images of kaolinite in Witbank Coalfield No. 4 Seam*

In Figure 78 the distribution of the kaolinite mineral is shown. The kaolinite is not liberated to a high degree and occurs as a syngenetic kaolinite mainly. Kaolinite is mainly associated with the Dull coal (inertinite rich) and would not be easily removed through beneficiation. The kaolinite enriched particles in mainly the ultrafine (minus 100 µm) size fraction.

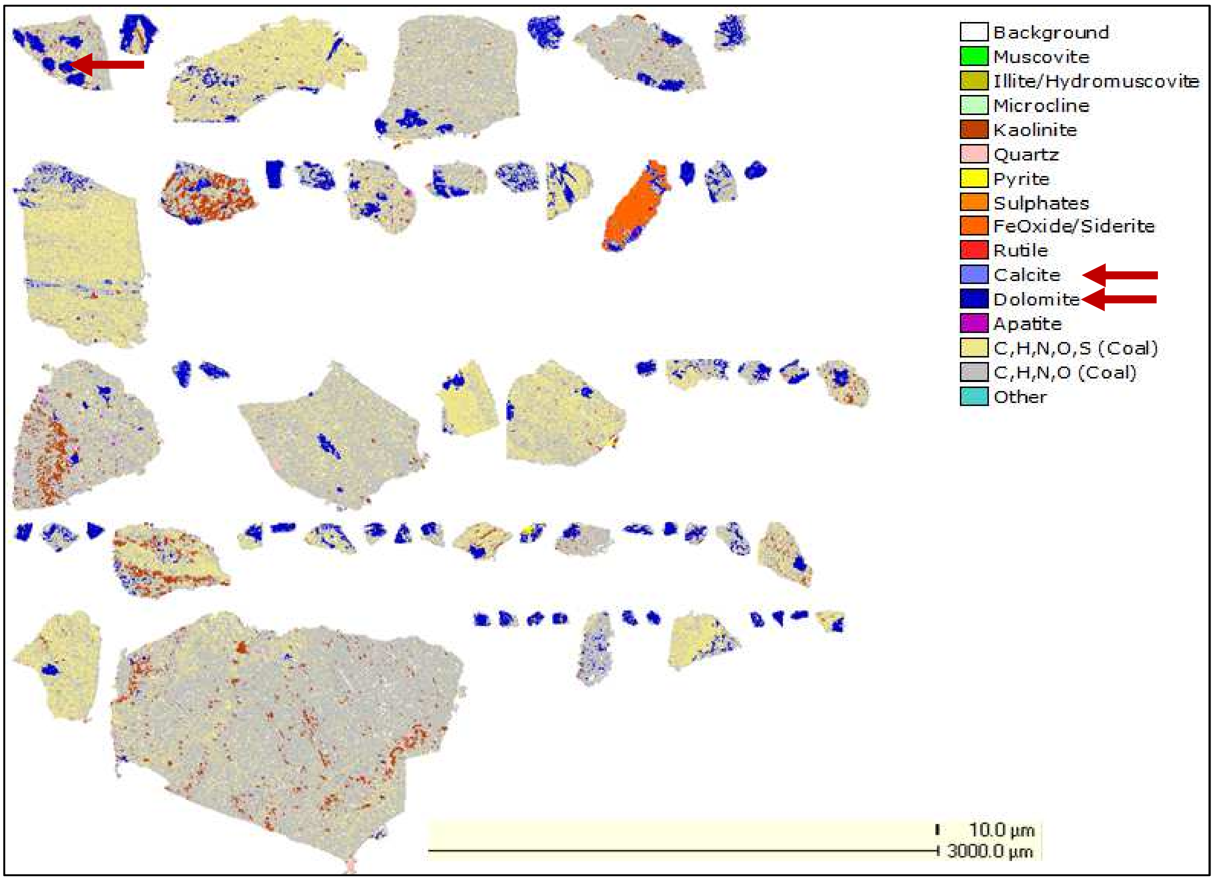

Figure 79: *QEMSEM images of calcite & dolomite in Witbank Coalfield No. 4 Seam.*

The dolomite rich particles as shown in Figure 79 appear to be well liberated. It is shown that the dolomite occurs with dull coal (inertinite rich) mainly. With very fine grinding the dolomite particles can be liberated. Dolomite enriched particles (above 60%) occurs as cleat fragments in the minus 60 micron particle range. The dolomite concentration was found to be enriched in the F1.6 (RD 1.60) washability density fraction.

Waterberg Upper Ecca

The QEMSEM analysis on the Waterberg coals (Table 18) was performed by classifying the mineral and organic matter in three basic components namely stone fragments, cleat fragments and the organic particles.

- Cleat fragments: Cleats are joint/fractures that form in coal. Sometimes the pyrite-rich, calcite-rich and dolomite rich particles that occur in coal are referred to as cleat fragments.
- Stone fragments: Stone originates from the mineralised bands present in coal seams as well as the floor and roof horizons. These consist of mineralised lithotypes of sandstone, siltstone, mudstone and liberated stone fragments.
- Combustible coal particles: The carbon rich phases are referred to as macerals, which can occur as either liberated particles (by crushing) or are intergrown with mineral phases (carbominerites).

Maceral determination on the QEMSCAN is based on sulphur determination in the organic particles (Van Alphen, 2008). Both reactive vitrinite and liptinite would have a higher proportion of organic bearing sulphur than inert inertinite (Van Alphen, 2008).

