SEM-EDS imaging of multi-stage cleat minerals formation in the South Walker Creek Coals, Bowen Basin

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Abstract. The South Walker Creek coals are moderately to highly developed fracture systems. These fractures can be recognized from the top to the bottom of the seam, with both open and closed apertures. They are filled with several different minerals, occurs either as single-phase infillings (monomineralic), or as mixed mineral deposits (polyminalivic). This paper presents scanning electron microscope (SEM) analysis of mineralogical association within coals fractures or cleats, as well as their origin and phase of development. SEM-EDS analysis indicates that the polyminalivic cleats seem to be more common in the coal seam compared to monomineralic cleats. The polyminalivic cleat infillings are composed of clay minerals, carbonates, and other minerals, such rutile and apatite, with minor occurrences of diaspore. This polyminalvic association within the single cleat spaces represents a multi-phase minerals formation, as a result of different stages of epigenetic activity. The hydrothermal fluid circulation are responsible for this epigenetic process, they are re-opened previous minerals filled cleats and transformed pre-existing mineral within the cleats, and/or to remobilization earlier minerals, which then precipitated in the cleat as epigenetic minerals.

1. Introduction
Coal is an organic sedimentary rock that consists of organic matter and mineral matter [1,2,3]. The combustible organic particles (macerals) are composed of lithified plant debris, and occur as discrete layers of organic material each with its own physical and chemical properties [4]. The non-combustible mineral matter is mainly made up a variety of primary and secondary minerals, such as clays, carbonates, silicates, phosphates, sulphides and others [5]. Mineral matter in coal can be seen in various forms and identified by megascopic or microscope observations. Fine grained mineral matter, discrete bands, thin layers or partings, nodules and fissure infillings of minerals present in a coal deposit may often be examined by the naked eye or with a geological loupe. Smaller accumulations of mineral matter need to be studied under the microscope, for example thin bands, micro cleat or cell lumen fillings, or even replacements of cell structure [6,7,8].

Optical microscope studies have some limitations, it could identify some minerals, such clays and carbonates occur in association with particular macerals, but it is difficult to identify more specifically the type of carbonates and clay minerals involved using only optical techniques. Scanning electron microscopy coupled with energy-dispersive X-ray spectrometry (SEM-EDS) provides a basis for
determination of mineral composition to identify specific mineral types, and also to study the size, shape and their minerals association. SEM-EDS was used to characterize mineralogical origin, type and their association within the South Walker Creek Coals, Queensland, Bowen Basin. SEM-EDS provide better evaluation of the nature and formation processes of the minerals within the coal seams. SEM study indicates that the South Walker Creek coals contain three phases of mineralization, syngenetic, diagenetic and epigenetic. Clay mineral of kaolinite and Illite/Smectite occur as syngenetic phases, mainly derived from clastic sediment input during peat accumulation, however, some other clay minerals, chlorite and illite was probably combination of syngenetic phase with early diagenetic remobilisation and cell lumen or pore-filling precipitation. Carbonates such as calcite and ankerite, as well as dickite, and nacrite, along with additional kaolinite, illite, and chlorite were precipitated in cleats and fractures at a later stage as a result of epigenetic activity [9]. However, their minerals association and formation within the single cleat spaces were not clearly describe and poorly understood. This paper describes cleat mineral formation by using SEM-EDS analysis and provides insight multi-stage epigenetic process within the cleat spaces.

2. Regional Geology

The South Walker coals were deposited in the northern part of the Permo-Triassic Bowen Basin (figure 1). This basin is a part of the interconnected Sydney-Gunnedah-Bowen Basin System in eastern Australia. The Sydney-Gunnedah-Bowen Basin System extends along the western margin of the New England Fold Belt, and is confined to the west by the older Thomson and Lachlan Fold Belt. The complex tectonic and structural history of the Bowen Basin has been led to many different studies of its geological development. Hammond [9] considers that the basin formed during the Early Permian by crustal extension. Fielding [9] suggests that later in the Permian the Bowen Basin can be interpreted as a foreland sedimentary basin, formed by a compressive tectonic regime at a continent-ocean plate boundary. During the tectonic evolution of the Bowen Basin, complementary depositional processes were taking place in different areas. The stratigraphic sections have been correlated to sedimentation in the different phases of this tectonic evolution. They were deposited in terrestrial (fluvial) to intertidal and marine environments.

