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Maceral Characteristics and Vitrinite Reflectance Variation of The High Rank Coals, South Walker Creek, Bowen Basin, Australia

Karakteristik Maseral dan Variasi Vitrinit Reflektan pada Batubara Peringkat Tinggi, South Walker Creek, Cekungan Bowen, Australia

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Abstract

The Permian coals of the South Walker Creek area, with a vitrinite reflectance (Rv_{max}) of 1.7 to 1.95% (low-volatile bituminous to semi-anthracite), are one of the highest rank coals currently mined in the Bowen Basin for the pulverized coal injection (PCI) market. Studies of petrology of this coal seam have identified that the maceral composition of the coals are dominated by inertinite with lesser vitrinite, and only minor amounts of liptinite. Clay minerals, quartz, and carbonates can be seen under the optical microscope. The mineral matter occurs in association with vitrinite and inertinite macerals as syngenetic and epigenetic mineral phases. The irregular pattern of the vitrinite reflectance profile from the top to the bottom of the seam may represent a response in the organic matter to an uneven heat distribution from such hydrothermal influence. Examination of the maceral and vitrinite reflectance characteristics suggest that the mineralogical variation within the coal seam at South Walker Creek may have been controlled by various geological processes, including sediment input into the peat swamp during deposition, mineralogical changes associated with the rank advance process or metamorphism, and/or hydrothermal effects due to post depositional fluid migration through the coal seam.

Keywords: maceral characteristics, vitrinite reflectance, South Walker Creek coals, Bowen Basin

Abstrak

Batubara berumur Perem dari daerah South Walker Creek, dengan vitrinit reflektan berkisar antara 1,7% sampai 1,95% (masuk kategori low-volatile bituminous - semi anthracite), merupakan satu-satunya batubara peringkat tinggi di Cekungan Bowen yang ditambang untuk pulverized coal injection (PCI). Studi petrologi pada lapisan batubara menunjukkan komposisi maseral yang didominasi oleh inertinit, dengan sedikit vitirinit dan liptinit. Mineral lempung, kuarsa, dan karbonat juga dapat diidentifikasi di bawah mi-kroskop organik batubara. Mineral-mineral tersebut muncul berasosiasi dengan maseral vitrinit dan inertinit sebagai mineral syngenetis dan epigenetis. Pola profil reflektan vitrinit yang tidak beraturan dari bawah ke atas lapisan batubara memberikan gambaran respon dari material organik yang berbeda-beda terhadap distribusi panas yang dihasilkan dari proses hidrotermal. Hasil pengamatan terhadap analisis maseral dan reflektan vitrinit menunjukkan variasi komposisi mineral dalam lapisan batubara South Walker Creek dikontrol oleh berbagai proses geologi, termasuk proses pengendapan batubara itu sendiri, proses peningkatan kematangan batubara, dan proses perubahan yang diakibatkan oleh pengaruh hidrotermal ke dalam lapisan batubara pasca proses pengendapan.

Kata kunci: *karakteristik maseral, reflektan vitrinit, batubara South Walker Creek, Cekungan Bowen*

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Introduction

The South Walker Creek deposit is located on the eastern flank of the Carborough Syncline, within the Nebo Synclinorium in the northern Bowen Basin (Figure 1). The coal-bearing sequence is part of the Rangal Coal Measures, which are comformably underlain by the Fort Cooper Coal Measures and overlain by the Rewan Formation. The Permian coals of the South Walker Creek area are one of the highest rank coals currently mined in the Bowen Basin. The mine works one of the highest rank coals currently extracted from the Bowen Basin, mainly for the pulverized coal injection market.

Studies carried out at UNSW (Fraser *et al.*, 2006) on the mineralogy of this coal seam have identified unusual mineralogical assemblages in the vertical sequence, with illite-chlorite assemblages resembling a metamorphic association in some parts of the seam and kaolinite rich assemblages of more normal sedimentary origin in others. Permana *et al*. (2010) and Permana (2011) show that the mineralogical variation in the South Walker Creek coals may be due to one of the three following possibilities: (1) changes in the nature of the sediment input to the peat swamp, (2) changes associated with rank advance process or metamorphism, or (3) changes associated with hydrothermal effects due to the late-stage fluid migration through the coal seam.

Uysal *et al.* (2000a) suggested that the hot fluid flow has transferred heat to specific coal measure units in specific areas in the northern Bowen Basin, increasing the coal rank and rank gradient. Moreover, Golding *et al.* (2000) suggested that a short lived hydrothermal event in the Late Triassic was a factor responsible for thermal maturation of the Late Permian coals in the central and northern Bowen Basin. They indicated that hydrothermal fluids may be effective in heat transfer for organic maturation and clay mineral diagenesis.

This paper is focused firstly on maceral characterization and the relationship between macerals and mineral matter occurrence. This is followed by the results of vitrinite reflectance analysis, to identify any correlation between the mineralogical variation and changes in coal rank or other thermal effects visible in the seam profile. Examination of the organic matter at a microscopic scale, including maceral studies and vitrinite reflectance analysis, may help to identify more clearly the processes involved.

Methodology

Coal Petrographic Analysis

Coal petrographic examination was applied to determine the rank and maceral composition of the coal seam in the South Walker Creek. Forty polished block sections were prepared for this analysis. Twenty four samples were collected from borehole 11424 and sixteen samples from borehole 11852. All the polished block samples were examined using a Zeiss Axioplan reflected light microscope, fitted with a Zeiss MPM photometer as well as both white (100 W halogen) and blue violet (HBO) light sources.

Maceral identification was conducted in reflected light using oil immersion objectives at a magnification of 20X and 50X. Because the samples for petrological study were small fragments and not fully representative of the coal plies, the analytical technique was based on qualitative assessment rather than measurement of maceral abundance. The observations were mainly focused on the maceral characteristics and their association with mineral matter occurrence in the coal samples. The identification and classification of macerals used in this study are based on Australian Standard 2856.2 (Australian Standard, 1998) (Table 1).