Table 18: *Mass percentage mineral distribution. Waterberg Feed and dense medium float fractions*

Mineral	Composite	RD 1.35 - 1.40	RD 1.50 - 1.70	RD 1.9 - 2.00
Sulphates/Gibbsite	0.0	0.0	0.2	0.1
Pyrite	1.2	0.4	1.0	1.2
Magnetite/Siderite	1.3	0.7	2.5	3.7
Calcite	1.9	0.3	3.6	2.2
Dolomite	2.0	0.4	2.1	1.5
Kaolinite	24.4	2.3	12.0	33.3
Quartz	10.0	5.0	8.7	13.4
Illite/Muscovite	1.4	0.4	1.0	2.0
Microcline	3.4	1.0	1.6	3.2
Vitrinite	28.7	69.4	35.9	17.2
Inertinite	25.0	19.5	29.9	21.3
Other	0.7	0.6	1.5	0.9
Total	100.0	100.0	100.0	100.0

It was discovered that reactive semi-fusinite and inertodetrinite would have sulphur levels between vitrinite and inertinite, but this discovery was not investigated in detail in the research.

The particles analysed are characterised according to three basic components and further classified in terms of their respective lithotypes based on mineral compositions (Table 19).

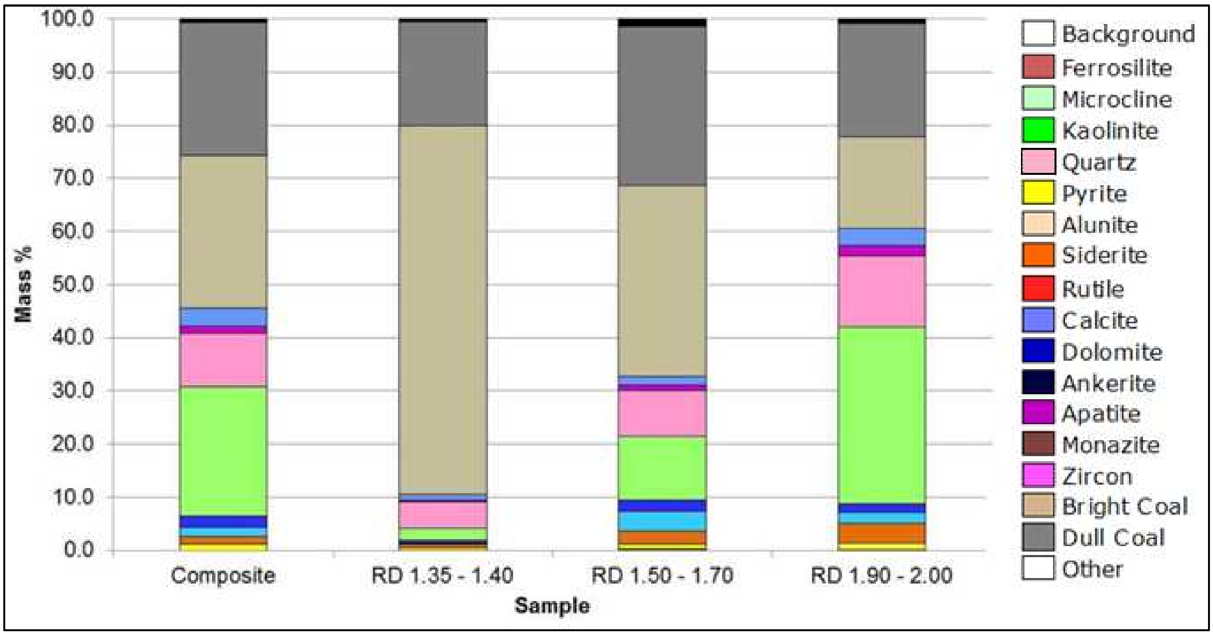

Figure 80: *Bulk mineralogy of the Waterberg coal samples (with QEMSEM)*

From the bulk mineralogy illustrated in Figure 79 it can be seen that the washed fractions 1.35-1.40 RD, 1.50 RD and 1.90 RD show a corresponding reduction in pyrite, quartz, siderite and kaolinite. Similar to the Witbank Coalfield No. 4 Seam, calcite is not readily decreased in the lower RD wash fractions.

Table 19: *Liberation of pyrite in the Waterberg Upper Ecca*

Sample	Locked	Liberated	Total
Composite	40.5	16.5	100.0
RD 1.35-	96.4	0.6	100.0
RD 1.50-	95.0	1.9	100.0
RD 1.90-	38.8	14.6	100.0