The coal bearing strata are mainly preserved on the protected tectonic platforms or synclinal margins. The Permian and Triassic sediments are mainly found in the Nebo Synclinorium, northern part of the Bowen Basin. Coal deposits in this area range from Early to Late Permian in age and occur in numerous stratigraphic units. There are mainly four economic coal bearing sequences in this area, the Collinsville Coal Measures, the Moranbah Coal Measures, the Fort Cooper Coal Measures and the Rangal Coal Measures. They were deposited in during regression and transgression phases of the Permo-Triassic sedimentation. The study area is located in the South Walker Creek within the Nebo Synclinorium on the eastern flank of the Carborough Syncline in the Northern Bowen Basin (figure 1). It lies on the flat to gently undulating flood plain of Walker Creek, overlain by unconsolidated alluvium, comprising interbedded sand and clays with gravelly sand near the base. The Rangal Coal Measures is the most economic coal bearing in this area, which stratigraphically underlain conformably by the Fort Cooper Coal Measures and overlain by the Rewan Formation. The Rangal Coal Measures consists of fine to medium grained labile sandstone, grey siltstone, mudstone and coal seams, with 150 m in thickness (figure 1). The most economic deposit of the Rangal Coal Measures at the South Walker Creek area is the Main seam, which splits to the north and the south to form the Main Tops and Main Bottoms coal seams.

The South Walker Creek coals are moderately affected by fault systems. Fractures and veins have been reported that have been mineralized by clays and carbonates. In addition, some dolerite dykes and sills occurring in some places in the Bowen Basin, and associated with the South Walker Coalas (figure 1). These geological characteristics have influenced the coal properties and characteristics in the area. Permana [9] have been identified that the main seam in the South Walker Creek consists of mineralogical variation through the vertical sequence due to a combination of processes, including clastic sediment input
to the peat swamp, thermal metamorphism due to burial sedimentation and hydrothermal influence. The distribution of the non-carbonate minerals assemblages cross cut the seam stratigraphy and appears to be primarily controlled by fault and other structural features; however, the illite–chlorite and diaspore-bearing assemblages resulted from hydrothermal fluid migration through the middle part of the coal seam. This indicate that some epigenetic minerals might be precipitated within the cleat spaces due to different epigenetic processes.

3. Methods
A series of representative coal polished sections from two boreholes (Borehole 11424 and 11852) of the South Walker Creek mine (Mulgrave and Walker Pits), Queensland, Australia, were analysed by using a Hitachi S3400-I scanning electron microscope (SEM) at the Mark Wainwright Analytical Centre, University of New South Wales. The SEM was equipped with backscattered electron (BSE) detectors and energy-dispersive X-ray spectra (EDS) microanalysis system, utilising NORAN System SIX software. The BSE image quality is crucial for SEM analysis, as the image was used and combined with EDS spectrum for characterization mineral matter in the coal samples. Application of SEM for coal analyses also requires specific of samples preparation. Coal samples are sensitive to the effect of the electron beam, which potentially damaged the surface of coal sample. For this reason, the polished block of coal samples were coated with carbon to obtain a more conductive surface and to avoid charging effects on the specimens which could possibly destructed the samples.

Figure 1. Location and regional geology of South Walker Creek Coal Mine; a) Distribution of the South Walker Creek coals deposit in the Bowen Basin; b) Simplified Geological map of the South Walker Creek area [9].
SEM basically has two modes of observation, SE (secondary electron) and BSE (backscattered electron) images. These observations give different information and it is desirable to have the BSE and SE images displayed simultaneously. The SE mode provides images similar to those from light microscopy in organic petrology and is used for determining morphology by contrasting grey levels. The BSE mode is used for distinguishing macerals from minerals, and further information on the minerals is easily obtained by EDS analysis. The characteristics of macerals from SE images have been summarized by [1]. They have also reported that different types of coal have different charging effects due to the interaction of electron beam with the coal surface. Bituminous and anthracitic coals have less charging effects, for example, than brown coals. A thinner carbon coating on the coal surface is the best way to get good BS detector results. Carbon is the best material for backscatter (BSE) work because it has a low atomic number. It is also suitable for SE work, although it is not as good as gold. The accelerating voltage is the most important variable during the SEM observation. This affects the image contrast and resolution. With the BSE mode, contrast increases with accelerating voltage but resolution of fine structure decreases due to the greater beam penetration and wider area of electron scattering. With the SE mode the images are better at lower accelerating voltage. Generally, the optimal voltage is the highest obtainable with minimum surface charging. This is commonly in the mid-range (15-20 kV) for coal studies [12]. X-ray (EDS) analysis is useful for identification of mineral particles and of minor elements in macerals. Huggins [13] has listed the minerals most commonly found in coal and how they can be recognized by energy-dispersive X-ray spectra under the SEM.

