# OUTLINE CHAP 6: APPLIED COAL PETROGRAPHY

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**Chapter 6: Applied Coal and Carbon Petrology**

All images in the following plates have been taken on southern African coals and related products. The plates deal with the applied aspects of coal petrography, with the intention of enhancing the understanding of the behaviour of macerals and associated minerals during coal beneficiation and utilization (pyrolysis, combustion, gasification, coking), as well as a consideration of the unburned carbon and neoformed minerals in coal ash generation. As coal is known to undergo oxidation and / or weathering, features not present in-situ may form; these features, along with other features known to result in anomalous behaviour in coal, are considered. Images of carbon-rich shale horizons from borehole cores pertaining to shale gas exploration in the Main Karoo Basin are also included. Anomalous and unusual features observed petrographically complete this chapter.

The majority of images were taken using a Zeiss Axio Imager M2M reflected light microscope, under non-polarised and polarized white light (LED source) with or without a retarder plate, using immersion oil, at x500, or using a dry lens at x100. Scale bars are included on all images. In instances where this deviates, the correct magnification and light conditions are provided.

Related reference sources are largely supplied per plate, and the following books are additional recommended reference sources:

* Crelling, J.C., and Rimmer, S.M. (2015). Southern Illinois University Petrographic Atlas of Coals and Carbons (<http://coalandcarbonatlas.siu.edu/>)
* Suárez-Ruiz, I., Crelling, J.C., (eds.) (2008). Applied Coal Petrology. USA: Elsevier. pp 388.
* Taylor G. *et al.* (1998). Organic Petrology. Berlin: Gebruder Borntraeger. pp 704.

Key to abbreviations on the images:

|  |  |
| --- | --- |
| AN | Anisotropic |
| Ca | Calcite |
| CH | Char |
| CL | Clay |
| I | Inertinite group maceral |
| ISO | Isotropic |
| L | Liptinite group maceral |
| P | Pyrite |
| Po | Pore |
| Qu | Quartz |
| V | Vitrinite group maceral |

**Plate 48: COAL BENEFICIATION: Impact of density fractionation (float-sink tests) on petrographic properties**

As demonstrated in Figures 3.1 and 3.2, different macerals, microlithotypes, minerals, and carbominerites have different density ranges, and pure particles will respond in a more or less predictable manner during density fractionation (float-sink tests). However, as coal particles, even in fine sizes, are generally aggregates of macerals and minerals, an appreciation of the petrographic composition in the parent coal is important in order to understand the yields at different density cuts. A 1.3 fraction will be enriched in vitrinite, but a coal with a low proportion of vitrite will have a very low yield at 1.3 g/ml, for example. A coal rich in inertodetrinite and small clays and quartz inclusions will report to the 1.8 sink fraction. Silicate particles rich in liptinite may behave anomalously, resulting in the float fractions reporting a higher ash content than expected as the particle density will become an average of the liptinite and silicate densities. Oxidised or weathered coals will also behave anomalously during density fractionation as the surface properties of the particles are altered. Vitrinite may report as higher yields in the 1.5 fraction rather than the 1.3 fraction, for example.

A series of photographs, including mosaic images covering a 10 x 10 mm area of the block mount using x100 magnification (dry lens) to maximize the number of particles in a field of view, demonstrate the change in coal quality between density fractions (1.3 – 1.9 sink, 1 - 13mm fraction), compared to the parent coal. The maceral group count including mineral matter in the table below provides a quantitative assessment in the proportions of organic and inorganic matter in the different density fractions. The yield information indicates the proportion of the mass of coal reporting to the different fractions.

**Plates**

Row A. Parent coal, with fields of view containing a range of coal particles – vitrinite, inertinite, pyrite, clays, and quartz. Medium rank C bituminous coal from the Waterberg Coalfield.

Row B. Float at 1.3, clearly showing the concentration of vitrinite-rich coal particles (vitrite). The yield is 15%.

Row C. Float at 1.7, clearly showing a higher proportion of inertinite. The proportion of vitrinite is still high due to the inclusion of fine clays bound within the particle (middle image) as well as vitrinertite particles, both of which alter the particle density (right image).

Row D. Float at 1.9, where the maceral count clearly shows a decrease in the proportion of vitrinite and increase in inertinite and mineral matter. The yield is 9%.

Row E. Sink at 1.9, clearly showing the concentration of mineral-rich particles. In this specific coal, much of the pyrite is hosted within the vitrite particles, and hence the pyrite-rich sink fraction also contains a higher than expected proportion of vitrinite. Without appreciating the deportment of the pyrite and vitrinite petrographically, it would be difficult to explain the anomalously high vitrinite content (and volatile matter) in the sink fraction. The washability curve produced for this coal would be unusual. More typically in southern African coals, the 1.9 sink fraction contains below 5 vol% vitrinite.

**Maceral Group Analysis (vol%)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Parent (-1mm) | 1.3 float | 1.5 float | 1.7 float | 1.9 float | 1.9 sink |
| Vitrinite | 16.1 | 58.2 | 53.3 | 30.3 | 7.4 | 20.0 |
| Liptinite | 7.2 | 4.7 | 3.5 | 7.5 | 6.4 | 0.4 |
| Inertinite | 52.3 | 33.2 | 41.1 | 50.2 | 66.5 | 19.6 |
| Minerals | 24.3 | 3.9 | 2.1 | 11.9 | 19.7 | 59.9 |
| Yield % |  | 15 | 33 | 15 | 9 | 26 |

**Plate 49: COAL BENEFICIATION: Impact of particle size on petrographic properties**

As depicted in Figure 3.11, in order to liberate minerals and gain a higher probability of concentrating enriched organic particles, it is necessary to crush to finer sizes. Macerals have inherent breakage properties. Liptinite has very high tensile strength and toughness; both enhancing particle strength. Vitrinite is inherently brittle, and typically reports to the finer size fractions on impact. Fusinite, unless impregnated with minerals (especially calcite), is generally soft and friable. Other inertinite macerals typically raise the strength of coal bands.

The petrographic results presented below (both maceral group and microlithotype analysis), were obtained from a series of samples prepared to specific size fractions (4 screened size fractions from 50 - >1 mm), crushed to -1mm (after screening) for petrographic analysis. The varying maceral and microlithotype composition is apparent, with vitrinite concentrating in the finest fraction, along with liberated mineral matter.

**Maceral Group Analysis (vol%)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 50-25 mm | 25-13 mm | 13 – 1mm | -1mm |
| Vitrinite | **7.9** | 7.4 | 7.0 | **26.6** |
| Liptinite | 11.1 | 4.8 | 4.6 | 4.2 |
| Inertinite | 69.9 | 66.9 | 67.6 | 45.3 |
| Minerals | **11.1** | 20.9 | 20.8 | **23.9** |