Mean maximum vitrinite reflectance was measured on the Axioplan using a monochromatic light of 546 nm wavelength in oil immersion. Mean maximum reflectance was used rather than mean random reflectance because it gives smaller standard deviation, and gives a more precise result as an indicator of the degree of coal metamorphism (Davis, 1978). Measurement followed by Australian Standard procedures of Australian Standard, 2000. The maximum reflectance measurements were obtained by rotating a polished section of the sample under the microscope until the bedding plane was parallel to the plane of the polarized incident light vibrations. The average (mean) of several measurements (≤ 50 points) was then calculated, and expressed as the mean maximum vitrinite reflectance (Rv_{max}). Measurement of vitrinite reflectance was mainly carried out on telovitrinite, but sometimes it was performed

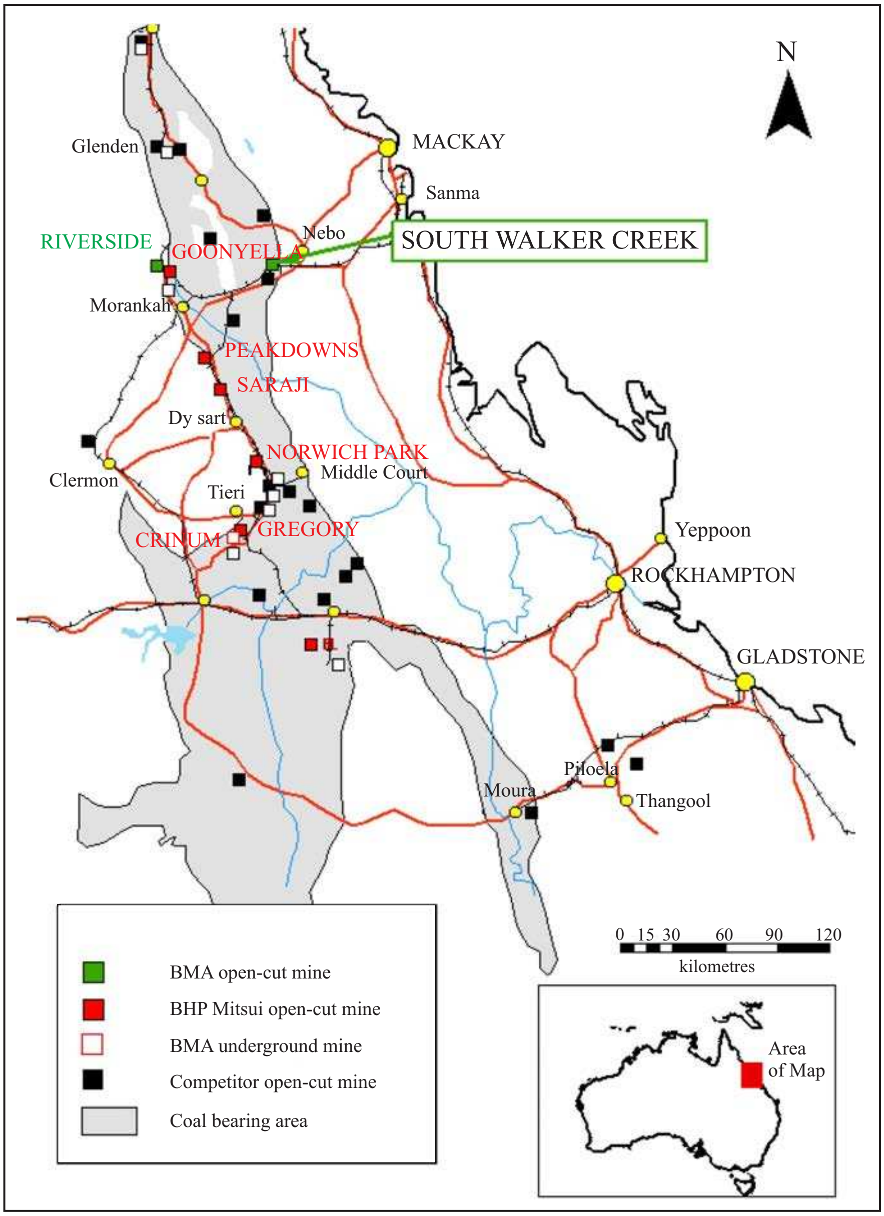

Figure 1. Locality map of the study area (modified from Davis *et al.*, 2006).

on gelovitrinite or detrovitrinite when telovitrinite was unavailable or unidentifiable.

As indicated above, hydrothermal fluids may have influenced the coal bearing strata in the northern Bowen Basin (Golding *et al.,* 2000; Uysal 2000a,b). Hot fluid flow may also have occured along the permeable zones of the coal in the South Walker Creek deposit. Measurement of vitrinite reflectance along and/or near the cleats, as well as close to veins in the coal seam, was included in the study. It was hoped that this approach might test whether there was heat flow in the coal produced by the movement of hot fluid along the permeable zones.

Maceral Composition

As might be expected from the predominance of dull coal lithotypes (Permana *et al.,* 2013), the maceral composition of the South Walker Creek

Table 1. Macerals occurring in the South Walker Creek Coals, classified according to Australian Standard (1998)

Maceral Group	Maceral Subgroup	Maceral
Vitrinite	Telovitrinite	Textinite
		Texto-ulminite
		Eu-ulminite
		Telocollinite
	Detrovitrinite	Atrinite
		Densinite
		Desmocollinite
	Gelovitrinite	Corpogelinite
		Porigelinite
		Eugelinite
Liptinite		Sporinite
		Cutinite
		Resinite
		Liptodetrinite
		Alginite
		Suberinite
		Fluorinite
		Exsudatinite
		Bituminite
Inertinite	Telo-inertinite	Fusinite
		Semifusinite
		Funginite
	Detro-inertinite	Inertodetrinite
		Micrinite
	Gelo-inertinite	Macrinite
		Secretinite

coals is dominated by inertinite with lesser amounts of vitrinite, and only minor liptinite. Table.1 shows typical macerals that have been identified in the South Walker Creek coals. Details of each maceral group and their characteristics are discussed in the following section.

