INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Tectonic Control on the Formation of Cleats in the Coal Beds of the Sajau Formation, Berau Basin, Northeast Kalimantan

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Manuscript received: January, 11, 2016; revised: April, 10, 2016;
approved: July, 3, 2018; available online: November, 23, 2018

Abstract - Coal seams of lignite- to subbituminous rank of Pliocene-age from the Sajau Formation of the Berau Basin are characterized by the presence of a natural fracture system, including cleats. Often, these opening-mode fractures consist of two orthogonal sets (face and butt cleats), both almost perpendicular to the bedding. This paper describes the distribution of orientation, spacing, and aperture of cleats formed in the seams of the Sajau Formation. All observations and measurements were conducted at macroscopic, mesoscopic, and microscopic scales. The butt cleat mean orientations are NE-SW and NW-SE, whereas the face cleat mean orientations are NNE-SSW and NE-SE, and the cleat dip is at a high angle of 75° to the north. The angles between the orientations of these cleat sets are nearly 90°; that is, they are orthogonal. The spacing of the macroface cleats is between 9.52 and 14.46 cm (averaging 11.61 cm), while the spacing of the butt cleats is between 2.3 and 11.3 cm (averaging 5.35 cm). The mean aperture is 0.54 mm. In contrast, the mean spacing of the mesoface cleats is 3.09 mm, and the aperture measurements of these cleats range from 0.0478 to 0.0741 mm (averaging 0.0549 mm). The results obtained from outcrops and X-ray CT (computed tomography) scan clearly indicate that the NNE-SSW face cleat orientations are strictly parallel to the elongation of the main tectonic structures in the studied area. Their origin may be explained by their relationship with local tectonic stress (the maximum principal stress, σ1, was horizontal). Partial least square analysis of data collected from cleats and faults in the area indicates that a power law distribution exists between the cleat characteristics (spacing, density, and aperture), and the distance of the faults ($R^2 = 0.56$). Cleat formation in the Sajau Formation was mainly controlled by the mechanical response to tectonic stresses, which generated a unique cleat network in the coal. Based on the SEM photography, it is concluded that the development of microcleats in the Sajau Formation resulted from both endogenic processes and tectonic activities as indicated by the change in the shape of the cleats, from straight line to curved shape and branching (intersection of multiple cleats that form a conical network at the end).

Keywords: Pliocene, coal, Sajau Formation, cleat, Berau Basin

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How to cite this article:
Sudradjat, A. and Hamdani, A.H., 2018. Tectonic Control on the Formation of Cleats in the Coal Beds of the Sajau Formation, Berau Basin, Northeast Kalimantan. *Indonesian Journal on Geoscience*, 5 (3), p.235-250. DOI: 10.17014/ijog.5.3.235-250

Introduction

In coalbed methane (CBM) exploration and production, cleats play an important role in coal permeability, coalbed gas generation, and storage. Although CBM has successfully been produced from both high- and low-rank coals, studies of cleat characteristics have mainly been limited to coal of bituminous rank (McCulloch *et al.*, 1974, 1976; Laubach *et al.*, 1992, 1998; Karacan and Okandan, 2000; Solano-Acosta *et al.*, 2007; Moore, 2012; Flores, 2013; Mardon *et al.*, 2014).

However, the successful development of CBM obtained from low-rank coal (lignite, subbituminous coal) in various basins in different parts of the world has well been documented. Examples include the huge reserves of coalbed methane found and produced in low-rank coal, such as in the San Juan Basin, Powder River Basin, Uinta Basin, and Raton Basin in the United States (Ayers, 2002); the Surat Basin and Bowen Basin in Australia (Scott *et al*., 2007); and the Ordos Basin in China (Xu *et al*., 2012; Songhang *et al*., 2010). Therefore, research on cleats of lignite and subbituminous rank is very important.

The origin of cleats is still debatable and controversial. Two separate concepts are associated with the process of cleat formation: endogenic and exogenic (Ammosov and Eremin, 1963; McCulloch *et al*., 1976; Ting, 1977; Laubach *et al*., 1998; Paul and Chatterjee, 2011). Endogenic cleats developed as a result of the coalification process *i.e.* by matrix dehydration, devolatilization, matrix shrinkage, and so on. On the other hand, exogenic cleats formed as a result of external stresses acting on the coal seam, including tectonic stresses, fluid pressure changes, folding, and the development of tensile stresses to which the coal seam is subjected during various periods. Su *et al*. (2001) mentioned that a single hypothesis on cleat formation was probably incorrect. The presence and the characteristics of cleats are among the important factors that greatly influence the capacity of the gas produced from CBM reservoirs.

The Berau Basin is one of the sedimentary basins in Indonesia that contains relatively widespread and thick multiple coal seams, within the Latih Formation and Sajau Formation. A study conducted by Advanced Resources International Inc. (ARII, 2003) estimated the potential "completable resources" of CBM in the Berau Basin within the Latih Formation to be about 8.4 Tcf. On the other hand, studies on the potential of CBM in the Sajau Formation are still insufficient (Figure 1).