**Microlithotype Analysis (vol%)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | 50-25 mm | 25-13 mm | 13–1 mm | -1mm |
| Mono maceral | Vitrite |  | **2.2** | 1.8 | 4.7 | **23.1** |
| Semifusite |  | 4.6 | 5.4 | 4.8 | 7.3 |
| Fusite/secretite |  | 0.7 | 0.6 | 1.0 | 3.0 |
| Inertodetrite |  | 28.5 | 27.4 | 35.6 | 16.5 |
| Liptite |  | 0.7 | 0.3 | 0.0 | 1.2 |
| Bi maceral | Vitrinertite | Vit + SF/FUS/SEC | 3.1 | 0.9 | 1.6 | 2.4 |
| Vit + Inertodetrite | 5.1 | 2.4 | 3.8 | 5.1 |
| Inertodetrite | SF/FUS/SEC/Intdet | 5.1 | 6.3 | 4.4 | 4.6 |
| Clarite |  | 0.2 | 1.2 | 0.3 | 0.2 |
| Durite |  | 18.1 | 15.1 | 14.7 | 7.4 |
| Tri maceral | Duroclarite V>I+L |  | 4.3 | 3.3 | 2.5 | 2.2 |
| Clarodurite I>V+L |  | 5.1 | 3.6 | 1.9 | 1.2 |
| Vitrinertoliptite L>V+I |  | 1.0 | 0.6 | 0.9 | 0.7 |
| Carbomin-erite | Carbargilite |  | 0.0 | 1.5 | 1.3 | 1.8 |
| Carbosilicate |  | 18.9 | 15.4 | 9.7 | 5.0 |
| Carbopyrite |  | 0.5 | 1.8 | 0.9 | 0.2 |
| Carbankerite |  | 0.0 | 0.3 | 0.0 | 0.2 |
| Carbopolyminerite |  | 0.0 | 0.0 | 0.3 | 0.0 |
| Rock | Minerite |  | **1.9** | 12.1 | 11.6 | **17.9** |

**Plates**

A, B, C: 50 – 25 mm fraction enriched in inertodetrite, durite and carbosilicates, with a low proportion of vitrite occurring primarily as finely laminated bands within inertite.

E, F, G: -1 mm fraction showing increased proportion of vitrite particles in the fines fraction, and an increase in liberated minerals (minerite), most of which are small quartz particles.

**Plate 50: COAL BENEFICIATION: Variable densities in borehole core samples**

The size and distribution of maceral and mineral components in a raw coal will determine the coals potential for upgrading via beneficiation (crushing and washing). Without understanding the distribution of the macerals and minerals, and their modes of occurrence and apparent density, it is difficult to accurately predict liberation at a particular crush size. Certain coal deposits are more banded than others, with the arrangements of the microlithotypes and minerals varying extensively. By petrographically assessing the macerals, microlithotypes, and minerals in a core section it is possible to predict the most suitable crushing size needed to liberate clean particles of vitrinite from inertinite and mineral matter, for example.

**Plates**

The images in the plate were taken on sectioned borehole core samples, set in epoxy resin and polished. Each scan area is 7.3 X 1.7 mm, composed of approximately 301 images automatically stitched together using Fossil Diskus software, taken at X 500 with an oil-immersion lens and LED light. The 100 µm scale bar is included on the images.

1. The sequence shows a continuous band of clean, mineral-free vitrinite, with a crack running up the right side. Such a coal does not require upgrading and is a prime market product. (Medium rank B bituminous coal, Moatize Coalfield, Mozambique).
2. The banded nature of vitrinite is apparent, with a thick vitrite section in the middle of the image, and finer bands of vitrite interspersed between layers of clay towards the top. It is likely that a low ash, vitrite product could be obtained by crushing and washing at low-density gravity concentration, with a second vitrite-rich higher ash product at a higher density fraction. (Medium rank C / B bituminous coal, Tuli Coalfield, South Africa)
3. The sequence shows a banded coal with vitrite, inertite, and carbominerite / clay-rich horizons, and a large carbonate cleat in the middle. Liberation of the clay minerals is not possible in this coal, and it is likely the coal will only be suitable as a run-of-mine unwashed power station feed in South Africa. (Medium rank C bituminous coal, Witbank Coalfield)
4. The sequence shows a dominance of inertite, with bands of semifusinite, fusinite, and inertodetrinite. Particles from this core will report to higher densities (RD 1.45 – 1.6) compared to column A. The volatile matter content in this sample is likely to be low, despite the coal rank. (Medium rank C bituminous coal, Witbank Coalfield).

Images courtesy of X. Makukule.

**Plate 51: UTILIZATION: Pyrolysis**

Coal conversion during heating in oxygen is essentially a two-stage process: 1) thermal decomposition of the coal particles, referred to as pyrolysis, resulting in devolatilisation and char formation; and 2) combustion or gasification of the char to produce heat energy and / or syngas. During pyrolysis, the sudden release of volatile gases (devolatilisation) is accompanied by drastic changes in the morphology and molecular structure of the carbon particle, forming char and ash. The microlithotype composition and coal rank determines the resultant char morphology.

Fusain and other inert inertinite macerals will not show any appreciable differences from the parent coal following pyrolysis, apart from a possible increase in reflectance. Vitrinite and the more reactive inertinitic components (such as reactive semi-fusinite) soften and swell from about 250-300oC and resolidify at approximately 700oC into the char form. Liptinite is highly reactive and is readily devolatilized, typically not resulting in char formation.

The solid products of pyrolysis can be qualified and quantified by applying the ICCP Char Classification Scheme (Table 3.4), or the Unburned Carbon Classification scheme (Table 3.7).

**Plates**

The plate shows a series of particles sampled at different temperatures under pyrolysis conditions. The parent coal was a crushed (passing an 850 µm screen), washed (12 wt% ash, 26.6 MJ/kg), Medium Rank C bituminous coal from the No. 4 Seam, Highveld Coalfield. The coal particles were fed into a large particle TGA operating under ambient pressure conditions in air. Each sub-sample was ramped to the desired temperature under the same ramp rate and air-flow conditions, then quenched and removed after a specified time.

A, B: Parent coal.

C, D: 450oC. Note the vitrinite particles show signs of devolatilisation, with the formation of pores. The vitrinite particles are a lighter shade of grey compared to the coal particles in A and B, indicative of a loss in volatile matter. Vitrinite is still clearly darker in shade than inertinite.

E, F: 650oC. All particles are more comparable in shade of light grey to white, although inertinite particles are still slightly lighter than vitrinite-derived particles. Vitrinite particles are still devolatilizing. Pyrite nodules are present in the devolatilizing vitrinite in image F. Several non-reacting inertinite particles are evident in this image.

G, H: 850oC. It is almost impossible to distinguish between vitrinite and inertinite based on shade alone. Textural differences are still evident in the non-reacting particles (top left image G). The particle in the centre of G is semi-reactive, developing a range of different pore sizes, and could be classified as a (still devolatilising) crassinetwork. Not all particles show devolatilisation pores; this is related to the nature of the coal and the pyrolysis conditions (limited oxygen availability).

**Plate 52: UTILIZATION: DTF pulverized fuel coal combustion chars**

The images are of combustion char residues from a Witbank coal sample (medium rank C, inertinite-rich, high-ash coal) typically used for pf combustion in South Africa, that have passed through a drop tube furnace (DTF) as part of the pre-utilisation assessment. The samples were screened to -38 microns, and then reintroduced to the DTF and sampled at four different residence times (P6 (shorter time) – P3 (longer time)), attaining temperatures in the region of 1200oC in under 2 seconds. Complete burn-out was not achieved for these particles. The resultant char samples were mounted and polished in the same manner as for coal petrography. The ICCP char classification scheme as tabulated below can be used to quantify and qualify the char forms observed in order to understand the conversion process. In this manner, different coals and the resultant chars can be compared prior to utilisation in a power station. The purpose of the plate is to provide visual evidence of pf char particles