4. Results

4.1 Field and Core Observations
The coal seams of the South Walker Creek area are moderately structurally deformed due to compressional stress regime. This tectonic activity leads to the development of several major faults in the pits of South Walker Coal mine. The main fault structure is normal faults which structural trend is N-NE, whereas some thrust faults is also exposed in some places in the mine area. The marked structures and bedding shear deformation can be defined along the fault zone. The siliciclastics are a common marked structure found in the fault zone, with mostly coated by dickite minerals, and shearing also identified within the coal seams, mainly in the Toolah Pit of the South Walker Creek coal mine. The orthogonal set of cleats is visible at a megascopic scale, which is perpendicular or oblique to the coal seam bedding planes. This cleat set has distinct face and butt cleat features; it is well developed and continuous in the bright bands but less developed in the dull coal lithotypes.

Lithotype of the South Walker Creek coals show to be finely to moderately banded, dull and bright in lustre and highly cleated, with the cleats mostly filled by mineral matter. Core log descriptions indicate that the main seams is dominantly dull and bright (40-60% bright) coal lithotypes, and dull with numerous bright bands (10-40% bright), along with minor dull (< 1% bright) coal lithotypes (Australian Standards). The South Walker Creek coals show moderately developed face and butt cleat, with both open and closed apertures. The cleats are filled with carbonate and clay minerals. It has been observed that the cleat systems are commonly restricted to bright coal layers and terminate at the dull coal, and the brighter coal lithotypes mostly have a higher density of cleat spaces than the duller coal bands.

4.2 Optical Microscopy and SEM-EDS
The optical microscope with reflected light combined with SEM-EDS analyses was used for characterizing the mode and mineral occurrences in the coal seams [9]. These techniques were also applied to identify the cleat systems development and minerals formation within the cleat fractures, as well as the sequence of mineral formation. Based on lithotype descriptions of two cores from Borehole
11424 and 11852 (in the Mulgrave and Walker Pit areas) indicate that the orthogonal sets of cleats are mostly developed in the bright bands, and terminate in dull bands. This could suggest that the orthogonal cleat sets are of endo-microcleat origin, and were formed within the vitrinite macerals during diagenesis and coalification. Optical microscope and SEM-EDS observations show superimposed of polygonal and chaotic cleat sets. These types of cleat patterns may be products of post diagenesis processes, associated with tectonic stress, and related features such as such faults and shear zones. The polygonal set has a smaller aperture, often occurs as open cleats, and its likely cross-cut the chaotic set. The chaotic set typically has a larger aperture and is mostly filled with mineral matter. This may indicate that the (open) chaotic set post-dates the (mineralized) polygonal cleat set. Under the optical microscope and SEM-EDS, single cleats or micro-cleats are commonly restricted in the vitrinite macerals, but some cleats are terminated abruptly at the inertinite macerals (figure 2). Master cleats mostly pass through the inertinite macerals. These cleats are commonly infilled by minerals, and parallel inclined or perpendicular to the bedding planes. In particular cases, microcleats are composed of angular fragments of vitrinite to form a “mylonite”, together with clay and/or carbonate minerals (figure 2a). Shear veins are also recognized in some samples, showing like “propagated veins”, usually in the vitrinite macerals (figure 2b). SEM observation shows that the cleat widths apertures range from 1 to 100 µm, with lengths range from 20µm to more than 1 mm. The micro-cleats are dominated by straight line forms, although some curved or sub-curved and rhombic shapes are also present. Closed microcleats are typically more intensively developed than open microcleats. The cleat-filling minerals are mostly consisting of clay minerals, carbonates, diaspore, rutile, andapatite, and in many cases that multiple minerals precipitated together within a single cleat- filling minerals.