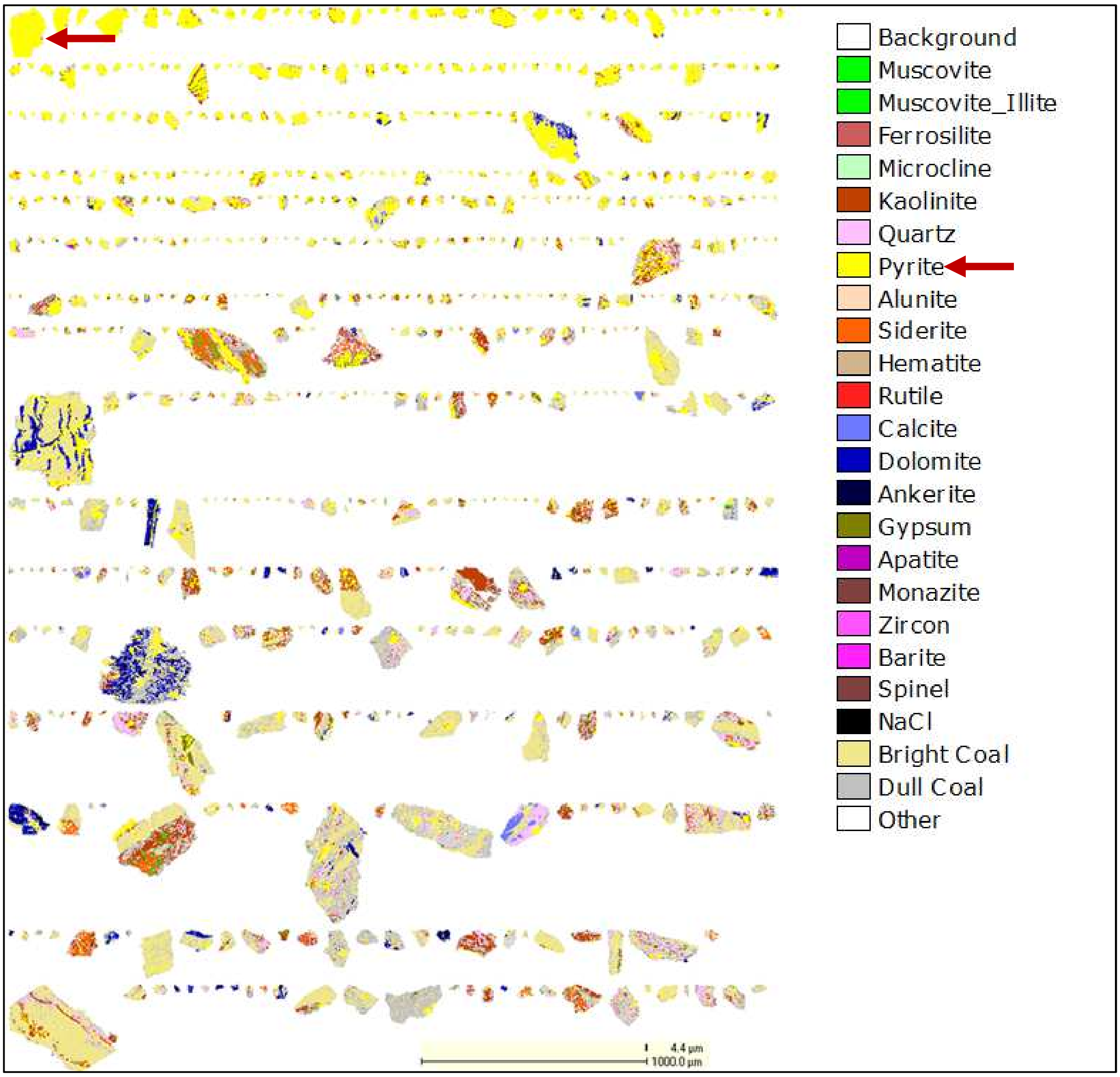

Figure 81: *QEMSEM images of pyrite distribution in Waterberg Upper Ecca.*

From Figure 81, the pyrite content can be readily reduced through washing. In contrast to the Witbank Coalfield No. 4 Seam, however, it can be seen in Figure 80 that the pyrite particles are associated equally with vitrinite and inertinite.