**ICCP Proposed Combustion Char classification scheme (ICCP www.iccop.org)**

|  |  |  |  |
| --- | --- | --- | --- |
| **CHAR TYPE** | | DESCRIPTION | |
| **Tenuisphere** | | Spherical to angular, porosity >80%, >50% of wall area <3µm. >75% fused material | |
| **Crassisphere** | | Spherical to angular, porosity >60%, >50% of wall area >3µm. >75% fused material | |
| **Tenuinetwork** | | Internal network structure, porosity >70%, >50% of wall area <3µm. >75% fused material | |
| **Crassinetwork** | | Internal network structure, porosity 40-70%. >50% of wall area >3µm. >75% fused material | |
| **Mixed porous** | | Char with 25-75 % unfused material. Porosity >60% | |
| **Mixed dense** | | Char with 25-75 % unfused material. Porosity 40-60% | |
| **Inertoid** | | Dense, porosity 5-40%, >50% of wall area >3µm. Fused or unfused | |
| **Fusinoid/Solid** | | Inherited cellular fusinite structure or solid particle with <5% porosity. > 75% unfused | |
| **Mineroid** | Particle with >50% inorganic matter. | |

**Plates:**

**A, B, C:** Sampled at P6 (shorter residence time, lower temperature than P3). Note various shades of grey of the char particles, indicating that devolatilisation is still occurring. The cenospheres can be classified as tenuispheres or crassispheres using the ICCP scheme, depending on wall thickness. Honeycomb shaped particles are classified as tenuinetworks or crassinetworks, depending on the degree of porosity. Inert unreacted particles are termed inertoids or fusinoids, depending on inherent structure. Note large banded particle in image C with variable degree of reactivity.

**D, E, F:** Sampled at P3 (longer residence time, higher temperature than P3). Note lighter shade of char particles and more developed porosity of particles. Some inertoids / fusinoids are present. The lighter grey colour is indicative of a higher carbon and lower volatile matter content. Note the almost completely consumed chars in centre of image E (very thin walled cenospheres). The large particle in the middle of image F represents a tenuinetwork, possibly derived from a mixed coal particle such as that in image C.

**Plate 53: UTILIZATION: Unburned carbon in ash from pf combustion**

Unburned carbon - carbon-based particles which have not completely reacted or been consumed during conversion – typically occur in coal combustion ash. Generally, the unburned carbon particles are dominated by inert inertinitic components, such as fusinite or dense inertinite. But essentially all types of char particles can occur as unburned carbon in ash. The unburned carbon content is related to the efficiency of the power plant to combust the coal quality supplied. Highly efficient power stations where the boilers are optimised to burn the coal quality supplied, the unburned carbon can be as low as 0.3%. In inefficient conversion processes, unburned carbon values in excess of 20 % have been reported.

Whilst there is no international standard classification for fly ash and unburned carbon in order to quantify and qualify the char and mineral forms, the ICCP Working Group on combustion fly ash, and other authors, have proposed a classification scheme as listed in Table 3.6. Wagner *et al.* (2008) proposed a classification scheme concentrating on the unburned carbon in gasification ash (Table 3.7). The ICCP char classification scheme can also be used to assess unburned carbon, although it does not have a category for oxidized or partially consumed char particles (refer to Plate 52 caption).

It is recommended when assessing the unburned carbon in combustion ash that the analyst is familiar with the petrographic composition of the feed coal. Fusinite (fossilized charcoal) in the feed coal can resemble char particles in the ash.

**Plates**

1. Thin-walled, porous honey-comb structure, termed tenuinetwork.
2. Same particle under cross-polars revealing degree of anisotropy in the char walls. The degree of anisotropy is related to the original rank and type of the particle, as well as the combustion conditions.
3. Large, mixed char particle, termed a mixed porous char. The banded appearance resembles that of the original coal particle. Mineral inclusions in the char walls may be impeding sections of the char from reacting.
4. Fusinite embedded in a baked clay matrix. The unreacted, original bogen structure of the fusinite is still evident.
5. Mixed char particle (mixed dense), including an isotropic inertoid particle. This char may have originated from a vitrinertite coal particle, with mixed reactive and inert macerals.
6. Carbominerite char particle. The mineral inclusions may have impeded combustion of the char. At first look it may appear as if the particle is porous, but it actually contains quartz particles. The original coal particle was likely to have been a silicate-rich inertodetrinite particle.
7. Isotropic, oxidised particle, possibly sclerotinitic in origin. The particle was still combusting when quenched, but pore development was limited. This particle does not fit comfortably in the ICCP Char Classification scheme and a scheme for unburned carbon such as that proposed in Table 3.7 could be more applicable.
8. Partially consumed char particle showing a high degree of porosity and very thin walls (tenuinetwork).
9. Large fusinoid particle. Fusinite is carbon-rich but requires high temperatures to combust the particle (if at all). Fusinite typically reports as unburned carbon in coal combustion ash.

**Plate 54: UTILIZATION: Minerals in fly ash from pf combustion**

During coal conversion at high temperatures (typically 1200 – 1400 oC), minerals in coal will predominantly transform in various phases and forms, some as amorphous glassy masses, spherical glassy cenospheres, optically attractive mullite (crystal laths), a variety of spinels (magnetite), or ferrospheres (hematite). Generally, glassy amorphous phase minerals account for over 80% of the material in an ash sample. As it is not possible to determine the mineralogical composition petrographically, it is necessary to undertake SEM-EDX or Qemscan analyses when assessing the neoformed minerals in coal combustion ash. Ash can be used in the road construction industry; it can be processed to remove the unburned carbon for sale in the cement industry, and it can be classified and used as a filler in the plastics industry. Ash enriched in small, hollow, glassy cenospheres is of particular value to the plastics industry, but not all power stations produce fly ash with enough of these particles. Ferrospheres (iron-rich spinels) may be of interest in the rare earth element industry or as a source of iron. Petrographic observation and analysis of the mineral forms in fly ash can provide useful information about the temperature and gaseous environment in the combustion process, and an indication of the mineralogy.

**Plates**

1. A partially heated clay particle.
2. Amorphous glassy phase, typical of fly ash and bottom ash.
3. Angular quartz particles with sharp edges. Quartz will not typically show alteration at typical pf combustion temperatures.
4. Neoformed mineral sphere with glassy matrix and inclusions of quartz, pyrite, and crystalline laths.
5. Two spinel spheres. The upper dense ferrosphere is possibly of composed of hematite or magnetite. The lower porous sphere has a glassy matrix.
6. Two large spinel spheres showing contrasting crystalline texture of hematite / magnetite, with mullite crystal laths including in the sphere to the left. The sphere on the right exhibits coarser crystals, and the one on the left has glassy inclusions.
7. Spinel sphere embedded in a glassy matrix.
8. Two neoformed mineral spheres containing iron and magnetite, as well as mullite and glass.

**Plate 55: UTILIZATION: Unburnt carbon and ash from chain grate stoker combustion**

Different combustion technologies may produce different ash forms and variable char types. As with pf combustion, an assessment of the ash and unburned carbon can provide information pertaining to the operating conditions of the furnace, the efficiency of the process, and allude to the coal-feed properties. Chain-grate stokers (also termed travelling-grate technology) are used as small-scale boilers for hospitals and manufacturing industries, for example. Coal lumps (not pf) move along a grate fed by air from the base, and the ash and unburned carbon falls into a hopper at the end. The technology can be efficient if operated correctly, and can also be used to co-fire coal with biomass or waste materials (such as tyres and spent products). By quantifying and qualifying the unburned carbon, it is possible to determine the efficiency, or inefficiency, of the stoker operation and corrective measures can be thus applied if required to improve the conversion process. A high proportion of unburned carbon particles could imply an inefficient process, due to, for example less-reactive coal or larger particle sizes than the stoker was designed for, or inadequate air flow and oxygen levels. The unburned carbon could be recovered and reused. Unburned carbon forms in this plate are derived from medium rank bituminous South African coal.