Vitrinite

The vitrinite maceral group in the South Walker Creek coals are mainly telovitrinite and detrovitrinite, with minor gelovitrinite sub-groups. The telovitrinite sub group is dominated by telocollinite, which occurs as massive structureless bands or elongated lenses, sometimes crossed cut by veins or cleats (Figure 2a). The massive telocollinite may sometimes contain fine mineral matter particles (Figure 2b), probably infilling cell lumens in the vitrinite precursor before gelification.

Desmocollinite occurs as structureless thin layers or bands, commonly associated with corpogelinite and semifusinite (Figure 2c). Desmocollinite is derived from fragmented and degraded plant materials during the early stage of coalification. Corpogelinite appears as rounded or ovoid bodies, and is mostly found as isolated particles. The occurrence of corpogelinite is usually associated with desmocollinite (Figure 2c). It may also occur as homogeneous corpogelinite, which was originally formed from the infilling of organic gels within cell lumens of the plant during burial metamorphism (Figure 2d). In the study area, corpogelinite is quite rare, possibly because of incorporation into telovitrinite or detrovitrinite.

Inertinite

The inertinite maceral group found in the South Walker Creek coals include fusinite, semifusinite, and macrinite, with minor micrinite and indertodetrinite. The principal structured inertinite (telo-inertinite) macerals, fusinite, and semifusinite, occur mainly as large lenses, or thin bands, with cell lumens commonly filled by mineral matter (Figure 3b). The empty cell lumens in some cases are fractured and pushed into one another, forming a bogen structure (Figure 3c). Other telo-inertinites, and funginites are found as round or oval shaped bodies consisting of one or more cell cavities, and are commonly associated with semifusinite and macrinite in tellocollinite macerals (Figure 3d). Diessel (1992) and Moore *et al.* (1996) indicate that fusinite and semifusinite are commonly products of terrestrial forest moor environments, forming either by incomplete combustion from fires in the swamp area or from biological activity (fungi or bacteria) under slightly oxidizing conditions.

The detro-inertinite in the coal seam is composed of inertodetrinite. Although this maceral is sometimes difficult to identify under the microscope because of intermixing with macrinite, the distinction may be made from their size. Inertodetrinite occurs as detrital material, commonly irregular in shape and sometimes with angular forms (Figure 3e), and is usually less than 0.03 mm in longest dimension. Inertodetrinite, macrinite, and funginite occur as dispersed detrital fragments in desmocollinite, associated with semifusinite

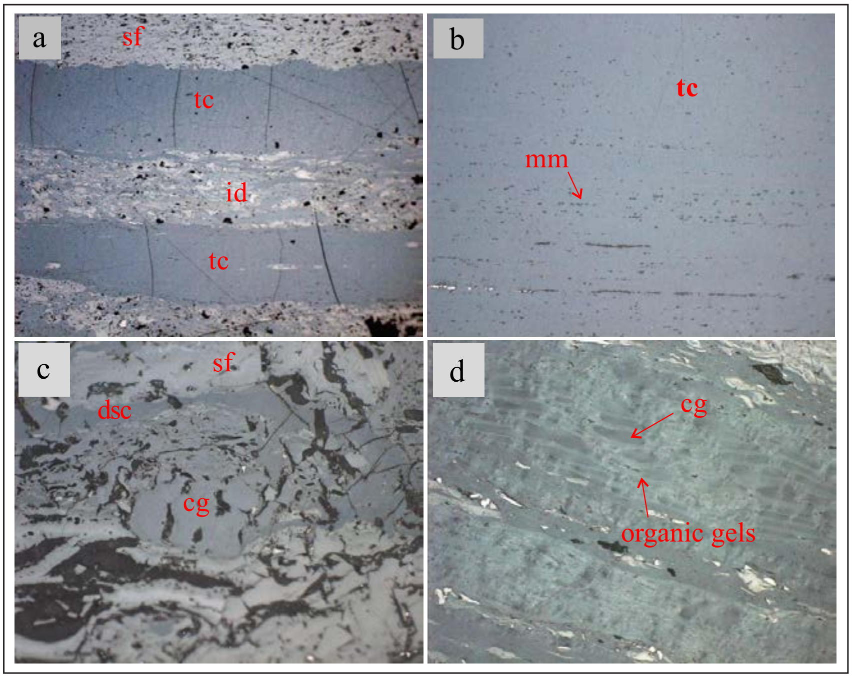

Figure 2. Photomicrographs of vitrinite macerals in the South Walker Creek coals (20x and 50x, oil immersion, and reflected light); a: Telocollinite (tc) and semifusinite (sf), with associated inertodetrinite (id), 20x, 11424-06; b: Massive telocollinite (tc) bands with dispersed mineral matter (mm) particles, 50x, 11424-11; c: Round bodies of corpogellinite (cg) associated with desmocollinite (dsc), 50x, 11424-16; d: Homogenous bodies of corpogelinite (cg), derived from the infillings of organic gels within the cell lumens of the plants, crossed polars, 50x, 11852-19.

(Figure 3e). The inerdodetrinite probably originated from broken fragments of other inertinite materials.

The gelo-inertinite in the South Walker coals mainly consists of macrinite. Macrinite occurs generally in the form of rounded bodies, as well as irregular and angular forms, showing a wide range of dimensions (no upper size limit), usually in telocollinite or desmocollinite and associated with inertodetrinite, semifusinite, and funginite (Figure 3d, 3e and 3f). Macrinite may have been formed from gelified plant material which was first biodegraded into humus colloids and subsequently dehydrated and oxidised during the coalification process (Diessel, 1992; Moore *et al.*, 1996).

Liptinite

The liptinite macerals in the South Walker Creek coals is predominantly exsudatinite. Under the microscope in fluorescence mode, exsudatinite is recognized by a bright yellow colour, and it occurs as vein infillings in vitrinite macerals (Figure 4a). Bitumen occurs in a similar way to that of exsudatinite (Figure 4b).

Mineral Matter

Mineral matter can be seen in various forms by megascopic analysis. Microscopic analysis is valuable for identifying more fully the mineral matter characteristics and occurrence, mainly grain size and shape of mineral matter, as well as the association with maceral components. Some minerals can be recognized in the South Walker Creek coals by using optical microscopy, namely clay minerals, carbonates, oxides, and phosphates. These are found within various sizes, shapes, and modes of origin, and are distributed within the macerals as well as in fracture and cleat infillings. The characteristics of each form of mineral matter under the optical microscope are described below.