4.3 Cleat-Filled Minerals
On the basis of the SEM images, the cleats are filled with several different minerals, including clay minerals, carbonates, apatite, dickite and rutile. These minerals occur either as single-phase infillings (monominerlic) or as multiple-phase mineral deposits (polymineralic). The multiple-phase mineral deposit is mainly divided into three groups: (1) clay rich minerals, dominated by kaolinite, with minor occurrences of illite and chlorite, (2) carbonates, dominated by calcite and ankerite, with minor amounts of of siderite, and (3) other minerals, dominated by rutile and apatite, with limited occurrences of diaspore (figure 2).

Kaolinite is the most common clay mineral presence in the cleat fractures. Kaolinite rarely occurs as a single-phase cleat infillings, associated with other clay minerals, and non-clay minerals, such as rutile or anatase and quartz. At high magnification the kaolinite crystals occur as irregular flakes or booklet textures in the cleat aperture, in some cases, kaolinite cleat infillings are cross-cut by rutile and anatase. A combination of both rutile or anatase and chlorite may also be found within the kaolinite-filled cleat, as well as chlorite intergrowths within euhedral rutile or anatase patches. Chlorite always occurs in association with either kaolinite or illite. Chlorite usually forms intergrowths in the kaolinite cleat minerals, forming irregular flakes along cracks or cleavages of the kaolinite components. Quartz may also be found in association with the kaolinite cleat infillings, occurring as sub-rounded particles in the cleat space. Illite also mainly occurs as polymineralic associated with fluorapatite, rutile and calcite. Illite occurs at the end of cleat spaces within the inertinite macerals, associated with fluorapatite. In some cases, well crystallized illite cleat infillings are cross-cut by prismatic rutile and anatase. EDS pattern of rutile or anatase is indicated by a high peak of titanium (Ti), with the additional presence of zirconium (Zr) and silicon (Si) in the spectrum (figure 2c).
Figure 2. Optical Microscope and SEM Images shows cleat mineral formation, a) Mylonitic texture together with clay and/or carbonate minerals; b) Offset “striped shear veins”, well developed in vitrinite; c) Ti (titanium) mineral associated with kaolinite (K) and chlorite (Ch), with high peak of titanium (Ti), with the additional presence of zirconium (Zr) and silicon (Si) in the spectrum; d) Monomineralic infilling of ankerite (A), with high peak of calcium (Ca), with lower of magnesium (Mg), and very low of iron (Fe) peaks; e) polyminalic infilling of kaolinite and calcite (ca), calcite shows a high single calcium (Ca) peak; f) Kaolinite (K) cleat infilling cross cut by Titanium mineral (Ti); g) Chlorite (Ch) intergrown with kaolinite (K), as well as lining in the cleat wall; h) Fluorapatite (Ap) cleat infillings, associated with illite (I) at the end of the cleat space; i) Interlayered calcite (Ca) and ankerite (An) in the cleat space, associated with titanium mineral (Ti) and chlorite (Ch).

Calcite and ankerite may occur as both single-phase and multiple-phase of cleat-filling mineral deposits. These minerals are commonly associated with kaolinite and illite, and in some cases with other clay minerals such as chlorite, diasporere and rutile or anatase. Monomineralic ankerite and calcite cleats are shown in figure 2d and 2e. The EDS pattern of these minerals indicates that the ankerite has a high peak of calcium (Ca), with lower of magnesium (Mg), and very low of iron (Fe) peaks (figure 2d), while calcite shows a high single calcium (Ca) peak (figure 2e). Calcite, as polyminalic cleat infillings is generally associated with kaolinite, illite and diasporc. Al rich minerals (diaspore) form linings on the cleat wall,
with calcite in the middle of the cleat space. In most cases, however, calcite is found in association with illite and kaolinite. Illite and kaolinite occur as linings on the cleat wall, with calcite a later intergrowth in the middle of the cleat space. In some cases, the illite may also be cross cut by chalcopyrite. Although rarely occurring as the main mineral in the cleat, rutile (or anatase) and apatite are commonly found in association with clays and carbonate mineral cleat-fillings. Rutile/anatase commonly occurs cross cutting the kaolinite and illite in the cleat, usually as prismatic crystals. Rutile/anatase may also be found as a rim along the edge of kaolinite-filled cleats. In some cases, rutile or anatase may also found in association with calcite in the cleat space.