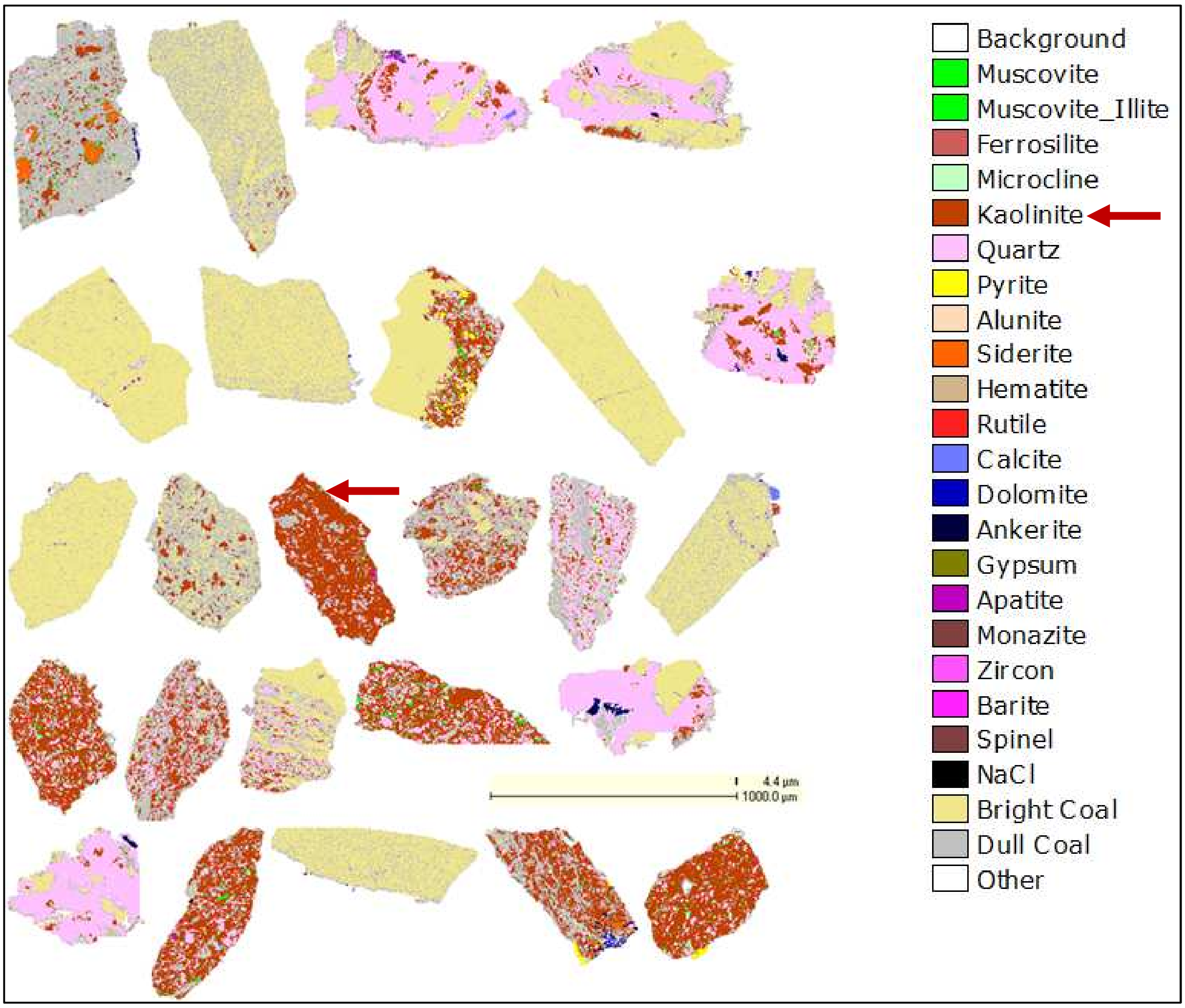

Figure 82: *QEMSEM images of kaolinite distribution - Waterberg Upper Ecca*

In Figure 82 it can be seen that the kaolinite particles are also intimately mixed with the organic matrix, but in this instance the vitrinite particles. Hence, washing at low RD's (below 1.40), would involve high amounts of kaolinite and could have an impact on the processing efficiency (Firth et al., 2011).

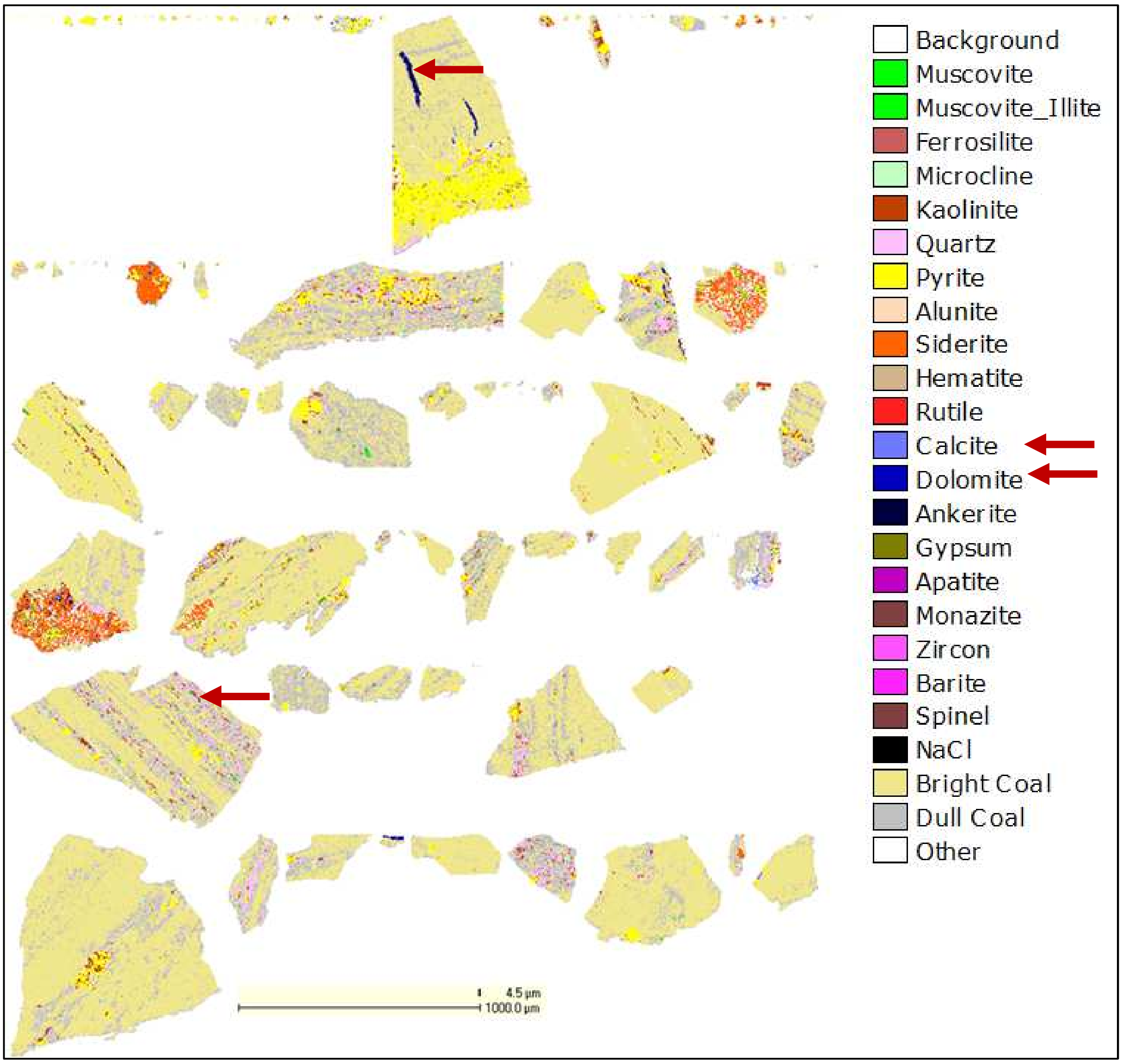

Figure 83: *QEMSEM images of finely distributed calcite & dolomite in the Waterberg Upper Ecca.*

In Figure 83 the occurrence of very fine dolomite (below 5 micron) is illustrated. In a few instances the dolomite occurs as fine cleats, but primarily as finely distributed matter over the lower sulphur bearing organic matrix.