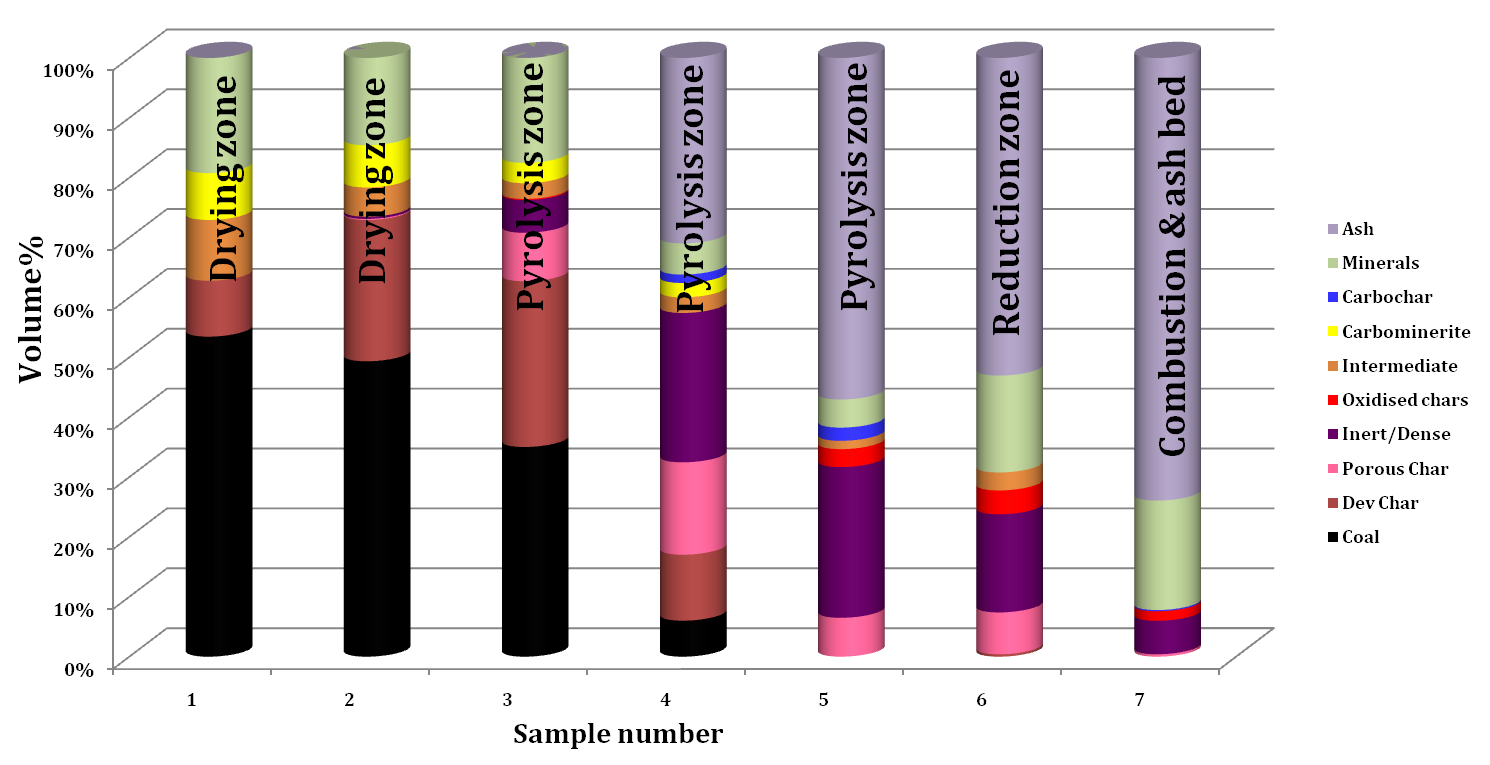
**Plates**

1. Porous unburned carbon particle, possibly still in the process of devolatilisation. The pores are not well developed. The particle has an incipient mosaic texture, possibly indicative of limited oxygen availability in the grate.

1. Large porous char with inertoid (mixed char) and glassy inclusions. The lenticular texture could result is similar to that produced in coke.
2. Large, mixed char with limited pore development due to the inertinite components. Fusinite and secretinite are readily observed.
3. Large char particle with a more reactive vitrinitic section to the right of the particle, and possibly an inertodetrinitic section to the centre and left, with variable reactivity. Minute pores are apparent in the vitrinitic band.
4. Large char particle with quartz and clay inclusions. This unburned carbon form would have been derived from a mineral-rich inertodetrite coal particle.
5. Amorphous orange-coloured mineral containing iron-rich spinel minerals towards base.
6. Mullite crystal laths in a glassy matrix.
7. Two large glassy cenospheres (top right and bottom left) joined by spinels and mullite crystals in a glassy matrix.

**Plate 56: UTILIZATION: Pyrolysis**

To understand pyrolysis occurring in lump coals (-75 mm to +6 mm), Highveld coal was homogenously placed in a Packed Bed Reactor (PBR) (Malumbazo *et al.,* 2012). The reactor can achieve a maximum temperature of 1250 0C under atmospheric pressure. The temperature was controlled by adjusting the air and nitrogen flow throughout the bed. After cooling, the reactor was opened like a coffin to enable sampling of the bed in profile. Seven equal sized fractions were dissected from the: drying zone (0 to 2000C), pyrolysis zone (2000C to 9800C), reduction zone (11600C to 12250C), and combustion and ash zones. Petrographically the morphological alteration of the feed coal to char was examined. These changes are illustrated in the plate opposite and figure below. The carbon type analysis was applied to quantify the particles and track the changes during pyrolysis.



**Plates**

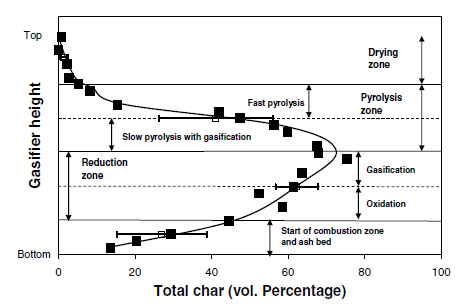
1. Feed coal showing banded vitrinite and inertinite coal.
2. Banded particle sampled from the drying zone showing signs of devolatilisation. The vitrite bands exhibit fairly large pores.
3. Char with a coke-like appearance, exhibiting plasticity.
4. Banded porous char particle sampled from the pyrolysis zone. The highly porous bands are likely to have been derived from vitrinite-rich coal bands.
5. Mixed char-particle from the combustion zone. This char possibly originated from an inertodetrite particle with mixed reactive and inert components. The more reactive components have caused the porous structure.
6. Ash particle sampled from the ash zone, exhibiting various forms of neoformed minerals.

**Plate 57: UTILIZATION: Gasification chars: Fixed-bed dry-bottom gasification**

Knowledge of the behaviour of particles during gasification is important in order to understand the conversion process and to maximise syngas production. Fixed-bed dry-bottom (FBDB) gasifier technology operation is affected by the permeability of the coal bed, particle reactivity, and ash formation, including other operational variables. The FBDB gasifier is a counter-current process designed to gasify lump coals (+6 – 75 mm). The gaseous agents (oxygen enriched air, and steam) enters at the base of the gasifier where the cooled, dry ash is removed. The coal enters the top of the gasifier, where it is pressurized. The coal particles move down through the gasifier, progressing through different reactions zones, as indicated in the figure below. Drying, pyrolysis, gasification, and combustion zones can be tracked by assessing the carbon conversion profile.

The samples in the plates were taken sequentially from a quenched, turned-out gasifier. Applying the carbon form analysis (Table 3.7; Bunt *et al.,* 2009), the different reaction zones in the gasifier were readily determined. The feed coal was a typical Highveld coal, ash-rich (around 30%), vitrinite-poor (less than 20 vol. %), medium rank C bituminous coal (approximately 0.62 RoVmr%).