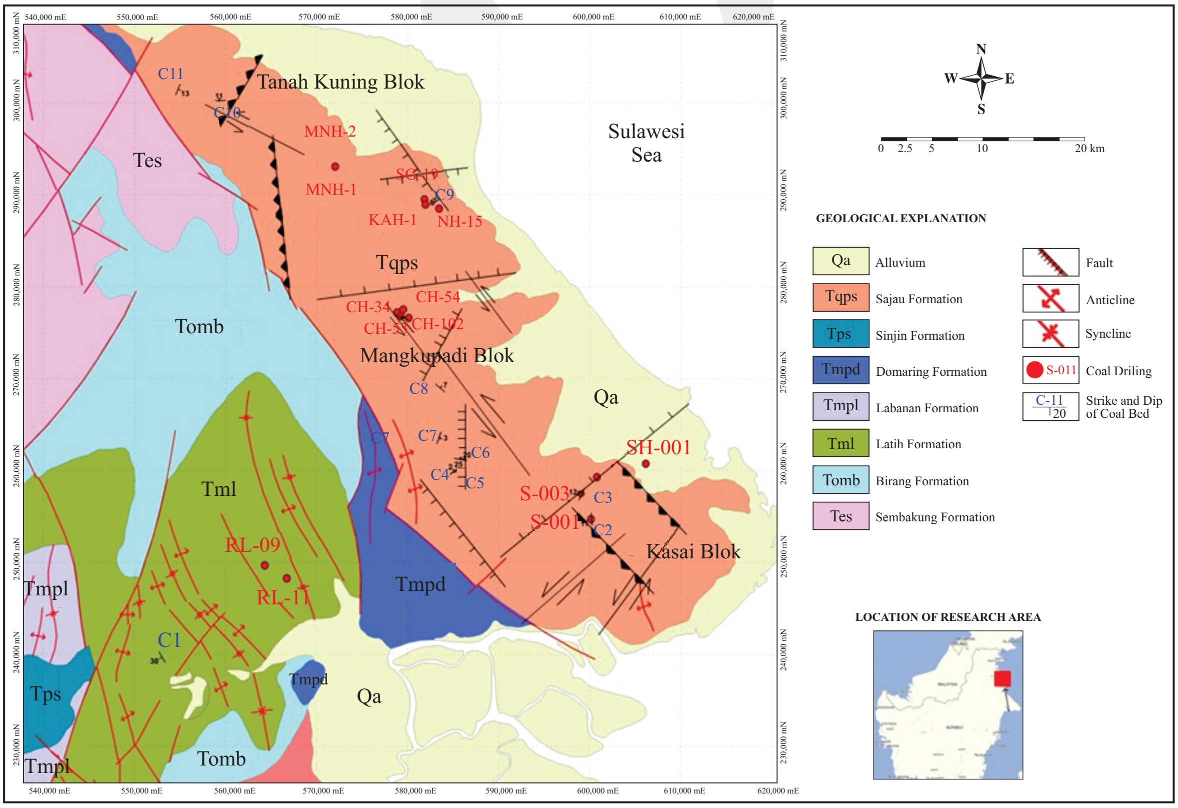

Figure 1. Geological and location map of part of the Berau Basin, showing the location of coal exploration drill sites and points where attributes of cleats were measured. Surface geology is from the 1:250,000 scale of Tanjungredeb Sheet published by the Geological Agency (Situmorang and Burhan, 1995).

The aims of the current study are, first, to define the cleat attributes, such as orientation, spacing, and aperture, of lignite and subbituminous coals. Variations in cleat spacing and aperture will be discussed in terms of their relationship with the distance of the lignite and subbituminous coal seam from the nearest fault. The second goal is to determine the origin of the network of cleats.

Geological Setting

The Berau Basin encompasses a wide variety of faults, structural elements, and trends. The formation of the basin was triggered by extension and subsidence during the Middle to Late Eocene, which created wrench faults and resulted in the appearance of major NW-SE-oriented axis. Subsidence stopped by the end of the Early Miocene. Two deep-seated NE-SW sinistral faults, the Mangkalihat and Maratua, were influenced by these structural trends in the Berau Basin. These faults play an important role in the arrangement of the NW-SE and NNW-SSE trending fold axes. It is concluded that the main direction of the compressional stress (σ1) of the cleats in the Berau Basin is NW-SE (Figure 2).

The Cenozoic units in the Berau Basin were deposited over a Paleozoic- to Mesozoic-aged basement, comprising metamorphosed and strongly tectonized rocks. The Cenozoic-aged sedimentary succession in the Berau Basin can be grouped into three major cycles of sedimentation: Cycle 1 (Middle Eocene to Late Eocene), Cycle 2 (Early Miocene to Late Miocene), and Cycle 3 (Pliocene to Late Pleistocene). Tectonic and relative sea-level changes influenced the lithological variation (Figure 3).

The oldest sedimentary cycle in the researched area is the Middle to Upper Eocene in the Sembakung Formation, which consists of a syn-rift volcanic-bearing siliciclastic-rich, nonmarine environment. The Eocene Sembakung Formation creates an economic basement and is underlain by the metamorphosed, Cretaceous, island-arc spilites of the Danau Formation.

The Sembakung Formation is unconformably overlain by the first post-rift sediments. These

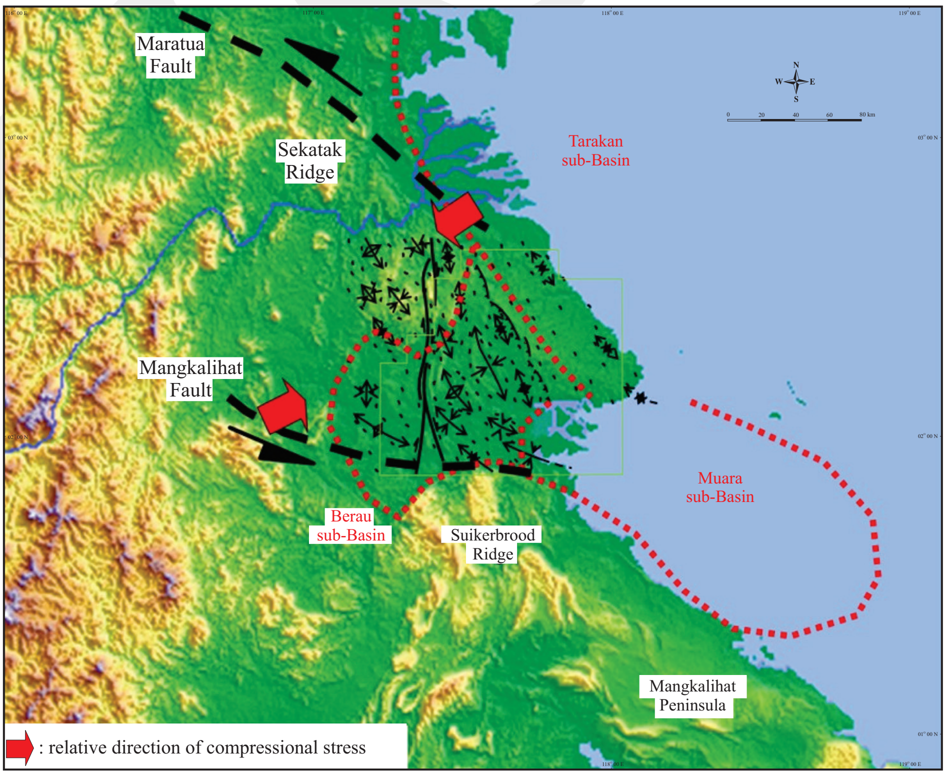

Figure 2. Tectonic setting in Berau Basin with two deep- seated faults (Salahuddin *et al*., 2011).