4.4 Multistage of Cleat Mineralization

The occurrence of intimate mixtures of minerals within single cleats makes it difficult to determine their mineral formation and origin, however SEM-EDS mapping can be obtained elemental composition of minerals within the cleat aperture. This allows identifying the minerals growth pattern from the rim to the middle of cleats spaces and interprets paragenetic sequence of cleat mineralization. Elemental mapping in carbonate-bearing cleat infills from the Carborough Pit of the South Walker Creek clearly shows that the aluminium (Al) and silicon (Si) are distributed in the outer part of the cleat space, well correlated with aluminosilicate rich minerals (kaolinite and chlorite). Other elements such as calcium (Ca), magnesium (Mg) and iron (Fe), however, are distributed in the middle of the cleat spaces associated with the occurrence of carbonates (e.g., calcite and ankerite). This may indicate that two or more generations of cleat mineralization, and that kaolinite and chlorite appear to have been formed earlier than the carbonates (figure 3).

Based on the minerals growth pattern and cross cutting relationship analysis under the SEM, the cleat mineralization in the South Walker Creek Coals may be divided into four stages: Silicate I (kaolinite and quartz), oxide (rutile or anatase), Silicate-II (illite-chlorite-diaspore-apatite), and carbonates (ankerite and calcite). Kaolinite and quartz were probably deposited in the early stages of cleat mineralization. Well crystallized kaolinite in association with sub-rounded quartz particles 1 -2 µm in diameter. This may indicate that the quartz was introduced to the cleat before the kaolinite.

Rutile or anatase commonly crosses cut perpendicular or oblique to kaolinite cleat infillings and occur as euhedral patches in the middle or on the edges of kaolinite cleat infills (figure 2f). This suggests that the rutile was deposited within the cleat at a relatively early stage, and was surrounded by later kaolinite deposition. At latter stages, kaolinite is developed at the edges of the cleat wall, with illite as irregular flakes attached to the kaolinite cleat infill. This may indicate that the kaolinite predates the illite in the cleat-filling material. Although the relationship is difficult to interpret, both the kaolinite and the illite then appear to have been invaded by diaspore-forming solutions in the last stage of mineral precipitation in this cleat fracture. Chlorite commonly occurs as inter-grown irregular flakes along cracks or cleavages of kaolinite cleat components (figure 2g). This may indicate that the chlorite mainly postdates the kaolinite. Chlorite may also occur in association with diaspore in the cleat space, as intergrowths in the diaspore cleat fills. This suggests that chlorite was deposited in early stage, and was surrounded by later diaspore formation due to the high concentration of Al in the hot solution within the cleat space.

Apatite occurs as an overgrowth component in the cleat associated with illite at the end of the cleat space (figure 2h). This indicates that apatite postdates illite formation. The final stage of cleat mineralization appears to have been deposition of the carbonate minerals, ankerite and calcite. These minerals are associated with kaolinite and illite within the cleat of the coal (figure 2i). Ankerite and calcite occur as elongate bodies, usually in the middle of illite and kaolinite cleat infills. This suggests that ankerite and calcite postdate the kaolinite and illite in the cleat fillings. Carbonate cleat mineralization commonly appears as layers, it seems that ankerite and calcite are inter-layered within the cleat space, with calcite being more likely have formed at a later stage than the ankerite.
Figure 3. Photomicrograph of minerals growth pattern in the cleat spaces; a) Interlayered calcite (Ca) and ankerite (An) in the cleat space, associated with rutile or anatase (Ti) and chlorite (Ch); b and c: results of elemental mapping for cleat minerals.
5. Discussion