**Figure depicting the total char profile through the turned-out gasifier. The carbon-form analysis enabled the determination of distinct zones within the gasifier (Bunt *et al*., 2009).**



**Plates**

1. Banded feed coal, with vitrinite and inertinite bands.
2. Devolatilising particle from hotter region of the gasifier (pyrolysis zone), with the swelling of the reactive vitrinite band constrained by the fusinite bands either side.
3. Sample extracted from the gasification zone. The whole particle has been charred (as revealed by the white shade), but the vitrinite and inertinite bands are still apparent based on texture. The porous band in the centre was constrained by the non-reactive inertinite bands (Image taken under crossed-polars with a lambda plate, hence slight textural colouration of the inertinite-derived char component).
4. Porous thin walled, isotropic char from the combustion zone. This vitrinite-derived char was not constrained by non-reactive components.
5. Unreacted fusinite (fusinoid) (left) and porous vitrinite-derived char component (bottom right) within same particle.
6. Reacting (bottom left) and unreacted coal particles (top). This indicates that some particles move through channels within the gasifier and are not given time to react, or other particles from hotter zones move back into the cooler zones. Petrographically it is possible to quantify the proportion of coal to char at different levels in the gasifier.
7. Inertinite-rich char particle showing variable degree of porosity with carbonate cleats.
8. Amorphous glassy phase mineral containing other minerals and tiny organic fragments.

**Plate 58: UTILIZATION: Gasification chars: Entrained flow gasification**

An entrained flow slagging gasifier (Koppers-Totzek type) was tested for application in South Africa burning typical South African coals.  The process used pulverized coal (usually less than 74 µm) blown into the gasifier with a mixture of steam and oxygen. The gasifier operated at atmospheric pressure and at high temperatures ranging from 1600–1900°C. The coal dust and gasification medium flowed co-currently in the gasifier, and, because of the small coal-particle size, the residence time of the particles was approximately one second. Although this residence time is relatively short, high temperatures enhanced the reaction rates, and, therefore, it was claimed that almost any coal can be gasified in the Koppers-Totzek system. Tars and oils were evolved at moderate temperatures but cracked at higher temperatures, so that there were no condensable tarry materials in the products. In most coals, the ash melted and flowed as slag. The product gas, known as [synthesis gas](https://www.britannica.com/science/synthesis-gas) (a mixture of carbon monoxide and hydrogen), was primarily aimed for used in ammonia manufacture.

The plates show a variety of coal-derived unburned char particles in the fly ash from this entrained-flow type gasifier. 35 - 65% unburned carbon was determined in trial tests indicating that the residence time in the gasifier was too short for these coals.

**Plates**

1. Tenuinetwork-type char. Thin-walled network with hollow core. This char form is typically observed in the Koppers-Totzek gasification samples, possibly derived from vitrinite, which is highly reactive. The extremely high temperatures effectively cause the reactive coal particles to form an unusual doily-type structure. Low oxygen availability may have been the reason that the chars were not consumed.
2. Similar to image A, slightly less porosity.
3. Particle with concentric rows of small incipient pores with a relatively dense central section. The core of the char possibly consists of less reactive material.
4. Characteristic reactive char in the center, with a mixed char type to the top right.
5. Mixed char form, possibly derived from maceral components with variable degree of reactivity.
6. Char particle on the left contains mineral inclusions. Char particle towards middle right has included inertinite.

**Plate 59: UTILIZATION: Coke**

Coals suitable for coking and subsequent application in the metallurgical industry have specific properties, as discussed in Chapter 3.4.5; namely: coals that possess high vitrinite contents (60 – 85 vol.%) in the bituminous B range of rank. Not all coals coke, and not all particles in coking coals react. To form a coke, the coal is heated in the absence of air, and the reactive components melt, vesiculate, and harden into sponge-like masses of almost pure carbon. The fluidity is believed to be due to the breakage of bonds between aromatic units due to heating. The maximum fluidity occurs between 350 – 450oC; from 450 – 550oC the melt progressively hardens into coke, forming a green coke. Green coke will still contain volatile matter. The green coke is then calcined at 1000oC to form metallurgical coke.

Petrography is used to evaluate the applicability of a given coal for coking, and to predict the strength and reactivity by assessing the texture and composition of the coke. As discussed in Chapter 3.4.5, the binder and filler phases affect the strength of the coke. The texture of the fluid phase is related to the initial reflectance of the reactive macerals. A quantification of the anisotropic components (mosaic, lenticular, ribbon) enables the assessment of the coke in terms of reactivity as well as linking back to the original coal (Table 3.5). Ribbon phase for example, originates from a higher reflecting, low volatile vitrinite; and the fine mosaic phase originates from higher volatile lower reflecting vitrinite. Blended coals will result in mixed textures.

Table 3.5 provides a coke classification scheme.

**Plates**

1. Isotropic vitrinite (%RoV <1.0)
2. Anisotropic - Fine mosaic (R%oV 1.1-1.3)
3. Anisotropic - Coarse mosaic (approx. %RoV 1.4-1.6)
4. Anisotropic - Ribbon mosaic (%RoV 1.6+)

**Plate 60: UTILIZATION: Coke continued**

Non-reactive inertinitic macerals retain their shape and texture during coking, and become embedded in the coke walls, where they are fused into the coke structure. Referred to as the filler phase, the inertinitic macerals play an important role in the furnace, providing strength to the particle and heat to the reduction process.

Coke can be made from coal and petroleum; petroleum coke (petcoke) does not have inertinite inclusions.

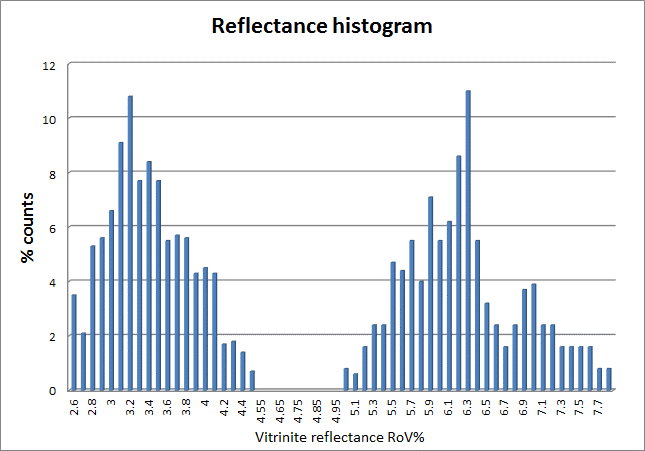
**Plates**

1. Large coke particle showing some degree of porosity (towards bottom L), inert filler components (towards top L), and circular mosaic texture, becoming increasingly courser towards the bottom right.
2. Same image as A, taken under crossed-polars with a retarder plate. The isotropic filler and anisotropic binder phases are enhanced by the use of the retarder / lambda plate. The circular mosaic phase is derived from high volatile bituminous coal.
3. Coke particle showing a greater degree of porosity compared to A, and incipient mosaic texture.
4. Same image as C, taken under crossed-polars with a retarder plate. The isotropic filler phase (fusinite inerts) are more apparent in the coke cell wall, as is the fine circular mosaic texture in the binder phase. Some of the pores are lined with vapour deposited carbon.
5. Composite image of a petroleum coke sample. Bottom left: mesophase (droplets), and ribbon texture dominating the particle.