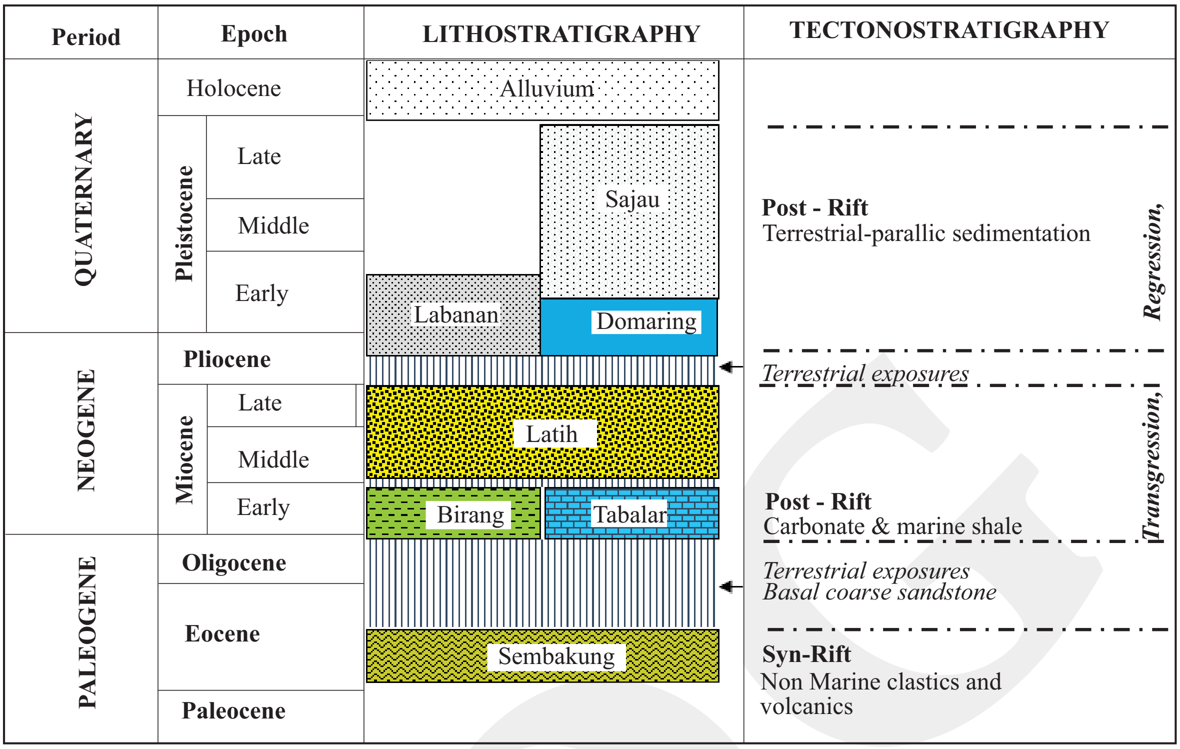

Figure 3. Stratigraphy of Berau basin and surrounding area (Modified from Lentini, M. R. and Darman, H. 1996; Noon *et al.*, 2003; and Situmorang and Burhan, 1995).

sediments are divided into three lithostratigraphic units: Birang (oldest), Tabalar, and Latih (the youngest) Formations. These post-rift sediments are characterized by transgressive carbonate and marine shale units developing during the Oligocene to Lower Miocene period. These are unconformably overlain by the second post-rift sedimentation youngest group which is characterized by coarse and terrestrially paralic sedimentation, with less developed carbonate.

The second post-rift sedimentation consists of three lithostratigraphic units: Labanan, Domaring, and Sajau Formations. The sedimentary succession in the second post-rift phase was deposited during a major regression associated with periods of regional tectonic uplift during the Pliocene age.

Outcrops in the Sajau Formation in the Tanah Kuning and Mangkupadi areas in the northern part of the basin and in the Kasai and Batu-Batu areas in the southern part were investigated. These outcrops typically comprise siliciclastic rocks and coal. The Sajau Formation in these areas is composed of interlaminated claystone, shale, sandstone, and conglomerates with coal. The formation contains mollusk and quartzite and is micaceous. The sedimentary structures that can be found are cross lamination and parallel lamination. In this formation, the coal thickness is 0.5 - 6.0 m, and the coal colours are black and brown. The rank is lignite to subbituminous. The measurement of cleat orientations from Sajau coal in the studied area clearly shows gradual to abrupt strike variations in cleat trends over short distances. Besides, cleat density can differ vertically and laterally within the same coal bed.

Definition and Classification

Cleats are defined as a fracture set with an angle between the cleat set strikes of nearly 90°. In this paper, cleats are divided (Nelson, 1983; Laubach *et al.*, 1998) into two basic types: face cleats (linear discontinuities that developed perpendicular to the bedding plane) and butt cleats (perpendicular to the bedding plane and oriented at nearly 90° to the face cleats).

Face cleats have a surface that is almost planar, persistent, laterally extensive in coal seams, long, and widely spaced. In contrast, butt cleats are nonplanar surfaces that are discontinuous and short and tend to abut their end into face cleats (Ammosov and Eremin, 1963, Tremain *et al*., 1991; Rodrigues *et al*., 2014). The term cleat orientation is used for strike and dip angle. Cleat spacing refers to the distance between two cleats as measured perpendicular to the cleats. Cleat density means the sum of cleats in certain areas.

Coal classification is based on coal rank, which refers to Gross Calorific Value (GCV) according to ASTM D388-12. The GCV is tested on a moist and mineral matter free basis (moist mmf). Moist refers to the natural inherent water contained in coal, but it does not include visible water on the coal surface.

Methods and Material

The research methods were based on field study and laboratory measurements. The cleats were measured at different scales: micro-, meso-, and macroscale. The macrocleats, which have relative cleat spacing in centimeter to decimeter are easily identified through the cleat attributes (spacing, aperture, and orientation), and are easily measured. Classifying the cleats into face and butt cleats was also easy. In contrast, the mesocleats (cleats with relative cleat spacing in millimeters) were identified and measured at the laboratory using the CT (computed tomography) scan method. Due to the micrometer scale of the microcleats, using the SEM technique to identify the cleats was necessary. In this research, identifying these three scales of cleats will yield useful information about the origin of cleats.

During the field investigation, the sampling pattern adopted for collecting data on cleats was the rectangular window sampling method (Pahl, 1981; Priest, 1993). Using this method, the cleat attributes (cleat apertures, height/length, spacing, distribution, and orientation) and cleat density (sum of cleats) were measured within the area of a rectangle. The size of the commonly used rectangular area is 1 m^2 (1 × 1 m), but a smaller area may be used depending on the outcrop condition (1 × 0.75 m) (Figure 4). The field measurement equipment used was a 3-meter metallic tape, a ruler, and calipers. Statistical analysis was performed for all cleat attributes for each location.

The relationship between the cleat attributes and the nearest fault distance was analyzed using the partial least square (PLS) method.