4.8 Petrographic Analysis Results

The samples for petrographic analysis comprised of ROM and borehole samples in the case of the Witbank No. 4 Seam and Borehole with large-borehole diameter samples in the case of the Waterberg Upper Ecca. The samples for petrographic analysis were obtained from the various sources and were homogenised to provide composite samples representative of the seams and coalfields from which they came. Homogenised composite samples along with the various washed density fractions samples were analysed and can be viewed in Appendix F.

The petrographic results (see Appendix F) indicate that the vitrinite content correlates with the Fuel Ratio (ratio of volatile content over fixed carbon) in each coalfield, but the two coalfields (Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca) are distinctly different. The Witbank Coalfield No. 4 Seam has the lower vitrinite content, but higher associated Fuel Ratio for each vitrinite content value, see Figure 84.

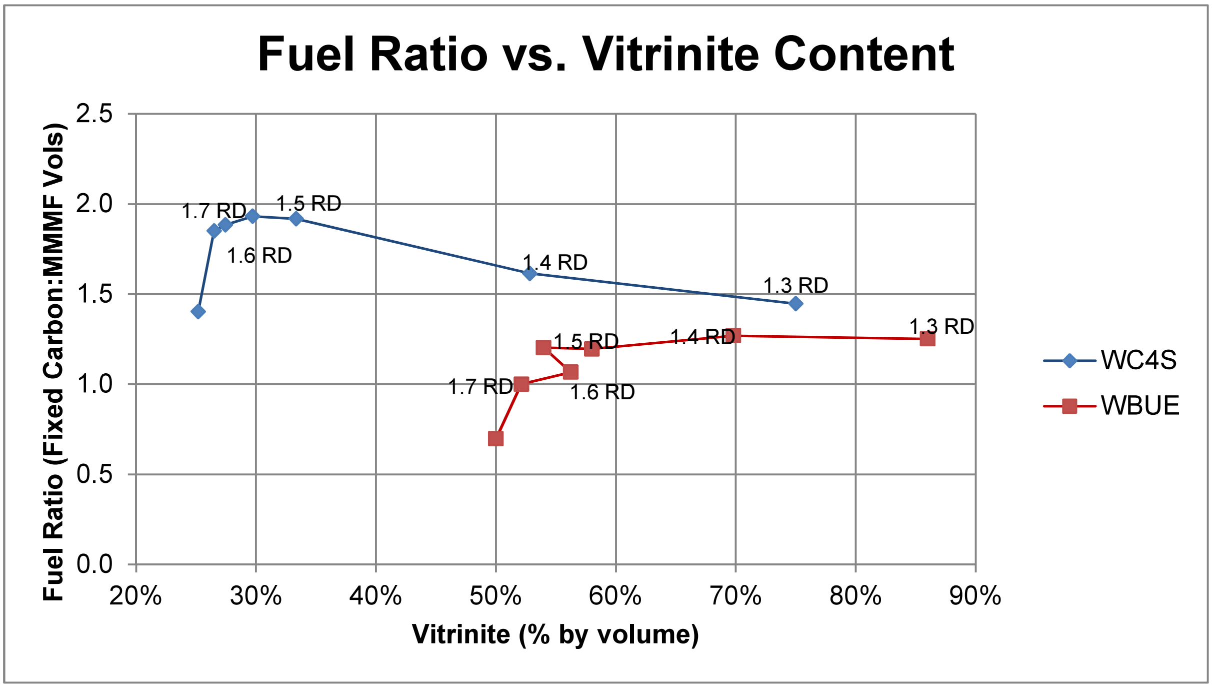

Figure 84: *Fuel ratio vs. Vitrinite content for Witbank Coalfield No. 4 Seam (WC4S) and Waterberg Upper Ecca (WBUE).*

In Figure 85 it can be seen that the carbominerite (mineral + maceral content > 25 %) content varies with washing densities and that the amount of carbominerite in the Waterberg Upper Ecca is higher than the Witbank Coalfield No. 4 Seam.

In Figure 84 it will be observed that the Witbank Coalfield No. 4 Seam has a low reactivity (low Fuel ratio) between the points at 1.6 and 1.5 RD. The reactivity of the

Witbank Coalfield No. 4 Seam only begins to match with the Waterberg Upper Ecca reactivity tendencies below a density of 1.40 RD.