**Plate 61: UTILIZATION: Calcined products**

Calcination, or calcining, is used to remove all the volatile substances in the coke or coal (typically anthracite) in order to improve the electrical conductivity of the material, as discussed in Chapter 3.4.5. Calcining aligns the carbon molecules into semi-crystalline forms. Typically calcining occurs at temperatures over 2000oC. Petrographically, it is possible to assess the reflectance as in indication of heat treatment.

The figure below demonstrates the use of reflectance analysis to assess the degree of heat treatment in anthracite. The anthracite has been calcined, which has elevated the reflectance values.



calcined anthracite

6.26 %RoVmr

anthracite

3.38 %RoVmr

**Plates**

A – C: Anthracite.

A) Monochromatic image with vitrinite reflectance readings recorded on the particles (%RoV).

B) Monochromatic image with vitrinite reflectance readings recorded on the particles (%RoV).

C) Same image as (B) under crossed-polars with retarder plate in light path, highlighting isotropy and anisotropy in the particles.

D – F: Calcined Anthracite.

D) Monochromatic image with vitrinite reflectance readings (%RoV); note these readings are now far higher due to the effect of calcination. Some stress cracks can be observed.

E) Monochromatic image with vitrinite reflectance readings (%RoV).

F) Same image as (E) under crossed-polars with retarder plate in light path, highlighting isotropy (vitrinite particle to right), and anisotropy (inertinite band in particle on left).

**Plate 62: ABNORMAL CONDITION: due to weathering (physical features) – cracks, fissures**

As discussed in Chapter 3.3.3, coals oxidise and weather when exposed to water and oxygen. Enhanced oxidation may result in spontaneous combustion of the coal. Weathering during stockpiling and transport may alter the inherent physical and chemical properties of the coal, affecting the intended use of the coal. Fluid properties required for carbonization drop rapidly as oxidation increases, destroying the coking ability of coal. Physical weathering may enhance or promote fissures and cracks in particles, and may render the particles highly friable leading to fines generation. Highly fissured and / or cracked particles may be due to *in-situ* weathering (ground water movement, underground river channels), or may form during beneficiation, handling, and / or stockpiling. The resultant enhanced surface area will impact coal properties.

Natural weathering and oxidation may result in petrographically observable and quantifiable microfissures, microcracks, microrpores (due to heating), oxidation rims (oxyrims), mineral alterations, leaching holes, and so on, as indicated in Table 3.2.

**Plates**

1. Inherent fissure in inertinite particle. This particle would be considered to be fresh with limited evidence of weathering or oxidation.
2. Extensive fissures in inertodetrinite particle. This coal seam has been exposed to an underground water flow and is highly fissured. The fissures appear to link between the quartz grains through the inertodetrinite particles.
3. Fissures and cracks in a vitrinite coal particle. Some minerals have been trapped in the larger cracks, indicative of fluid movement. There is no clear direction of propagation.
4. Shattered vitrinite particle with calcite infilling some cracks. The cracks and fissures are most likely related to high pressure fluid intrusions, resulting in shattered coal particles. As the particle is essentially cemented by the calcite, it is unlikely to result in fines generation.
5. Extensively cracked particle, essentially rendering the particle as highly friable. This coal had been stockpiled.
6. Small, highly cracked and fissured duff particle on right of image. In instances where weathered discard duff particles are added to coal shipments to increase the shipment mass and reduce the discard pile, problems may arise with regards to handling, beneficiation, utilization, and even self-heating.

**Plate 63: ABNORMAL CONDITION: Effect of heat and oxyrim formation**

Coal may be exposed to heat *in-situ* due to igneous intrusions, in-seam coal fires, or to self-heating and spontaneous combustion in coal stockpiles / discard piles, or during transportation. With exposure to increasing temperature, coal particles may exhibit sharp changes in reflectance leading to oxyrim formation, increases in reflectance, and even devolatilisation pores, but may not necessarily achieve spontaneous combustion. Igneous intrusions, which occurred during the break up on Gondwana in the Triassic Period, resulted in numerous dolerite sills and dykes through the coal seams of southern Africa. The heat from the dolerite intrusions resulted in the devolatilization of coals in certain areas; mining activity is generally avoided in these areas and in aureoles around the intrusions. In some instance, coals sold in the market may contain heat affected particles from “hot” stockpiles and included to make up required masses. Petrographically it is easy to observe and quantify such inclusions. It is important to quantify the proportion of heat affected particles in a sample as these particles negatively affect coal beneficiation, and do not combust easily as the chemical structure of the surface has been altered.

**Plates**

1. Two vitrinite particles with different reflectance values. A small portion of the sample contained vitrinite particles with reflectance values between 0.46 to 0.49 %RoV. The majority of the particles reported reflectance values between 1.3 to 1.8 %RoV. The sample is believed to have been taken in close proximity to a sill (igneous intrusion), as the other samples higher up the borehole core report average reflectance values of around 0.46 %RoVmr. The sample immediately below only contained heat affected particles with elevated reflectance values.
2. The bottom left particle is a high reflecting devolatilizing coal particle, clearly different from the rest of the sample where the vitrinite particles are not heat affected. The exploration area intersected dolerite intrusions, and the high temperatures associated with the intrusions resulted in the devolatilisation of the coal in contact with the intrusion.
3. Narrow, light-coloured oxidation rim on right margin of the particle. The rim may have occurred around the whole particle, but crushing during sample preparation has broken the particle apart. The particle also shows evidence of devolatilisation by the pores that have developed in the vitrinite bands. This particle has seen elevated temperatures on a coal stockpile, and may have been blended in with unheated coal.
4. Thick, light-coloured oxidation rim on particle margin and lining the cracks. The exact process of oxyrim formation remains unclear. It is possible the particle was exposed to high temperature gases passing by, which only affected the available surface area. The oxyrim in the crack is thinner than the outer oxyrim. The sample was taken from a self-heating coal discard pile in the Witbank Coalfield.
5. Dark oxyrim on margin of particle. The oxidation rim includes tiny stress cracks that appear to penetrate into the non oxyrim zone. Dark oxidation rim formation is believed to be due to humic acid accumulation. Dark oxyrims are observed in weathered coals that have not been exposed to high temperatures.
6. Extensive oxyrim formation along with stress cracks on particle margin. The rim is darker than the particle interior, but both indicate exposure to high temperatures. It may be that the darker rim formation occurred over time due to weathering, and subsequently the particle was exposed to high temperatures, resulting in the high reflectance. The sample was taken from a burning discard pile.

**Plate 64: ABNORMAL CONDITION: Mineral Alteration due to weathering / oxidation**

Minerals in coal will alter when exposed to oxygen and water, as well as solutions with variable pH. Mineral alteration appears to be one of the earliest changes due to weathering and oxidation identifiable petrographically. Pyrite and carbonate minerals appear to alter to iron (jarosite, limonite, hematite) and calcium sulphates (gypsum). Sulphuric acid produced by the inorganic oxidation of pyrite reacts with calcite and clays, and concentrates iron in alteration minerals. White and yellow mineral salt deposits can be observed around coal stockpiles, often as soon as a few days. In order to accurately identify the mineral phases and alternations, it is necessary to complement coal petrography with SEM-EDS and XRD analyses.