<u>Clay minerals</u>

Clay minerals in the South Walker Creek coals generally occur as small to large lenses or layers; or

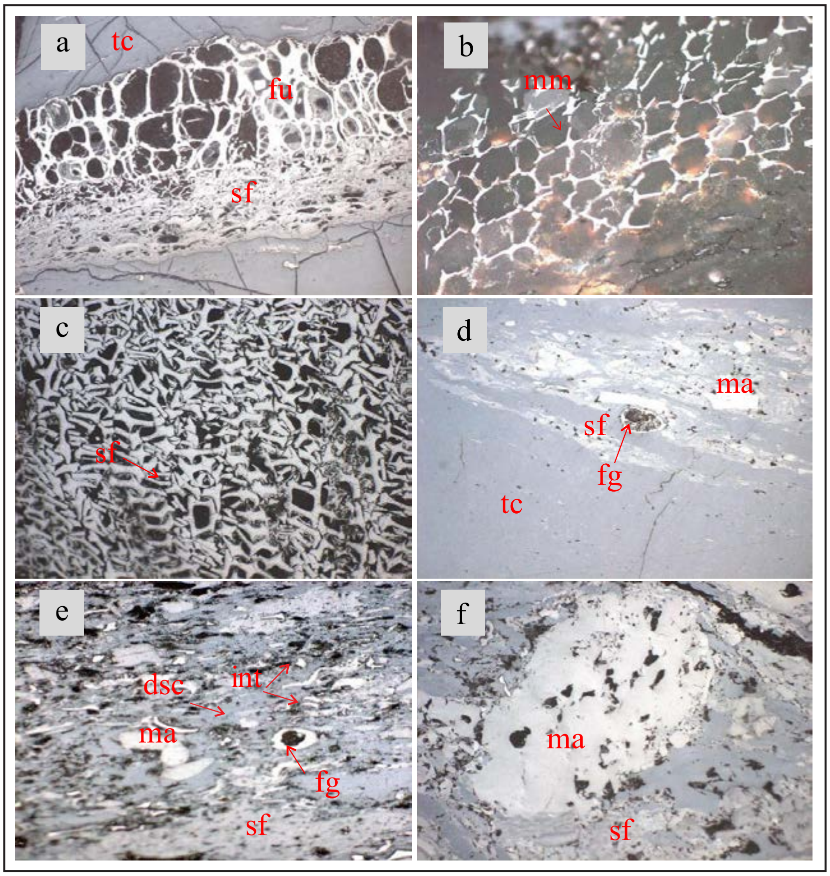

Figure 3. Photomicrographs of telo-inertinite macerals (reflected light, oil immersion, 20x and 50x); a: Fusinite (fu) with cell lumens grading to semifusinite (sf), 20x, 11852-20; b: Fusinite (sf) with cell lumens filled by carbonates, 50x, 11424-22; c: Semifusinite (sf) showing bogen structure, with cell lumen fractured, 50x, 11424-22; d: Oval shaped bodies of funginite (fg), associated with semifusinite (sf), telocollinite (tc), and macrinite (ma), 50x, 11852-17; e: Inertodetrinite (int) with semifusinite (cf), macrinite (ma), and funginite (fg), 11424-26; f: Oval body shape of macrinite (ma), 11852-17.

as fine-grained cell lumen infillings and cleat infillings (Figure 5). Massive bodies of clay minerals occur in some telocollinite macerals (Figure 5a), while fine- grained clay minerals infill cell lumens of semifusinite (Figure 5b). Massive bodies of clay minerals may have been introduced into the peat swamp by water or wind during organic matter deposition. Alternativelly, the cell lumen clay infillings may possibly have formed at a slightly later stage of peat accumulation, perhaps even after initial burial, by deposition from aqueous solutions.

In some cases, clay minerals in the coal seam are also found as monomineralic cleat or fracture infillings in massive bands of telocollinite (Figure 5c), or as polymineralic cleat infillings associated with other minerals such as carbonates (Figure 5f). Clay minerals occurring in this way were probably deposited after the consolidation of the coal bed, where they were precipitated in cracks or fissures from solutions derived from altered primary minerals, or from fluids introduced separately into the buried coal seam.

Quartz

Quartz is relatively rare in the South Walker Creek coals. Where it does occur, it is generally found as small rounded particles associated with tellocollinite and semifusinite macerals. Some quartz, however, also occur as elongated crystals infilling cell lumens of the fusinite macerals (Figure 5d). Quartz fragments in the South Walker Creek coals may have been originally transported to the peat

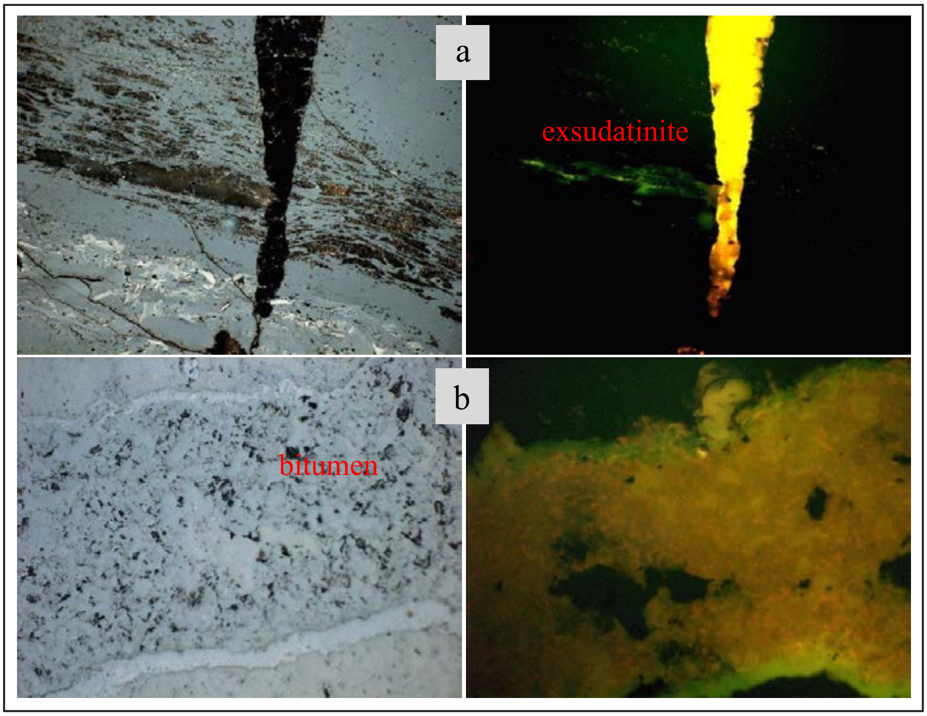

Figure 4. Photomicrograph of liptinite macerals in the South Walker Creek coals (reflected and fluorescence light, oil immersion, 50x); a: Exsudatinite commonly occurring as veins in vitrinite, 11424-06; b: Bitumen infills in veins, 11424-09.