CT scan is a nondestructive method that can provide structural information about coal in 3-D view of the cleat attributes, cleat orientation,

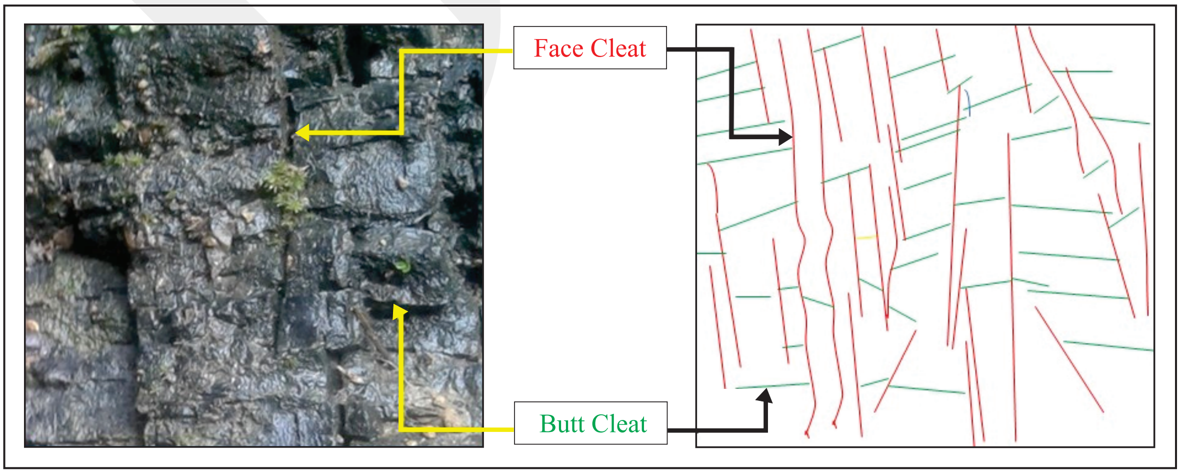

Figure 4. Cleat attributes, including orientation, length, aperture, spacing were measured for each fracture within a sampling area (black box) using rectangular window sampling.

microfracture, porosity, mineral filling, and coal matrix (Wellington and Vinegar, 1987; Mazumder *et al*., 2006; Yanbin *et al*., 2013).

The CT equipment used was the General Electric Bright Speed T scanner. The X-ray source was a 225 kV Fein Focus focal spot, which allows for resolutions up to 10 μm for 4.8 mm objects. The detector 3-D Toshiba image intensifier Kogeo seismic tool kit was used to recontsruct the 3-D of cleats distribution in coals.

CT scan observations were conducted at the Laboratory of Coal Bed Methane, Oil, and Gas Research Centre, Lemigas, Jakarta, and the Department of Radiology at Fatmawati Hospital, Jakarta. The SEM analysis was performed at the Centre for Geological Survey in Bandung.

All the cleat orientations were plotted in rosette diagrams and stereograms for each coal.

Results and Discussion

Coal Classification

The coal from the Sajau Formation generally has low calorific value and varies within a wide range of 5686 to 9285 BTU/lb. Based on this GCV value, most coals are classified as lignite to subbituminous coal rank according to the ASTM D388-12 coal classification standard (Table 1).

Macrocleat Characterization

Cleat characterization of the outcrops was taken from ten locations in three coalmine sites, those are, three measurements in Kasai Block, four in Mangkupadi Block, and three in Tanah Kuning (Figure 1). The cleats were located near the fault zones and folds, and some were close to the fault (Figure 5).

Figure 5. Photographs showing well developed face and butt cleats in the Tanah Kuning Block (Location : C10)

The measurements of the strike/dip of the macrocleats in Kasai Block were taken in three locations, namely, C2, C3, and C4, which were near the E-W normal fault zone. The strikes of the face cleat in Kasai Block are characterized by an average strike of N 243° E and/or N 63°E with a standard deviation of 18.6°. In the butt cleat, the average strike is N 62°E and/or N 242° with a standard deviation of 34°. The dips of the face

Table 1. Coal Rank and Coal Classification of Selected Sajau Coal

No.	Well Number	Sample Number	GCV BTU/Lb (Moisture mmf)	Coal Classification ASTM D388-12
1	SH-101	SH-101/2	9,285	Sub bituminous C
2	SH-106	SH-106/3	7,736	Lignite
3	CH-102	CH-102/2	8,663	Sub bituminous C
4	CH-34	CH-34/1	7,966	Lignite
5	CH-54	CH-54/3	5,686	Lignite
6	CH-53	CH-53/1	8,402	Sub bituminous C
7	MNH-1	MNH-1/1	9,260	Sub bituminous C
8	MNH-2	MNH-2/2	8,173	Lignite
9	KAH-1	KAH-1/1	7,624	Lignite
10	NH-15	NH-15/1	7,545	Lignite

and the butt cleat are very steep at an average of 85° and 87°, respectively.

In Mangkupadi Block, the orientation of the face cleat was measured in C5, C6, C7, and C8, which are influenced by the NW-SE fault direction, and have shown an average face cleat orientation of N 246° E and/or N 66° E with a standard deviation of 21° and an average butt cleat orientation of N 327° E and/or N 147° E with a standard deviation of 35°. The dips of both the face and butt cleats are steep at an average of 81°and 85°, respectively.

In Tanah Kuning Block, the cleat orientations were measured near the NW-SE fault zone in C9, C10, and C11. The average strike of the face cleat is N 242° E and/or N 62° E with a standard deviation of 180°. The average strike of the butt cleat is N 326° E and/or N 126° E. The average dip of the face cleat is 78°, and the average dip of the butt cleat is 86°.

Table 2 shows that the spacing of the face macrocleats ranges from 8.2 to 14.2 cm (~11.46 cm on the average for various coal beds). Butt cleats tend to be less well developed in many coal seams, more difficult to measure, and exhibit a less regular spacing (~ 2.4 to 11.4 cm).

Mesocleat Characterization

To identify a cleat attribute, density, and orientation at the mesoscale, the 3-D x-ray CT technique was used (Table 3). The face mesocleats more developed than the butt mesocleats, and the

Table 2. Macrocleat Attributes and Cleat Orientation from Sajau Coal

Block	Location No	Face Cleat			Butt Cleat		
		SP (cm)	AP (cm)	Strike (N..^{0} E)	SP (cm)	AP (cm)	Strike (N..^{0} E)
Kasai	C2	9.5	0.8	243	2.5	0.1	337
	C3	14.2	0.6	243	8.5	0.2	335
	C4	11.4	0.8	62	11.3	0.1	162
Mangkupadi	C5	14.5	0.5	70	4.3	0.2	133
	C6	8.7	0.6	328	6.2	0.2	58
	C7	8.2	0.6	246	8.2	0.1	118
	C8	12.4	0.4	318	2.4	0.2	48
Tanah Kuning	C9	13.2	0.5	324	3.6	0.1	56
	C10	10.4	0.2	74	2.4	0.1	174
	C11	12.1	0.4	65	3.2	0.2	65
Average		11.46	0.54		5.26	0,14	