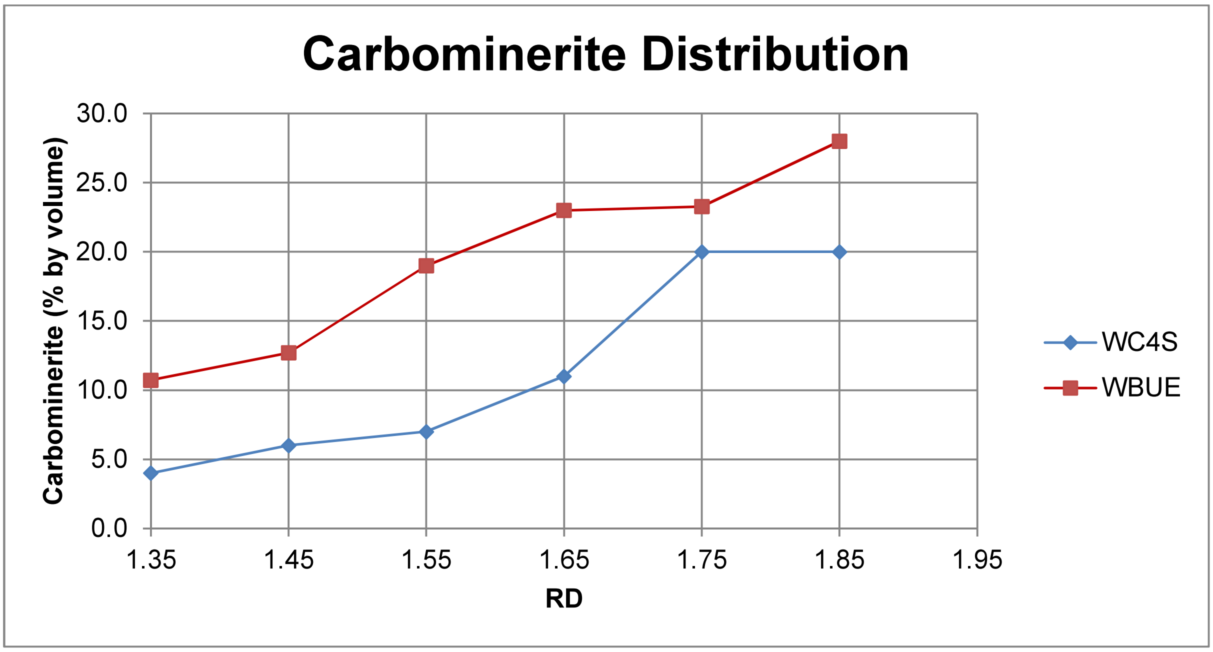

Figure 85: *Carbominerite distribution at various washing RD's for the Witbank Coalfield No. 4 Seam and Waterberg Upper Ecca.*

4.8.1 Partitioning of Macerals

Witbank Coalfield No. 4 Seam

In Figure 86 the distribution of the maceral content is displayed at the various density fractions following beneficiation. The proportion of vitrinite is the highest at low density 1.30-1.40 RD fractions as expected, but at low yields referring to the washability curve. From the QEMSEM analysis it was observed that the vitrinite is well liberated, but there is some mixing between the vitrinite and inertinite.

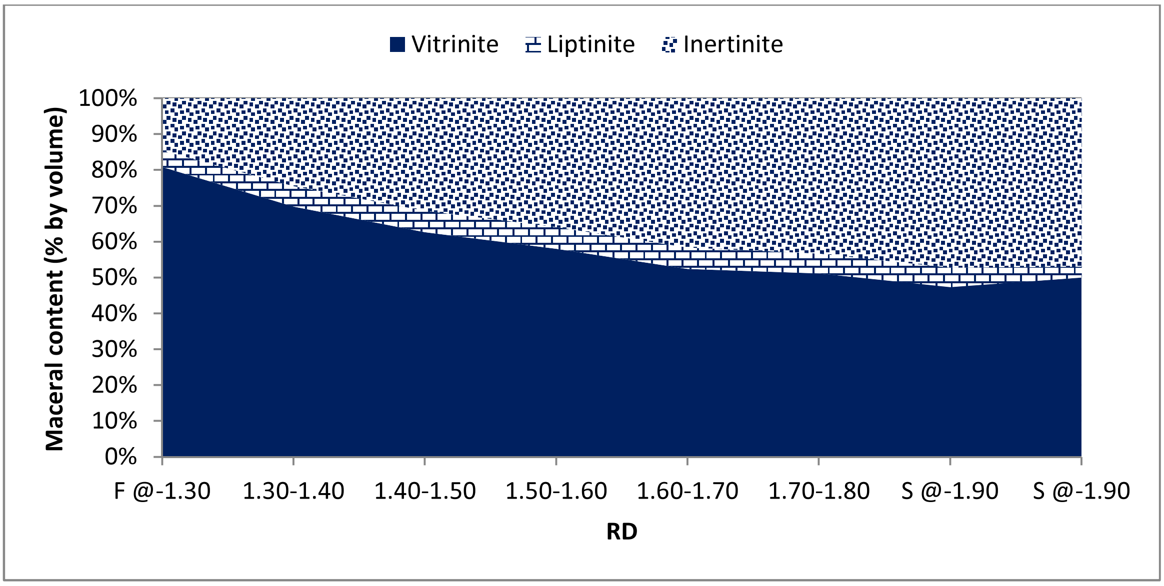

Figure 86: *Maceral distribution at various density fractions – Witbank Coalfield No. 4 Seam*

From the liberation modelling (M-Curve) of the vitrinite in both the Witbank Coalfield No. 4 Seam (Figure 87) and Waterberg Upper Ecca (Figure 89) it can be seen that the Vitrinite in the coal is well liberated. A relatively good correlation between CV and Vitrinite content is observed as per Figure 86.