swamp as mineral grains, and mixed together with other detrital materials, such as clay minerals, to form thin and irregular layers and lenses within the maceral components.

Carbonates

Siderite is one the carbonate minerals clearly identified under the optical microscope in the South Walker Creek coals. Siderite is found as small to large spherical nodules (up to 1.5 mm) in vitrinite and inertinite. It appears as crystal aggregates with a radial and concentric structure (Figure 5e). The features of these siderite nodules, especially the compaction of the organic matter around them, indicate a syngenetic origin during deposition or early diagenesis of the peat accumulation. The presence of siderite in the coal seam also indicates a lack of sulphur in the system (Boardman, 1989; Biggs, 1996; Middleton and Nelson, 1996).

Other carbonate minerals may also occur as cell lumen infillings within the fusinite macerals, or as well developed cleat or fracture infillings in association with clay minerals within the telocollinite macerals. This carbonate is clearly a result of chemical precipitation during a relatively late stage of the coalification process, after burial and compaction had been completed (Uysal *et al.*, 2000c).

Vitrinite Reflectance Variation

The mean maximum reflectance (Rv_{max}) values from the borehole 11424 are slightly higher than those from borehole 11852. The range of individual maximum vitrinite reflectance measurements for the samples from borehole 11424 is between 1.61 and 2.02%, with mean maximum reflectance (Rv_{max}) values ranging from 1.71 to 1.95%. However, the individual vitrinite reflectance values for the samples from borehole 11852 range from 1.51 to 1.87%, with the mean maximum reflectance (Rv_{max}) ranging from 1.64 to 1.83% (Table 2).

The mean of the maximum reflectance (Rv_{max}) values indicate that the coal rank in borehole 11424 (Rv_{max} =1.61-2.02%) falls into the low volatile bituminous to semianthracite classification (ISO-11760,

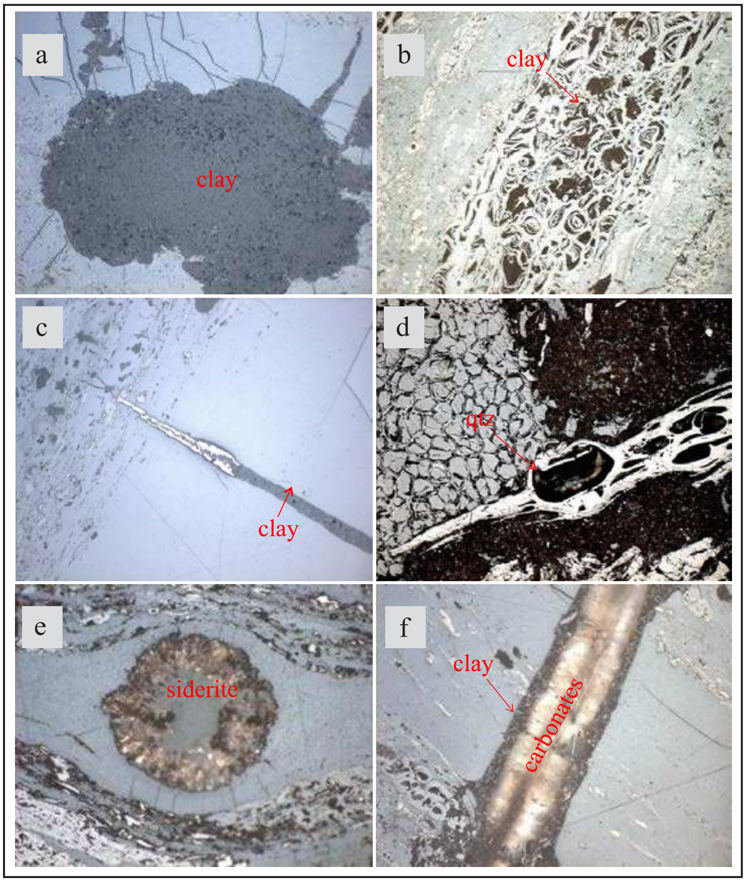

Figure 5. Photomicrographs showing mineral matter occurrences in the South Walker Creek coals (reflected light, oil immersion); a: Massive bodies of clay minerals in telocollinite, 20x, 11852-7; b: Clay minerals infilling cell lumens in fusinite, 20x, 11424-13; c: Clay minerals in cleat inflllings of vitrinite macerals, 20x, 11852-2; d: Fine rounded crystal of quartz (qtz) in a cell lumen infilling of fusinite, 20x, 11424-27, e: Siderite nodule in a vitrinite band, 50x, 11424-22; f: Carbonate minerals in association with clay in cleats, 20x, 11852-10.

2005), while that of borehole 11852 (Rv_{max} 1.52-1.87%) is entirely within the low volatile bituminous range. Although the individual Rv_{max} values cover a quite wide range, it can be summarized that the coal rank in the South Walker coals ranges from low volatile bituminous to semianthracite level.

To obtain a vitrinite reflectance profile, the values for the individual samples from each borehole (11424 and 11852) were plotted against depth within the respective coal seams. The vitrinite reflectance (Rv_{max} *vs.* depth) for 11424 and 11852 (Figure 6) show an irregular pattern from the top to the bottom of the seam.