SP: Cleat spacing; AP: Cleat aperture

Table 3. Mesocleat Attributes from Sajau Coal

Block	Well. No	DF (m)	DFC	FC (N/cm)	Face Cleat		Butt Cleat	
					SP (mm)	AP (mm)	SP (mm)	AP (mm)
Kasai	SH-101	306.20	12	4.77	2.92	0.0523	1.43	0.0219
	SH-106	302.40	12	5.25	3.12	0.0469	1.50	0.0273
Mangkupadi	CH-102	1176.00	7	2.58	4.43	0.0429	1.82	0.0219
	CH-34	70.00	5	8.78	3.21	0.0741	1.10	0.0291
	CH-54	180.00	6	7.54	2.76	0.0539	1.15	0.0289
	CH-53	250.00	4	7.20	3.16	0.0541	1.18	0.0291
Tanah Kuning	MNH-1	4280.00	7	3.91	2.64	0.0697	1.80	0.0257
	MNH-2	4390.00	5	3.08	3.25	0.0508	1.60	0.0258
	KAH-1	1064.00	5	3.12	2.52	0.0478	1.55	0.0228
	NH-15	760.00	6	6.31	2.96	0.0531	1.22	0.0280

FC: cleats frequency (N/cm); DFC: cleat cross cutting density; SP : cleat spacing (mm)g; AP : cleat aperture (mm).

apertures of the face mesocleats were generally larger than those of their butt counterparts. The spacing of the face mesocleats ranges from 4.00 to 12.00 mm, while that of the butt mesocleats ranges from 1.10 to 1.82 mm.

CT scan images were obtained from three orthogonal directions: X, Y, and Z. The meso-cleat system can be interpreted in the original XY-plane. If the number of stacked images and stepping sizes in the Z-direction is satisfying, the same analysis can be performed in the XZ- and YZ-directions. Combined CT images from the YZ- and XZ-planes were saved as a bitmap image and then converted into *segY.* Using a 3-D rendering software, the CT image was reconstructed into a 3-D cleat distribution (Ketcham *et al*., 2010; Lubis *et al*., 2011; Hamdani, 2015). A majority of the face and butt cleat–related fractures are visible in the reconstructed CT images

The 3-D reconstruction from the CT scan indicates two directions of the face and the butt cleats: NNE-SSW and NW-SE (Figure 6). The measurement directions of the cleats on various outcrops within the range of N 18°-264° E belong to the face cleats, and those within the range of N 62°-337° E belong to the butt cleats. Figure 7 shows the CT scan results and the interpretation of the direction of the orientation of the cleats.

As seen in Figure 7 (lower left), σ1 has a NE-SW direction. Two cleat orientations have been identified: NNE-SSW (face cleat, red colour) and NW-SE (butt cleat, blue colour) direction. The cleats with the NW-SE direction were abutting into the NE-SW cleats (Hamdani, 2015).

The direction orientation of the face cleat is similar to the direction of the compressional stress (McCulloch *et al*., 1974, 1976). Based on the interpretation of the NNE-SSW direction of the face cleats from Sajau coals, it is concluded that the direction of the compressional stress in the Berau Basin is NE-SW.

Microcleat Identifications by SEM

Scanning electron microscope (SEM) analysis was used to measure the microcleat attributes; that is, the aperture and spacing along various transects were identified. Each discontinuity was either a face or a butt cleat, depending on the abutting relationships. The butt microcleats less developed, and show smaller apertures as the face microcleats. The measurements of the cleat aperture range from 0.3 to 0.7 µm (face cleat) and from 0.1 to 0.3 µm (butt cleat).

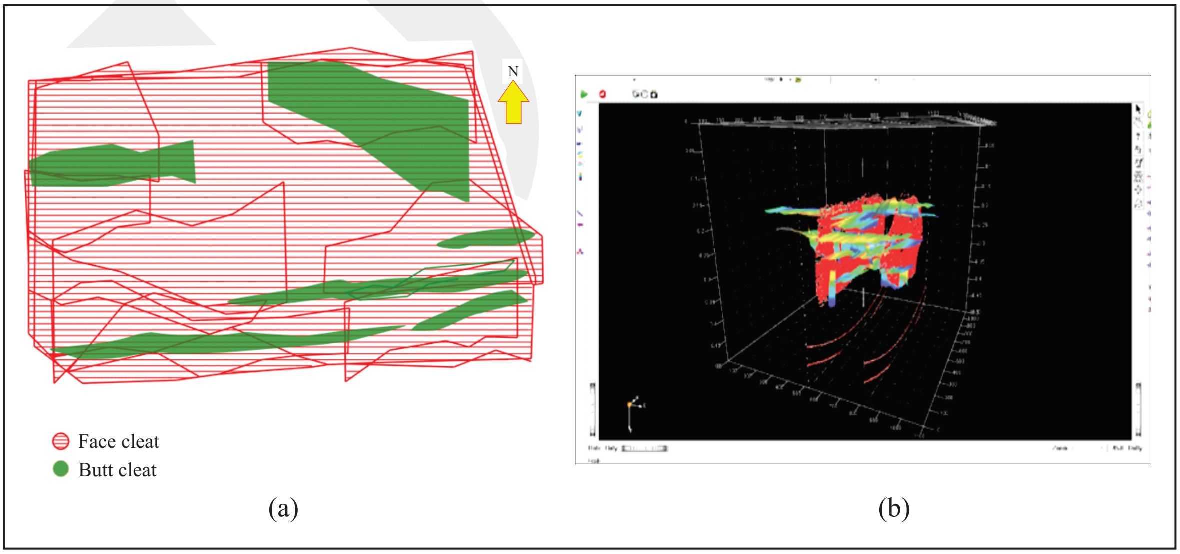

Figure 6: Illustrating 3D rendering CT scan of the cleats direction (a) from slice image of z-axis direction; 3D rendering CT scan (b). Face cleats have NNE-SSW direction (red colour and gradational colour), and butt cleats have NW-SE direction (green colour and solid colour).