**Plates**

1. Pyrite occurring as infilling of cell-wall structure is showing evidence of leaching. The pyrite may have been epigenetic, possibly replacing syngenetic clays which prevented compaction of the cell walls; a mineral form would have been responsible for retaining the cell-wall structure during peatification and coalification. As some of the cell cavities are empty, it is likely that the pyrite has leached out. This may result in acid water formation (sulphuric acid).
2. Salt mineralization around edges of coal particles. The mineralization may be jarosite.
3. Salt mineralization around edges of coal particles. The mineralization may be iron oxide possibly enriched in hematite (red colouration).
4. Calcite veins, occurring as epigenetic minerals in a vitrinite particle, appear to be being replaced by sulphates, leading to gypsum formation. The occurrence of gypsum in weathered coals is common.
5. This form of alteration mineral is not observed in freshly mined coal samples, but is frequently found in stockpiled or weathered coals. The sample was left exposed for 1 month during weathering experiments. Thus, the mineral alteration is a useful indicator when assessing blend or contaminated samples. The neoformed mineral is likely to be an iron oxide.
6. Alteration and / or mineral replacement in a cleat. It is probable that the cleat was pyrite, which has been replaced by iron oxides / ferrous sulphates at the margins.

**Plate 65: Dispersed organic matter in carbonaceous shales**

The determination of primary vitrinite and its reflectance reading is vital for determining the peak thermal maturity experienced by a sedimentary rock (ASTM, 2014).

The images in this plate are of a stratigraphic series through the Permian Ecca sequence in the Main Karoo Basin, South Africa. Carbonaceous shales and associated sandstones/mudstones are encountered. The samples were taken from different horizons from the KWV borehole, drilled in the Eastern Cape: (top) Ripon, Collingham, Whitehill, and Prince Albert (bottom, above basement). A portion of the core sample was prepared perpendicular to the bedding plane and mounted in epoxy resin, ground and polished in accordance with SANS ISO 7404-2.

The samples are vitrinite-lean; in fact, most samples do not appear to contain vitrinite. A variety of solid bitumens and inertinite fragments are observed in most samples. Inertinite includes fusite and inertodetrite fragments. The TOC values reported include the carbonates as well organic carbon matter in many samples, potentially resulting in elevated values where there is a high carbonate component in the sample. Only samples from the Whitehill or Collingham Formations contain appropriate organic matter on which to obtain reflectance data. The mean reflectance readings indicate that the samples are over mature, with readings falling between 2.5 and 6 %RoV. No samples exhibited any degree of fluorescence.

**Plates**

A – B. Ripon Formation. Fine grained mudstone with occasional inertinitic fragment or bitumen-like deposit. Depth: 1436 m; TOC: 0.68; %RoVmr: not determined

C – D. Collingham Formation. Fine grained matrix with included quartz and pyrite grains and bitumen or algal mats. Depth: 2296 m; TOC: 2.36; %RoVmr: 3.437

E - F. Whitehill Formation. Fine mudstone matrix with rare organic fragments, possibly vitrinite in origin. Extensive amount of pyrite, as well as bitumen-like globules. Depth: 2299 m; TOC: 2.28; %RoVmr: 3.486.

G – H. Prince Albert Formation. Fine grained matrix with quartz grains, and devoid of pyrite. Rare inertinitic fragments and carbonates. Depth: 2317 m; TOC: 0.50; %RoVmr: not determined

Samples courtesy of Mr Christopher Baiyegunhi

**Plate 66: Aspects to watch out for**

Coal petrography is an interesting field, but it can also pose many challenges for the inexperienced petrographer. A few aspects are highlighted below.

**Plates**

A – B. The need to use fluorescence or blue light to accurately determine liptinite. In this instance, the cracks are infilled by the epoxy resin (yellow-green) and other cracks contain exudatinite (darker orange) (B). Under white light (A), it is not possible to determine the exudatinite in the cracks. Plates 31 and 34 show other examples of the need to use fluorescence to accurately determine liptinite.

C – D. it is necessary to vary the light intensity when examining particles with high reflectivity. In image (C) the fusinite and pyrite particles appear very white. When the light intensity is lowered (D), the difference between the two inclusions becomes very obvious. Fusinite has the sharper edges and it less bright. Pyrite generally has a bright yellow-white colour.

E - F. Do not misidentify particles without appreciating the context. In Image (E), a high reflecting char is included in the maceral matrix, indicative of the particle having formed prior to coalification. It would be classified as fusinite (fossilized charcoal). However, where such particles are liberated due to crushing during sample preparation (F), the analyst may confuse the fossilized char with a heat-affected particle formed as a result of an igneous intrusions or spontaneous combustion (also refer to Plate 63).

**Plate 67: Further aspects to watch out for**

A – B. Petrographic analysis of anthracites can be complicated. It is advised to assess the coals using polarized light or crossed-polarised light with the use of a retarder / lambda plate. It is necessary to understand the structure of vitrinite and inertinite as the shade of grey between the components becomes almost identical at the higher ranks. In image (A) (white light, non-polarized) it is difficult to determine vitrinite and inertinite. Image (B) enhances the inertinite due to anisotropy (centre of particle) (crossed-polars with lambda plate).

C. Even pyrite grains are difficult to distinguish when the reflectance of a particle is enhanced. Pyrite acquires a slight blue tinge at this level of rank, differing from the more yellow-white colouration in lower ranks. (4.28 %RoVmr).

D. Collotelinite is the preferred vitrinite maceral for reflectance analysis. However, there are instances when collotelinite may report a range of reflectance values. In this image (monochromatic light), the lighter bands have reflectance values of 0.91 – 0.92 %RoV, and the darker bands 0.81 – 0.84 %RoV; both bands resemble collotelinite. Readings for both bands should be taken.

E. All liptinites fluoresce in lower rank coals (up to %RoV 1.5), but with varying degrees of intensity. The fluorescence intensity is related to the rank of the coal as well as botanical origin. In rare instances, oxidized liptinite may occur, which may exhibit very weak fluoresce intensity, not adequately determined optically. It is important to be able to recognize liptinite based on texture as well as fluorescing capacity.

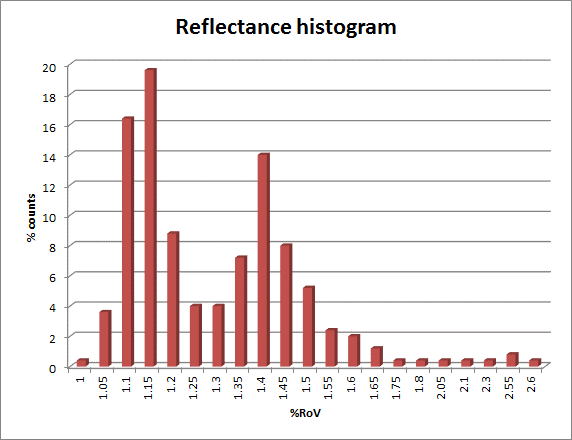
F. Cork type structure infilled with humic colloids. The structure resembles both suberinite and corpocollinite. Suberinite, by definition, is a liptinitic material, originating from suberin-impregnated cell walls of cork tissue (Diesell, 1992); it occurs in lignites and subbituminous coals. Corpocollinite is a maceral of the vitrinite maceral group occurring in low rank bituminous coals. In the lower rank coals, the cell-wall structure would be far darker than the inner humic substance.

G. Polishing effects where highlighted in Plate 1, but require reiteration. Polishing residue and scratches can provide artefacts on the surface of the sample, and petrographers need to be aware of what to expect in a coal sample. The oval watermark in this image appears to darken the vitrinite within the watermark. The pockmarked line is due to scratching rather than the leaching of a mineral.

H. Petrography can be very complex. Many Gondwana coals are allochthonous or hypoautochthonous, where the peat and partially coalified vegetation is reworked several times and deposited as fragments in an organic matrix. All coals are different, which makes petrography an exciting and challenging field.