The irregular pattern of this reflectance profile is unusual. Normally Rv_{max} would be expected to increase gradually with depth in the borehole section, or remain relatively consistent with depth within the individual coal seam, which in this case is around 10 m in thickness. Glikson *et al.* (2000), however, have documented an irregular maturation profile within one seam in the northern Bowen Basin. They suggested that this pattern possibly represented a response in the organic matter to uneven heat distribution as a result of hydrothermal influence. A similar process may be indicated in the coal seam profile of the South Walker Creek area. Although the overall rank of the individual coal seam is relatively high, the irregular reflectance profile may possibly be a result of hydrothermal processes associated with fluid injection superimposed on more uniform burial effects.

Table 2. Maximum Vitrinite Reflectance of Borehole 11424 and 11852 from the Mulgrave Pit of the South Walker Creek Area

Borehole 11424					Borehole 11852			
Depth		Sample No	Range of Rv_{max} (%)	Rv_{max} (%)	Depth	Sample No	Range of Rv_{max} (%)	Rv_{max} (%)
From	To							
74.42	74.46	11424-3	1.82 - 1.93	1.8	37.89	11852-1	1.51 - 1.74	1.67
74.65	74.68	11424-4	1.71 - 1.81	1.75	38.02	11852-2	1.79 - 1.87	1.83
74.75	74.77	11424-5	1.72 - 1.84	1.79	38.3	11852-3	1.59 - 1.69	1.63
75.18	75.27	11424-6	1.77 - 1.90	1.82	38.79	11852-4	1.71 - 1.81	1.75
75.32	75.43	11424-7	1.91 - 2.02	1.95	38.99	11852-5	1.59 - 1.69	1.66
75.50	75.54	11424-8	1.75 - 1.93	1.85	39.64	11852-7	1.66 - 1.84	1.76
76.24	76.43	11424-10	1.70 - 1.85	1.8	39.94	11852-8	1.66 - 1.76	1.73
76.47	76.52	11424-11	1.77 - 1.86	1.81	40.39	11852-9	1.63 - 1.81	1.71
76.66	76.76	11424-12	1.71 - 1.86	1.79	41.04	11852-10	1.56 - 1.83	1.71
77.00	77.04	11424-13	1.72 - 1.86	1.79	42.14	11852-12	1.62 - 1.68	1.64
77.85	77.93	11424-14	1.78 - 1.88	1.81	42.8	11852-14	1.62 - 1.70	1.66
78.12	78.19	11424-15	1.81 - 1.99	1.89	43.35	11852-16	1.75 - 1.82	1.78
78.50	78.62	11424-16	1.71 - 1.83	1.76	43.75	11852-17	1.64 - 1.76	1.69
79.61	79.78	11424-17	1.68 - 1.83	1.74	44.85	11852-19	1.64 - 1.74	1.69
80.01	80.27	11424-18	1.71 - 1.85	1.78	45.09	11852-20	1.65 - 1.80	1.73
80.66	80.82	11424-19	1.71 - 1.88	1.77	45.55	11852-21	1.63 - 1.71	1.68
80.89	81.02	11424-20	1.73 - 1.82	1.78				
81.10	81.22	11424-21	1.78 - 1.90	1.82				
81.73	81.89	11424-22	1.76 - 1.89	1.82				
84.11	84.22	11424-25	1.79 - 1.95	1.85				
84.42	84.51	11424-26	1.82 - 1.91	1.87				
84.55	84.68	11424-27	1.86 - 1.94	1.9				
84.81	84.96	11424-28	1.61 - 1.78	1.71				

Fractures and cleats are possibly effective transporters for fluid movement in the coal seam. Glikson *et al*., (2000) suggested that fluid flow occurred along the fault systems and fracture-enhanced permeability zones in both mudrock and coal, as well as in the silisiclastic rocks of the northern Bowen Basin. The relatively higher value of vitrinite reflectance in the thin coal below the main seam of the borehole 11424 (Figure 6), may indicate a higher temperature due to the different thermal conductivity of the non-coal material above and below the main coal bed.

To provide further evidence of hot fluid movement along the cleats of the South Walker Creek coal, measurements of vitrinite reflectance were made near and or along cleat fractures in sixteen samples of from borehole 11852. The majority of the sixteen samples indicate no increase in Rv_{max} adjacent to the microcleats. From the discussion above, if the hot fluid flowed along the cleats, it should be indicated by increasing Rv_{max} toward the cleat, or relatively high Rv_{max} values near the cleats due to hot fluid circulation within the coal seam. However, the lack of such a trend in this case could indicate that any fluid flowing along the cleats was not hot enough to increase the reflectance, because the coal rank was already high when the hot fluid flowed through the coal seam. The hot fluid in such a case may only have impacted on the development of cleat and fracture mineralization within the coal seams, and not on the reflectance of the organic matter. Alternatively, a later overall rank increase

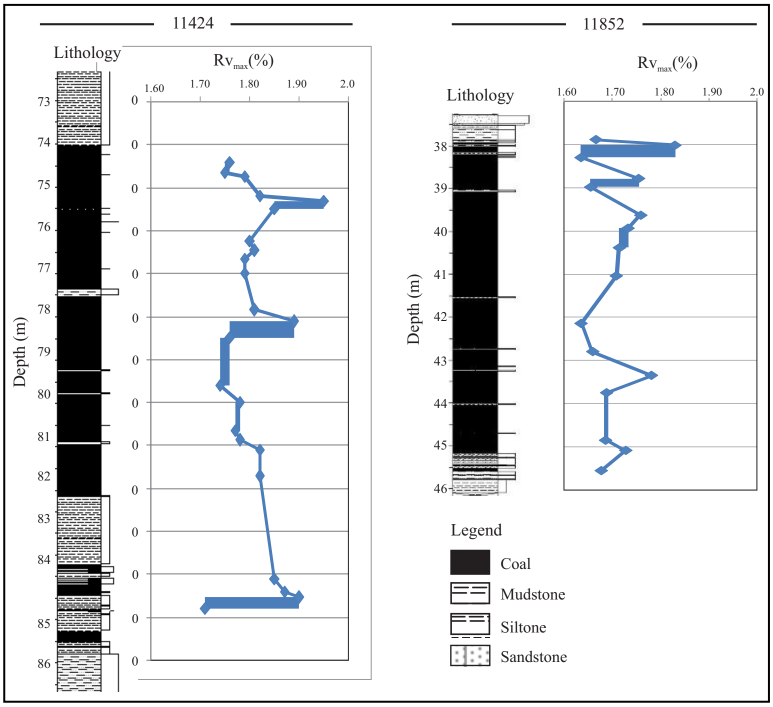

Figure 6. Profile showing variation in vitrinite reflectance (Rv_{max}) with depth in the coal seam from Borehole 11424 and 11852 in the Mulgrave Pit at South Walker Creek.

may have obliterated any more localized reflectance variations around the mineralized cleat fractures.