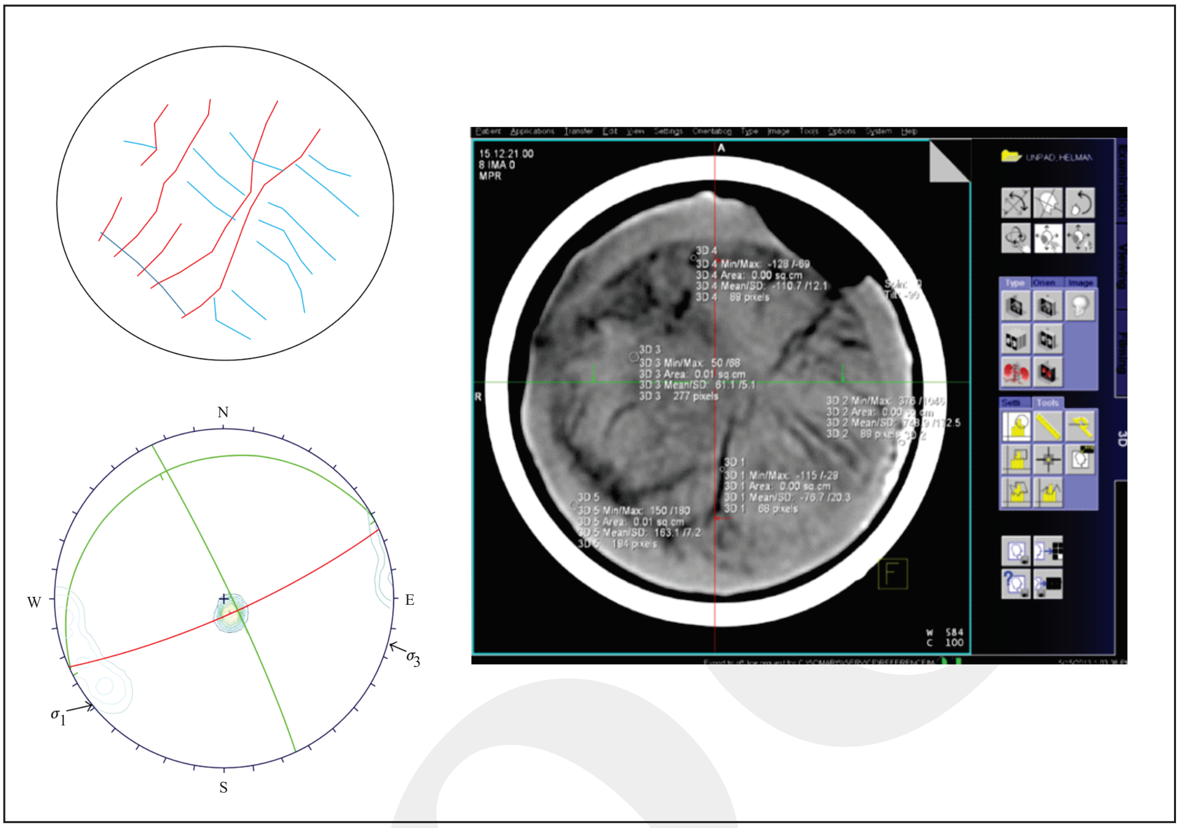

Figure 7. Slice image of SH-101A (Z-axis direction); orientation (upper left) and Schmidt lower hemisphere equal projection net of cleats orientation (lower left).

Discussion

Mechanism of Cleat Origin

Many ideas on how cleats are formed have been widely shared by various experts, such as the theory related to formation during coalification processes (Ammosov and Eremin, 1963; Ting, 1977; Laubach, 1991; Close, 1993). Another idea states that cleats that are identified as on opening mode (type I) can be formed through internal pressure working against remote compression (Olson and Pollard, 1989) as well as through compression, extension, and other manifestations of tectonism (Nelson, 1985; Pollard and Aydin, 1988).

Results of research on various cleat scales have shown that endogenous (matrix swelling) and exogenous (tectonic) processes possibly work together on coal in the Sajau Formation. This is indicated by the different structural types of cleats. Based on observations of the structural type of microcleat, it can be known whether the coal has been deformed or not. The structural deformation in the studied area consists of brittle deformation series (cataclastic structural coal) and ductile deformation series (wrinkle structure coal). Cataclastic structural deformation occurs in relatively weak tectonics, while wrinkle structural deformation is present in strong tectonics.

The SEM techniques on coal samples can identify the possible mechanisms of cleat formation. The endogenous (swelling matrix, fracture dilatation, and compacting) and the exogenous (tectonic) processes work together in the presence of distributing coal cleats.

For example, in the development of the microscopic characteristics of microcleats in coals, SEM analysis is performed on the coal samples from CH-102, CH-54, and CH-34 (Figures 8a - c), which are located in the vicinity of E-W normal fault no. 29, as seen in Figure 8d.