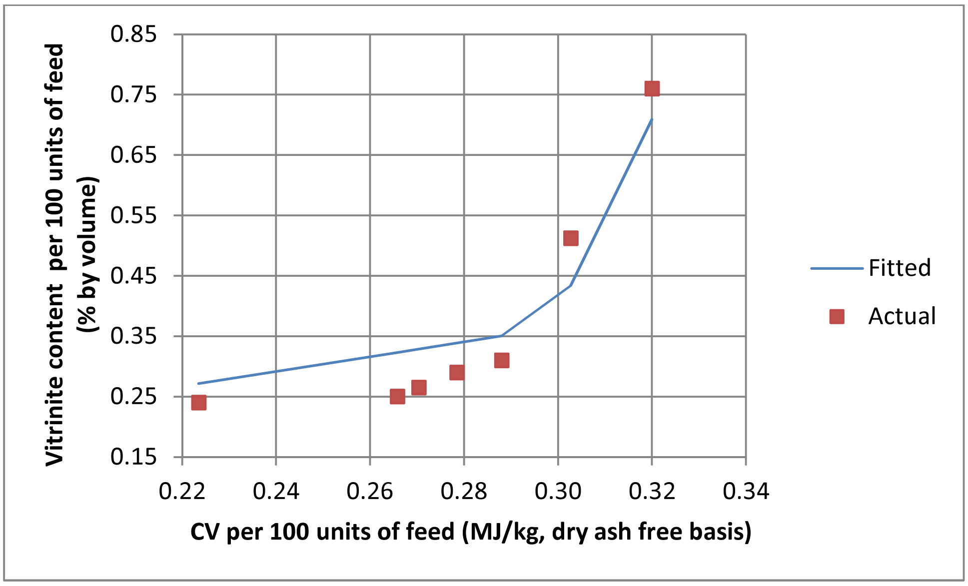

Figure 87: *Vitrinite and CV relationships through liberation analysis for the Witbank Coalfield No. 4 Seam*

Waterberg Upper Ecca

The Waterberg Upper Ecca displays a very low vitrinite content profile at RD's above 1.45, this would likely be contribution for the poor CV values at higher cumulative yield values. The proportions of reactive inertinite (reactive semi-fusinite) in the density fractions are also low at 3 % (See Appendix F for the Petrographic Analysis Report).

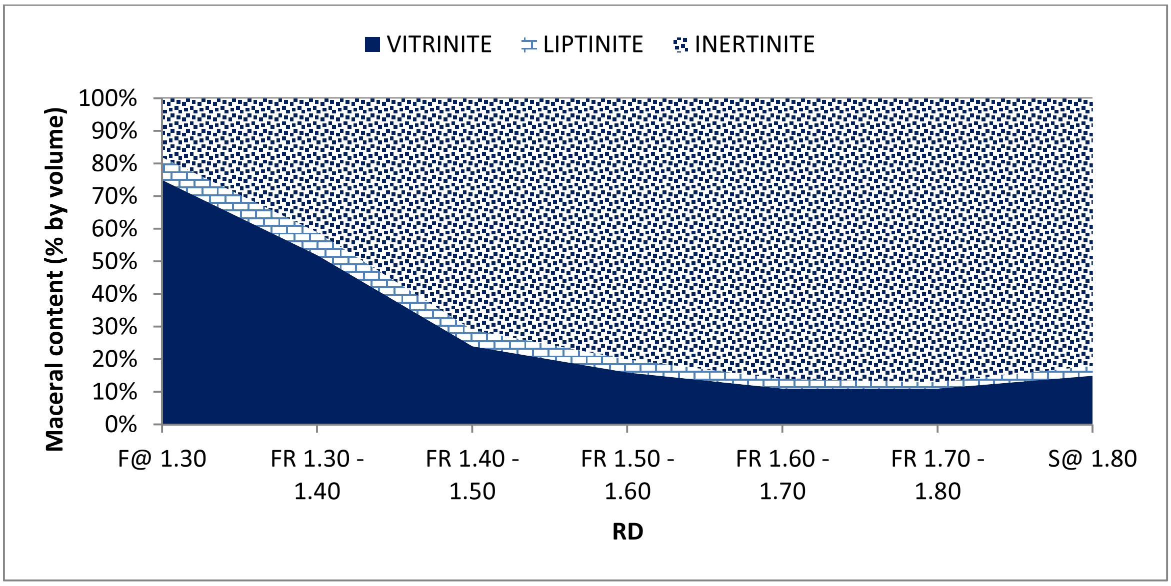

Figure 88: *Maceral distribution at various density fractions –Waterberg Upper Ecca*

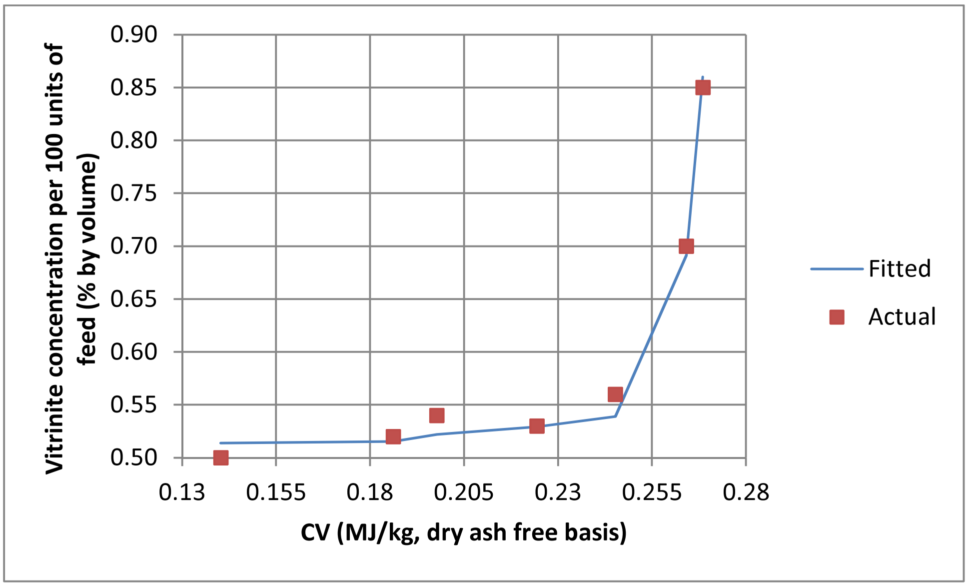

Figure 89: *Vitrinite and CV relationships in Waterberg Upper Ecca through liberation analysis*

4.8.2 Partitioning of Microlithotypes

From a coal beneficiation perspective the microlithotypes are important as they relate to combinations of macerals and minerals and their distribution. The raw data is shown in Appendix F. This relate to the amount of near gravity material in the coal. Carbominerite can give an indication of the expected near gravity material challenges.