Discussion

Source Rock Potential

Glikson *et al.* (1999) have suggested that the occurrence of bitumen has an important role as source of gas in Bowen Basin coals. Bituminite was probably formed from light and heavy oils which were polymerized as bitumen in vitrinite cleats after diffusion through inertinite cavities (Glikson *et al.*, 1999). Exsudatinite, on other hand, is derived from oils or bitumen expelled during the coalification processes. Simoneit (1994) and Glikson *et al.* (2000), have reported that the occurrence of these secondary macerals can be associated with hydrothermal systems.

The high rank of the coal, coupled with hot fluid flow in the permeable zones of the coal seam, not only influenced the mineral alteration, but also the organic metamorphism. The occurrence of bituminite and exsudatinite in the coal seam may be associated with such hydrothermal processes. These macerals were probably formed from light and heavy oils which were polymerized as bituminite or exsudatinite in micro-cleats within the vitrinite.

The disappearance of kaolinite and illite, coupled with increases in illite, chlorite, and diaspore, might suggest that kaolinite and illite/smectite were possibly the main precursor for generation of illite and chlorite (Permana, 2011). The transformation of kaolinite and I/S to illite and chlorite in the seam may be associated with elevated temperatures with rank advance, approaching those of low grade metamorphism, in this particular coal seam.

The correlation of similar mineralogical changes with coal rank advance has been reported by several other researchers. Kisch (1966) indicated an absence of kaolinite in the anchimetamorphic zone at anthracite or meta-anthracite rank levels. Kubler (1967) have reported that kaolinite in shaly mudstone disappears in the lower part of the diagenesis zone, at Rv between 0.9% and 1.6%. This is similar to trends reported by Foscolos *et al.* (1976), with kaolinite in the Lower Cretaceous shales of NE British Columbia usually being absent at the rank levels equivalent to 1 to 1.5% Ro, and to the illitization of kaolinite in the Carboniferous of Upper Silesia at Ro > 1.2%, reported by Srodon (1979).

More recently, Susilawati and Ward (2006) indicated that kaolinite in the clay partings of the Bukit Asam coals, Indonesia, disappear at Rv 1.7%, while in the actual coal seam kaolinite persists to much higher levels, up to Rv 2.2%. Therefore, it may be summarized that kaolinite in shales tends to disappear in the range of reflectance 1.2% to 1.9%, but in some cases in coal seams it may persist up to Rv 2.2%.

A similar situation may have developed in the low volatile bituminous to semi-anthracite coals of the South Walker Creeks deposit. Kaolinite in this seam may have disappeared at the rank equivalent to 1.52% to 2.02% Rv_{max}, and been replaced by the development of illite and chlorite. However, Permana (2011) shows that the mineralogical variation observed within the coal seam does not necessarily match with the reflectance profile. The abundance of illite and chlorite assemblages in the middle of the seam is not associated with higher levels of vitrinite reflectance. Although the vitrinite reflectance and the clay mineral assemblage both vary within the seam, and the vitrinite reflectance (1.52 to 2.02%) is high enough to be associated with transformation of kaolinite and illite/smectite to illite and chlorite, the transformation does not appear to have occurred in a direct association with the reflectance variation within the coal seam.

The irregular pattern of the vitrinite reflectance profile from the top to the bottom of the seam (Figure 6) may represent a response in the organic matter to an uneven heat distribution from such a hydrothermal system. However, there does not seem to be any systematic variation in the reflectance associated with the changes in the vertical mineralogical profile. There is also no measureable variation in individual coal samples adjacent to carbonate or other cleat infills. This could be because the heat effects associated with any hot cleat-infilling fluids were not enough to impact on the already high reflectance of the adjacent vitrinite. Thus, the mineralogical variation within the seam resulted from sedimentary processes of coal deposit, changes in burial history and rank advances, and changes associated with hydrothermal effects due to late-stage fluid migration through the coal.

Conclusions

The maceral composition of the South Walker Creek coals is dominated by inertinite with minor vitrinite, plus a small liptinite component. Mineral matter occurs in association with vitrinite and inertinite macerals as syngenetic and epigenetic mineral phases.

The profile of vitrinite reflectance (Rv_{max} *vs.* depth) shows an irregular pattern from top to the bottom of the seam. This pattern may possibly represent the response of the organic matter to uneven heat distribution from a hydrothermal system. However, the measurement of vitrinite reflectance along the cleat or adjacent to cleat fractures has not found evidence that fluid flow along those fractures was responsible for increasing the reflectance value in the coal seam. This could probably indicate that any fluids flowing along the cleat were not hot enough to increase the coal rank, or that the coal rank was already high when the hot fluid passed through the coal seam. Alternatively, any such variation around the fractures may have been overprinted by broader-scale rank advance processes.

The rank of the coal is sufficiently high for the mineralogical variation within the seam, such as the transformation of kaolinite and illite/smectite to illite and chlorite, to be associated with elevated temperatures during rank advance (equivalent to low grade metamorphism). However, the mineralogical variation does not appear to match the reflectance profile observed within the seam.

The mineralogical variation within the seam resulted from a combination of processes, including the sediment input to the peat swamp during deposition, changes associated with rank advance or metamorphism, and changes associated with hydrothermal effects due to late-stage fluid migration through the coal.

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References

Australian Standard, 1998. *Coal petrography. Part 2: Maceral analysis*. AS 2856-2, 32pp.

Australian Standard, 2000. *Coal petrography-methods for microscopical determinations of the reflectance of coal macerals*. AS 2856-3, 16pp.