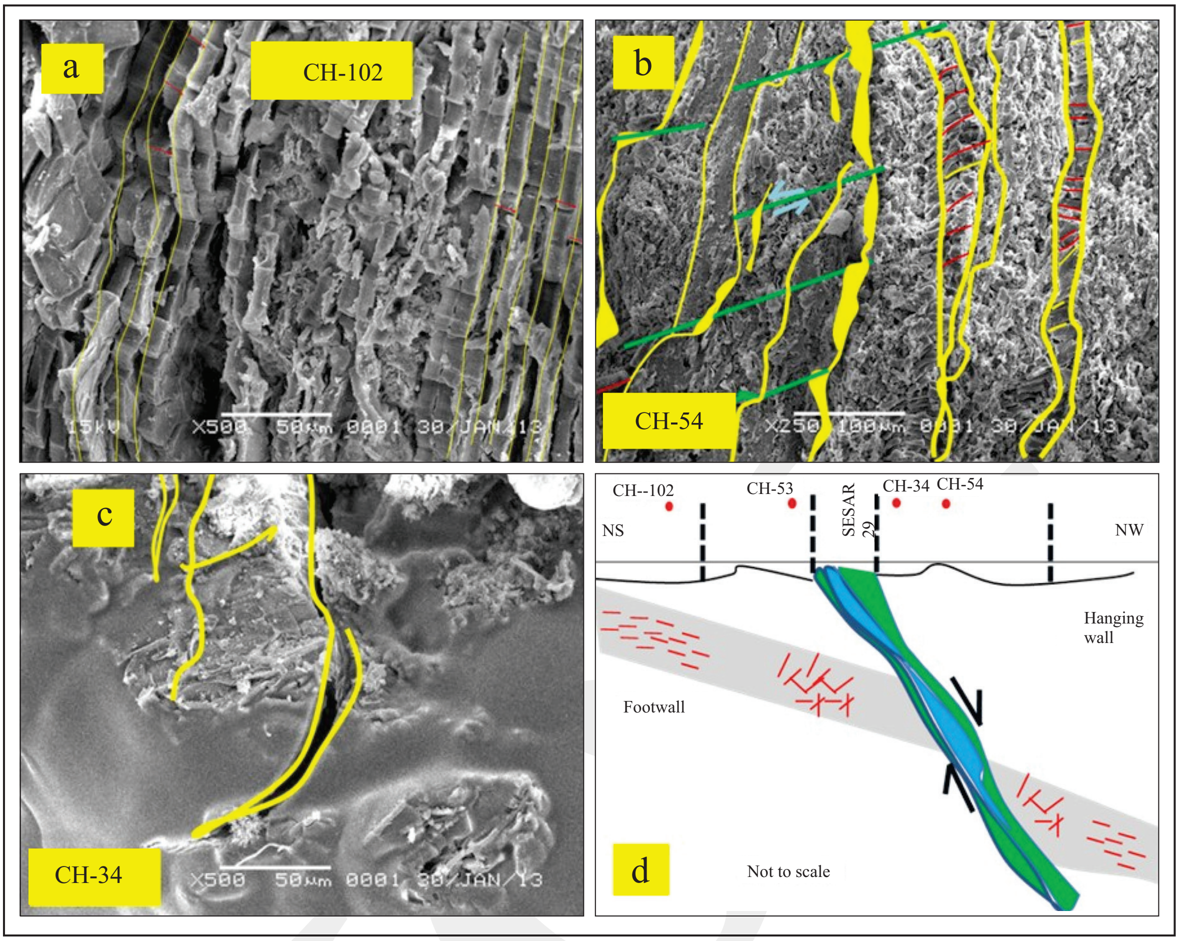

Figure 8. Type of coal cleat deformation in Sajau Coal based on SEM investigation.

The SEM picture of coal samples from CH-102 (Figure 8a), which is located about 1176 m from E-W normal fault no. 29, shows that microcleats consist of face and butt cleats. These cleats are commonly characterized by an orthogonal, thin-line shape resulting from the intersection between the face and the butt cleat, with tight cleat spacing and no displacement. These cleats have a typical endogenous origin and were formed during peat formation and coalification through the swelling matrix, fracture dilatation, and compacting or a combination of these factors.

The SEM microphotograph of the coal samples from CH-54 (Figure 8b), which is located more than 180 m from the fault zone, shows a cataclastic coal deformation. The deformation is characterized by the presence of two or more intersections between cleats or another microfracture, and has a step-shaped or dendritic morphology, a little displacement of cleats, and well-developed branching cleats (intersecting cleats, tapered at the end of the cleat) (Figure 9b).

CH-34 is located in the fault core zone (+ 70 m), where strong tectonic forces should affect the coal, possibly causing cleat deformation. As shown in Figure 8c, the shape of the cleats is curved (wrinkle coal), while the primary coal structure of the cleat is not found, and this is referred to as part ductile deformation.

Faults, Joints, and Cleats

Tectonically, the structural geology in the Berau Basin is influenced by the deep-seated NW-SE sinistral Mangkalihat and Maratua faults (Salahuddin, 2011). These faults played an important role in the arrangement of the folds with the NW-SE and NNW-SSE axes. Based on the

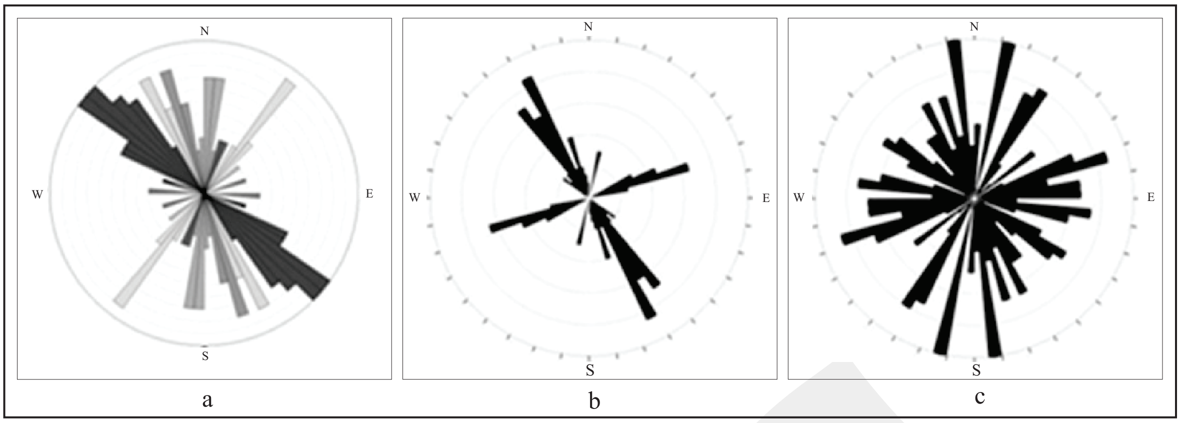

Figure 9. Rosette diagrams of faults (a); coal cleats orientation (b), and rock joints in Sajau Formation (c).

reconstruction of the structural elements in both field measurements and laboratory analysis, it is concluded that the majority of the fold axes in the Berau Basin are oriented toward NW-SE (Figure 10), the σ1 direction of the shear joint in Sajau sediments is relatively oriented toward NE-SW (Figure 7, lower left), and the σ1 direction of the cleats are relatively oriented toward NE-SW (Figure 7, upper left). Therefore, all elements of structural geology (fault, fold, joint, and cleats) have a similar direction for compressional stress (σ1): northeast-southwest (NE-SW). This relationship between the structural elements in the Sajau Formation can be seen in the rosette diagrams showing the cleats, joints, and faults (Figure 9.)