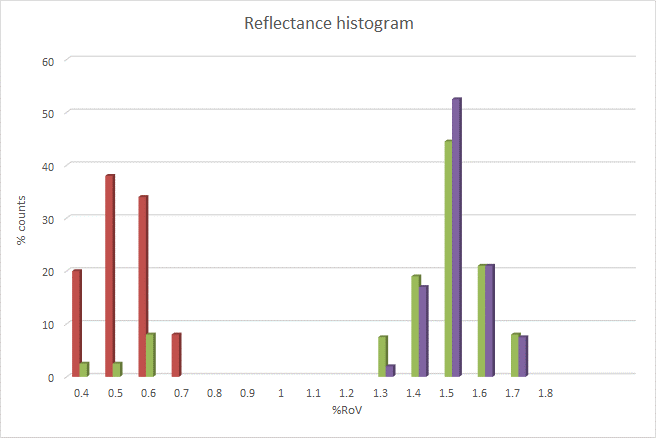
**Plate 68: Use of petrography as a forensic tool**

Frequently, a petrographer may be tasked with determining whether a shipment of coal consists of a single source or a blend or coal. Coal blending is a regular occurrence to meet specifications, but issues do arise where the blending has not been conducted correctly, or even to the buyer’s knowledge. The seller may “blend” in some coal from stockpiles or waste particles to increase the shipment tonnage. Whilst routine chemical analyses may not reveal a 5 – 10 % blend component as the analysis is a bulk analysis, coal particles do not behave as a bulk when fired in a boiler, for example. This may lead to anomalous behaviour. Petrographically, where each particle is considered, blend determination and apportionment is easily conducted.



The reflectance histogram to the left and image (A) reveal two to three blends occurring in this coal sample. The particles between 1 – 1.5 %RoV fall into the coking range of rank and may be compatible. The particle above 1.5 %RoV to 2.5 %RoV are unlikely to be compatible for coking and may hinder the process. Image (A) (monochromatic light) highlights this point, with the particle in the centre reporting 2.56 %RoV and the other particles around 1.30 %RoV.

The reflectance histograms below represent three borehole core samples. The samples intersected a sill towards the base, which resulted in maturation of the coal over a very short distance (less than 30 cm). In this instance the middle sample (green in histogram below) may appear to be a blend of the samples either side, but by understanding the context and sample origin, it can be concluded that the change in reflectance is due to the igneous intrusion. Images B – D depict the change in reflectance.



Green: 1.43 %RoVmr

Standard Deviation: 0.371

Purple: 1.58 %RoVmr

Standard Deviation: 0.045

Red: 0.48 %RoVmr

Standard Deviation: 0.040

**Plate 69: Witbank Coal Seams No’s 2, 4, and 5.**

The Witbank Coalfield is situated in a retroarc foreland basin in the Main Karoo Basin of South Africa. The peat accumulated in a fluvio-deltaic environment during the Permian, with a gradual warming of climate from subarctic to temperate. The climate influenced the vegetation type and the transformation of the vegetation during peatification. The Plate opposite and results table below capture the petrographic differences in the coals from the lower No. 2 Seam, No. 4 Seam, and the upper No. 5 Seam. The No. 2 Seam vegetation grew in glaciofluvial and glaciodeltaic environments, predominantly in freshwater, and gave rise to vitrinite-rich horizons, with thinner horizons richer in inertinite macerals (Falcon, 1989) (Images E – F). The No 4. and No. 5. Seams formed in fluvial, deltaic dominated environments, a period of cyclotherms and fast changing climate and floras (Falcon, 1989). The No. 4 Seam reports a far higher inertinite content, indicative of a drier environment and an environment where the peatified material was reworked, now occurring as inertodetrinite, and typically deposited with silicates (Images C – D). The No. 5 Seam formed in a more waterlogged environment as indicated by the high vitrinite content, with inertinite-rich horizons characteristic of drier periods during peatification (Images A – B). These medium rank C bituminous coal samples have been washed at a RD 1.9 to remove the mineral matter. In the series of photographs opposite, the No. 2 Seam sample (Images E- F) was slightly heat affected due to the presence of a dolerite sill.



**Plate 70: Interesting geological features, unusual macerals, minerals**

As each coal deposit is unique in terms of its petrographic composition, and peatification and coalification are transitional processes, a wide variety of maceral forms exist. This makes petrography exciting, as well as challenging. As coal forms in a sedimentary environment, it is possible to determine geological features and processes at play. The series of images following try to capture a few interesting geological features.

1. Compaction ratios: It is possible to determine the compaction ratio of the organic matter by assessing the draping of vegetable matter (now macerals) over included minerals and macerals. In this instance, draping has occurred over a piece of fusinite, deposited in a water-logged, sedimentary environment where the organic matter was preserved. The fusinite has deformed the underlying layers, making it difficult to determine the correct orientation of the sedimentary structures. The compaction ratio in this image appears to be close to 8:1. (Medium rank bituminous coal).
2. Various transformation stages. The devolatisation pores in this vitrinite particle are infilled with fine fragments of organic and inorganic matter. This clearly indicates that devolatilisation occurred during the late stages of peatification, when there was still movement of the vegetation (autochthonous environment). The vitrinite particle formed in an anaerobic environment, but was subsequently exposed to heat, hence the devolatilisation pores. It is likely that the detrital material was transported by water and deposited within the vitrinite pores. The sample originates from a coal in the coking coal range of rank (Medium rank B bituminous coal).
3. Microfaulting. A micro strike – slip plane is evident in this image, indicative of some tectonic events impacting on the coal after coalification.
4. Microfaulting. A micro strike – slip plane is evident in this image, possibly causing crack propagation.
5. A series of images from an inertodetrinite particle have been stitched together. Vitrinite appears to meander through the inertodetrinite, possibly indicative of secondary vegetation growth on the detrital vegetation (the inertodetrinite).

**Plate 71: Unusual features**

1. The middle section of the image appears to represent a series of flow-like structures, similar to micro cross-bedding observed in sedimentary formation, possibly indicative of a wave induced current. Alternatively, the vitrinite may consist of broken cell walls of slightly higher reflectance than the vitrinite matrix. This is an example of different opinions between petrographers. (Medium rank C bituminous coal, Springbok Flats Coalfield).
2. The fusinite fragments included in the vitrinite matrix exhibit three distinctive shades of grey to white. This is possibly indicative of varying degrees of exposure to peat fires and / or oxidation. The fragments are included parallel to the bedding plane, indicating deposition into a water-logged, sedimentary environment. (Medium rank C bituminous coal, Highveld Coalfield).
3. The sharp contact between two maceral groups is evident. The top section of the image is reworked, detrital vegetation forming inertodetrinite with a high mineral matter content. The bottom section represents a vitrinite band, with minor very thin clay inclusions. The sharp contact may indicate that the vitrinite formed from a branch or a single botanical structure in an anaerobic environment. The reworked material was subsequently deposited in association with the vitrinite. (Medium rank C, Hwange Coalfield, Zimbabwe).
4. The image shows a hole which was previously infilled by a syngenetic mineral. The mineral would have been included at the time of peatification as indicated by the draping of the maceral bands. The mineral has subsequently leached out, but the hole has been retained. (High rank C anthracite, Kwazulu-Natal Coalfield).
5. Beautiful syngenetic siderite growth in vitrinite matrix. The vitrinite layers (alternating bright and dark) are slightly deformed due to the mineral growth. (Medium rank C bituminous coal, Springbok Flats Coalfield).
6. Secondary or even tertiary mineralisation. The pyrite framboids (syngenetic) have attained concentric rings of a secondary iron-sulphide deposit (epigenetic), resulting in a botryoidal appearance. When assessed by SEM-EDS, the rings contain varying proportions of iron and sulphides. The additional sulphides may have originated from hydrothermal fluids; the coalfield is extensively intruded by igneous sills and dykes. (Medium rank C bituminous Coal, Limpopo Coalfield).