Biggs, M.S., 1996. The distribution and significance of iron minerals in the Callide Coal Measures, East Central Queensland. Queensland University of Technology.

Boardman, E.L., 1989. Coal measures (Namurian and Westphalian) Blackband Iron Formations: fossil bog iron ores. *Sedimentology*, 36, p.621-63.

Davis, A., 1978. The reflectance of coal. *In:* Karr, C.J. (Ed.), *Analytical method for coal and coal product I.* Academic Press, New York, p.27-81.

Davis, B., Esterle, J., and Keilar, 2006. Determining geological controls on the spatial distribution of phosphorus within coal seams mined at South Walker Creek Mine, Bowen Basin, Central Queensland, Australia. *In*: Hutton, A. and Grifin, J. (Eds.), Advances in the study of the Sydney Basin. *Proceedings of the 36th symposium on Advances in the study of the Sydney Basin*, p.28-35.

Diessel, C.F.K., 1992. *Coal-bearing depositional systems.* Springer-Verlag, Berlin, 721 pp.

Foscolos, A.E., Powell, T. G., and Gunther, P.R., 1976. The use of clay minerals and inorganic and organic geochemical indicators for evaluating the degree of diagenesis and oil generating potential of shales. *Geochimica et Cosmochimica, Acta,* 40, p.953-966.

Fraser, S., Esterle, J.S., Ward, C.R., Henwood, R., Mason, P., Huntington, J., Connor, P., Sliwa, R., Coward, D., and Whitbourn, L., 2006. *Automated Mineralogical Logging of Coal and Coal Measure Core.* End of Grant Report, ACARP Project C13014, CSIRO Exploration and Mining Report P2005/281, p.112.

Glikson, M., Boreham, C.J., and Thiede, D.S., 1999. Coal composition and mode of maturation, a determining factor in quantifying hydrocarbon species generated. *In:* Masterlarz, M. and Golding, S. (Eds.), *Coalbed Methane: Scientific and Economic Evaluation,* Kluwer Academic Publisher, Dordrecht, p.155-185.

Glikson, M., Golding, S.D., Boreham, C.J., and Saxby, J.D., 2000. Mineralization in eastern Australia coals: a function of oil generation and primary migration. *In:* Glikson, M. and Mastalerz, M. (Eds.), *Organic matter and mineralization.* Kluwer Acaedmic Publisher, p. 329-358.

Golding, S.D., Collerson, K.D., Uysal, I.T., Glikson, M., Baublys, K., and Zhao, J.X., 2000. Nature and source carbonate mineralization in Bowen Basin coals, Eastern Australia. *In:* Glikson, M. and Mastalerz, M. (Eds.), *Organic matter and mineralization.* Kluwer Acaedmic Publisher, p.296-313.

Kisch, H.J., 1966. Chlorite-illite tonstein in high rank coals from Queensland, Australia. Notes on regional epigenetic grade and coal rank. *American Journal of Science,* 264, p.264-397.

Kubler, B., 1967. La cristallinite´ de l'illite et les zones tout a fait superieures du metamorphisme. *In: Etages tectoniques Colloque de Neuchatel* 1966, p.105–121. Universite Neuchatel, A La Baconniere, Neucha^ tel.

Middleton, H.A. and Nelson, C.S., 1996. Origin and Timing of siderite and calcite concretions in late Paleogene non-to marginal-marine facies pf the Te Kuiti Group, New Zealand. *Sedimentary Geology*, 103, p.93-115.

Moore, T.A., Shearer, J.C., and Miller, S.L., 1996. Fungal origin of oxidised plant material in the Palangkaraya peat deposit. Kalimantan Tengah, Indonesia: Implication for "inertinite" formation in coal. *International Journal of Coal Geology,* 30, p.1-23.

Permana, A.K., 2011. *Mineralogical variation and changes in the South Walker Creek coals, Bowen Basin, Queensland, Australia.* M.Sc. Thesis (unpublished), University of New South Wales, Australia, 276 pp.

Permana, A.K., Ward, C.R., Li, Z., Gurba, L.W., and Davison, S., 2010. Mineral matter in the high rank coals of the South Walker Creek area, northern Bowen Basin. In: Beeston, J.W. (Ed.), *Proceedings of Bowen Basin Symposium - Back in (the) Black, Geological Society of Australia Coal Geology Group and Bowen Basin Geologists Group,* Mackay, Queensland, p.27-34.

Permana, A.K., Ward, C.R., Li, Z., and Gurba, L.W., 2013. Lithotype and Chemical Characteristics of the South Walker Creek Coals, Bowen Basin, Australia. *Journal of Geological Resources*, 23 (1), p.47-57.

Simoneit, B.R.T., 1994. Organic alteration and fluid migration in hydrothermal systems. *Geological Society Publication,* 87, p.261-274.

Srodon, J., 1979. Correlation between coal and clay diagenesis in the Carboniferous of the Upper Silesian Coal Basin. *In*: Mortland, M.M. and Farmer, V.C. (Eds.), *Proceedings, Initial Clay Conference*, Oxford 1978, p.251-260.

Susilawati, R. and Ward, C.R., 2006. Metamorphism of mineral matter in coal from the Bukit Asam deposit, south Sumatra, Indonesia. *International Journal of Coal Geology,* 68, p.171-195.

Uysal, I.T., Glikson, M., Golding, S.D., and Audsley, F., 2000a. The thermal history of the Bowen Basin, Queensland, Australia: vitrinite reflectance and clay mineralogy of late Permian Coal Measures. *Tectonophysics*, 323 (1–2), p.105-129.

Uysal, I.T., Golding, S.D., and Audsley, F., 2000b. Clay mineral authigenesis in the Late Permian Coal Measures, Bowen Basin, Queensland, Australia. *Clays and Clay Minerals,* 48, p.351-365.

Uysal, I.T., Golding, S.D., and Glikson, M., 2000c. Petrographic and isotope constraints on the origin of authigenic carbonate minerals and the associated fluid evolution in Late Permian coal measures, Bowen Basin (Queensland), Australia. *Sedimentary Geology,* 136, p.189 - 206.