A complex geological history including factors such as igneous intrusion and tectonic events has been involved in the thermal maturation in the Bowen Basin. Mallett [14] have provided a comparison of thermal histories in different parts of the Bowen Basin. They have focused on three geological processes which may have impacted on the thermal maturation, burial by younger sediments, burial by tectonic processes such as folding and overthrusting, and periods of anomalous heat flow associated with intrusions. In particular in the northern Bowen Basin, they concluded that the Triassic events and Cretaceous heat flows were factors included in the thermal maturation of coals in the Nebo Synclinorium. Glikson [15] and Uysal [16] reveal that the paleogeothermal gradients in the northern part of the basin, including the South Walker Creek area, are relatively higher than the south area, due to hot fluid circulation along the fracture and fault zones. Fractures and cleats are favourable pathway for fluid movement in the coal seam and suggest that fluid circulation along the fault systems enhanced permeability zones in both mudrock and coal, as well as in the siliciclastic rocks of the northern Bowen Basin [15]. The South Walker Coals in the Northern Bowen Basin have been identified that mineralogical variation in the vertical sequence shows an unusual pattern, with kaolinite-rich assemblages are dominated in the top and bottom of the seam section and an illite-chlorite assemblages the middle, resemble a metamorphic association [9,17,18]. Carbonate cleat-filings, such calcite and ankerite are abundant in the middle part of the seam section, attributed to hot fluid circulation. Many of the cleat and fracture fillings are composed of intermixed minerals (polymineralic), with different phase of formation, which suggest multi-stage mineralisation process. The progressive illitization of kaolinite and illite/smectite, in coal seams may be due to either rank advance process at deeper burial and hot fluid flow circulation. The latter was probably responsible for the association of ille, chlorite and diaspore with kaolinite in the cleat mineralization process [9].

SEM-EDS observations show the evidence of multiphase process of cleat mineral formation in the South Walker Creek coals. Typical of layering carbonate minerals in the cleat space indicates that carbonates post-date the kaolinite, forming thin intercalated layers in the middle of otherwise kaolinite-filled cleat spaces, and with diaaspore intergrowths in the carbonate-filled middle of the cleat space. The hydrothermal fluid brought high concentrations of Mg, Fe and Ca, and acting as a source of ankerite and calcite formation in the cleat. Al ions may also have occurred in the solutions, forming the diaspor in the middle of the cleat space (figure 4). This may suggest that the ankerite, calcite and diaspore are derived from precipitation of hydrothermal solution within the cleat space. Hatch [19] indicates that similar paragenetic sequences of multiphase mineral formation in coal cleat may have been formed by the variable composition of the fluid flow, which re-opened previous cleats and precipitated minerals episodically in the cleat space. This crack opening process is termed “crack-seal” deformation. Dietrich and Ramsay [20] demonstrated that in some fibrous vein infillings associated with low grade metamorphism “crack seal” developed by multiple increments of microcrack opening followed by sealing of the microcrack by deposition material from solution.

The formation of epigenetic carbonates in the final stages of cleat mineralization in the present study area may indicate a similar crack-seal mechanism. The hot fluid flow in the permeable zones in particular cleat spaces re-opened the previous kaolinite-filled cleats, followed by sealing of the re-opened cleats by ankerite and calcite precipitated from the solution. Repeated crack seal increments involving calcite and ankerite in the cleat built up more complex fibrous veins. Emplacement of igneous intrusions in the study area, or possibly wider basin tectonics may have provided the hydrothermal system, injecting hot fluid solutions along the permeable zones of the coal seam. Dawson [21] reported that the isotopic signatures of the carbonate mineral indicate mixed or igneous sources as well as microbially derived carbonate for calcite within the Bowen Basin. Post-depositional formation of dawsonite (NaAlCO₃(OH)₂) in cleat space
of the Permian coal from the Bowen-Gunnedah-Sydney (BGS) Basin is thought to be related to a basin-wide magmatic source, where the seepage of magmatic CO\textsubscript{2} associated with meteoric porewaters led to aluminosilicate breakdown and provided sodium (Na) and (Al) to from the dawsonite [22, 23]. A similar process may have introduced Al and Ca, as well as Mg and Fe, to the South Walker Creek coals, forming calcite, ankerite and diaspore in the permeable zones of the coal seam.

Figure 4. SEM Images illustrating possible crack-seal development; a) Fibrous cleat, composed of the inter-layered kaolinite (K) and carbonates; b) Enlarged view of image, representing multi stages of cleat mineral formation, ankerite (A) and calcite (Ca) occur as layering carbonate minerals in the cleat space, associated with kaolinite rims at the edges of the cleat wall, and diaspore intergrowths within the carbonates; C: Sketch of crack-seal development.
6. Conclusions
The main coal seam of the South Walker Creek is well developed cleat system. The cleats are both open and closed aperture, filled by minerals. The mineral formation in the cleats occurs either as single mineral (monomineralic) or inter-mixed mineral (polyminalic) and three types of cleat mineral formations. Optical microscope and SEM-EDS approach recognized the polyminalic association in the single cleat spaces represents a multi-phase minerals formation or crack sealing development, as a result of different stages of epigenetic processes. The paragenetic cleat mineral formation shows that first and second stages may be linked with the mineralogical composition of the coal and non-coal rock associated with the coal, formed due to remobilizing of earlier silicate rich material by ground water solutions, followed by precipitation within the cleat fractures. However, the two later stages may have been formed due to hot fluid movement in the permeable parts of the coal seam, followed by either transformation of pre-existing minerals within the seam, and/or remobilization of earlier mineral, which was then precipitated in cleat as epigenetic minerals.