Witbank Coalfield No. 4 Seam

From Figure 90 the carbominerite content in the Witbank Coalfield No. 4 Seam seems to increase significantly towards the higher RD fractions. The minerite does as expected and increases towards the higher RD fractions.

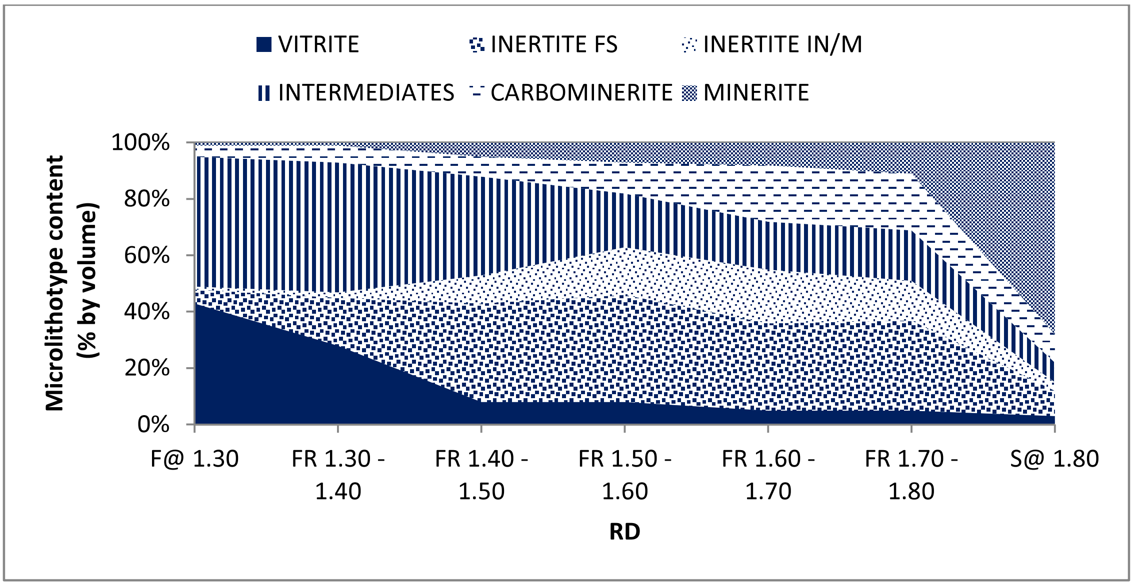

Figure 90: *Partitioning of microlithotypes in Witbank Coalfield No. 4 Seam*

Waterberg Upper Ecca

From Figure 91 the carbominerite content in the Waterberg Upper Ecca in contrast to the Witbank Coalfield No. 4 Seam seems to be relatively constant, but does seem to increase slightly towards the higher RD fractions. The minerite does as expected and increases towards the higher RD fractions. The fines (-0.5 mm) is rich in vitrite, but also contain a comparatively high quantity of minerite.

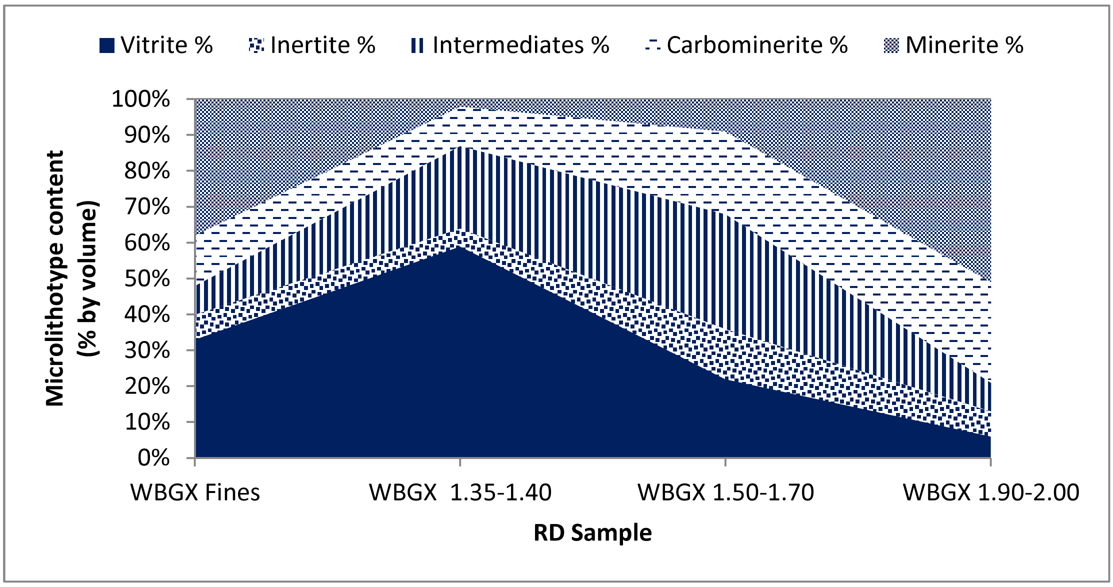

Figure 91: *Partitioning of microlithotypes in Waterberg Upper Ecca*

Note that the fraction depicted 'WBGX Fines' in Figure 91, is the minus raw 0.5 mm sample from the Waterberg Upper Ecca.