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References
[1] Stach et al, 1982 Textbook of Coal Petrology, 3rd ed.: Berlin, Gebruder Borntraeger, pp. 535
[2] Ward C R 1984 Coal Geology and Coal Technology. Blackwell Oxford, pp. 345
[3] Thomas L 2002 Coal geology: San Francisco, CA, John Wiley & Sons, Ltd, pp. 384
[4] Taylor G H 1998 Organic Petrology. Gebruder Borntraeger, Berlin-Stuttgart, pp.704
[5] Ward C R 2002 Analysis and significance of mineral matter in coal seams. International Journal of Coal Geology 50: 135-168
[6] Kemezys M and Taylor G H 1964 Occurrence and distribution of minerals in some Australian coals. Journal of the Institute of Fuel 37:389-397
[7] Ward C R 1986 Review of mineral matter in coal. Australian Coal Geology 6: 87-110
[8] Permana A K, Ward C R, Li Z and Gurba L W 2013 Distribution and origin of minerals in high-rank coals of the South Walker Creek area, Bowen Basin, Australia, International Journal of Coal Geology 116-117, p 185-207
[9] Hammond R L 1987 The Bowen Basin, Queensland, Australia: an upper crustal extension model for its early history. In: Hower, J.C. and Gayer, R.A. (Authors), International Journal of Coal Geology 50: 215–245
[10] Fielding C R, Falkner A J, Kassan J and Draper J 1990 Permian and Triassic depositional systems in the Bowen Basin. In: Beeston, J.W. (Ed.), Proceedings Bowen Basin Symposium, Geological Society of Australia, Queensland Division, Brisbane, p.21-25
[11] Hamilton L H and Salehi M R 1986 Use of scanning electron microscopy in coal petrology. Journal of Coal Geology, Geological Society of Australia, 8: 77-85
[12] Huggins F E, Kosmack D A, Huffman G P and Lee R J 1980 Coal mineralogies by SEM automatic image analysis. Scanning Electron Microscope 1: 531-540
[13] Mallett C W, Russel N and McLennan T 1990 In: Thermal history of the Bowen Basin. Bowen Basin Symposium 1990 Proceedings. Geological Society of Australia, p. 15-20
[15] 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 Academic Publisher, pp. 329-358

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

[17] 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. (Editor): Bowen Basin Symposium 2010-Back in (the) Black. Geological Society of Australia Inc. Coal Geology Group and the Bowen Basin Geologist Group, Mackay, October, 2010, pp. 27-34

[18] Permana A K 2011 Mineralogical variation and changes in the South Walker Creek coals, Bowen Basin, Queensland, Australia, University of New South Wales, Thesis, pp 343

[19] Hatch J R, Gluskoter H J and Lindahl P C 1976 Sphalerite in coals from the Illinois Basin. Economic Geology 71: 613-624

[20] Ramsay J G 1980 The crack-seal mechanism of rock deformation. Nature 284, 135-139

[21] Dawson G K W, Golding S D, Esterle J S and Massarotto P 2012 Occurrence of minerals within fractures and matrix of selected Bowen and Ruhr Basin coals, International Journal Coal Geology 94, p 150-166

[22] Goldbery R and Loughnan F C 1970 Dawsonite and nordstrandite in the Permian Berry Formation of the Sydney Basin New South Wales. American Mineralogist 55:477-490

[23] Baker J C, Bai G P, Hamilton P J, Golding S D and Keene J B 1995 Continental-scale magmatic carbon dioxide seepage record by dawsonite in the Bowen-Gunnedah-Sydney Basin system, eastern Australia. Journal of Sedimentary Research 3: 522-530