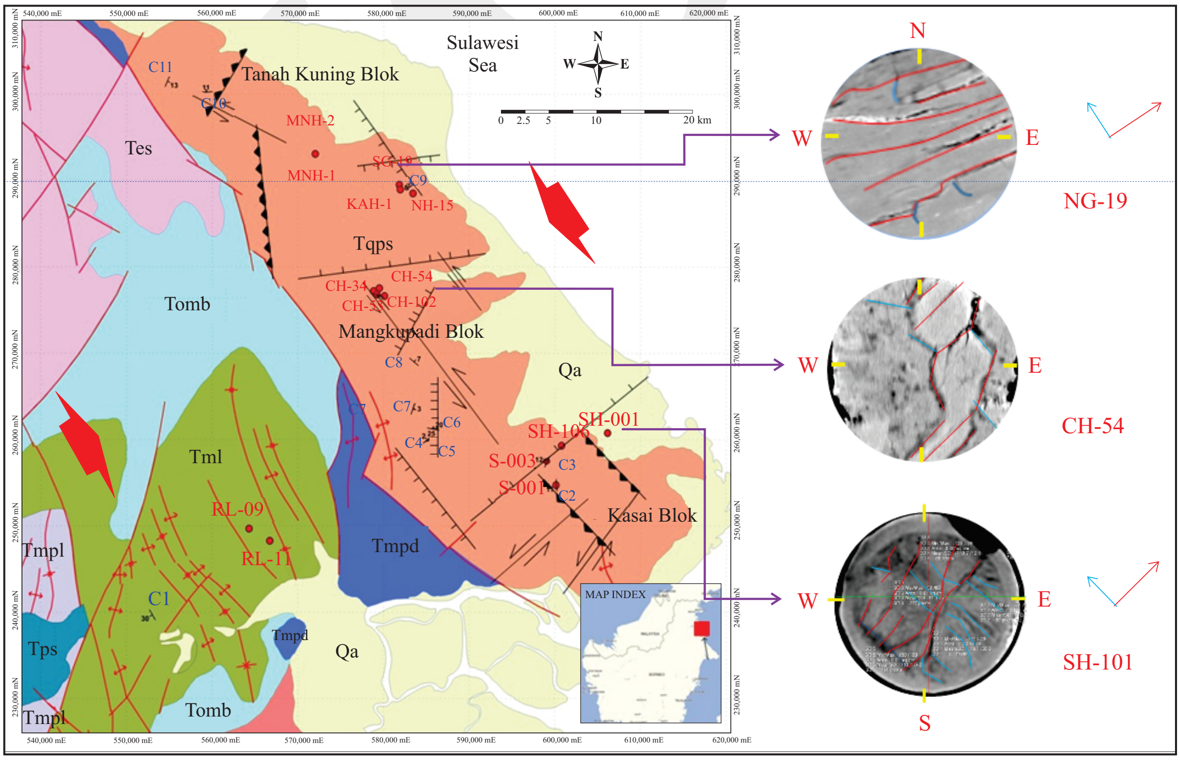

Figure 10. Structural geology (folds, faults, and cleats) arrangements in Berau Basin and CT scan image of representative coal samples (Solid Red Arrow: relative direction of compressional stress; red line: face cleats direction; blue line: butt cleat direction).

In the coal-bearing Sajau Formation in the Berau Basin, there is an observable parallelism between the face cleats and the preferential orientation of the fault lineament (NW-SE). Measured cleats from the same coal indicate an azimuth direction in agreement with the contemporary stress field, suggesting an active tectonic stress during the cleat development.

Collected evidence shows that a tectonic mechanism influenced the orientation of the coal cleats in the eastern section of the Berau Basin during the Pliocene-Pleistocene period. It is extrapolated that most cleat systems in the Sajau coals in the eastern section of the Berau Basin are subject to important exogenous (tectonic) control, in addition to inherent endogenous controls during coalification.

Statistical Analysis Using SEM-PLS

Structural equation modeling (SEM) is used in this research to determine the relationship between fault variable and cleat attribute variable. One of the new approaches and powerful tools introduced by Wold (1982, 1985) and Lohmőller (1989) is partial least squares (SEM-PLS), which is often called soft modeling. By using PLS, it is possible to reconstruct a structural equation model with relatively small sample sizes, and it does not have normal multivariate assumptions.

This study involves two construct variables and five indicator variables. The exogenous variable constructs are a fault that was measured through a variable indicator of the fault distance (X-1), while the endogenous variable constructs are a cleat that was measured through the measurement of four variable indicators: (1) cleat frequency (X-2), (2) cleat cross-cutting density (X-3), (3) cleat spacing (X-4), and (4) cleat aperture (X-5).

In this SEM-PLS, two models were proposed: inner and outer models. The inner model is the specification of the relationship between latent variables (structural model), also called inner relation, and describes the relationship between variables based on a substantive theory of research (Figure 11).

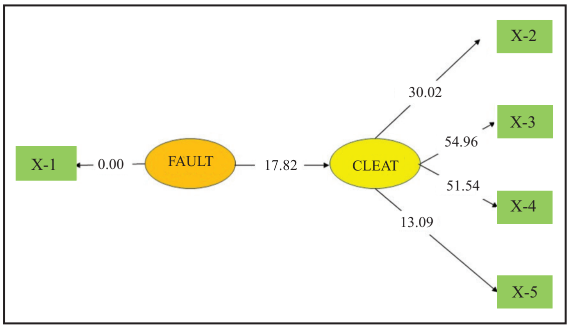

Figure 11. Inner model of the fault control of the cleat attributes and t-Test Value.

The outer model, or the measurement model, is used to perform an analysis relationship between all variables. This model determines whether the variable indicators used to measure a variable construct of cleats are valid or not, as well as whether they are reliable or not (Figure 12).

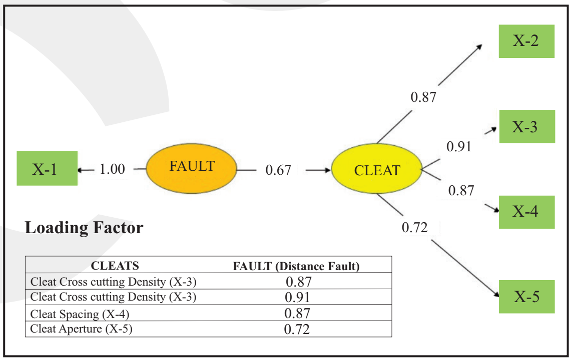

Figure 12. Outer model of the fault control of the cleat attributes and loading factor.

The numbers listed in the inner model diagram (Figure 11) are *t*-arithmetic. It appears in the figure above that all the *t*-values for all variable indicators and variable constructs are above 1.96, indicating that all indicator variables are significant in forming the intended construct. The R^2 value of these variables was used to determine the significance of the ability of a fault variable (X-1) in explaining cleat attribute variables (X-2, X-3, X-,4 and X-5). The statistical parameter structural model is shown in Table 4.

The equation model of the relationship between fault and cleat attributes is:

Table 4. Statitical Parameter Structural Model

Variable Construct	Variable Indicator	$T_{calculated}$	Standardized Path Coefficients	R^2	$F_{calculated}$	Pr> |t |
Fault	X1	17.82	- 0.640	0.56	10.354	0.000
Cleat	X2	37,02				
	X3	54,96				
	X4	51,54				
	X5	13,09				

$$\eta = \beta\eta + \xi + \varsigma \quad (1)$$

where
η: endogenous variable construct (cleat)
ξ: exogenous variable construct (fault)
ς: variable inner residual
β: path coefficient

The student's *t*-test gives a value of 17.82 with a *p*-value of 0.000. These results indicate a significant influence of the variable fault (X1) on the variable cleats. A coefficient of determination (R^2) of 0.56 means that 56% of the changes in the variable attributes of the cleats (cleat frequency, cross-cutting cleat density, cleat spacing, and cleat aperture) can be explained by the changes in the variable of the fault (fault distance; X1). The value of the *F* table for df1 of 10 and df2 of 1 is 4.75 at a significance level of 5% (*F* arithmetic >*F* table); that is, 10.354 > 4.75. Therefore, the fault variable was interpreted and has a significant effect on cleat attribute exchange.

Before it proceeds, it has to be determined whether the models adequately fit the data. Therefore, a goodness-of-fit test is used. This test consists of a validity test and a reliability test.

The validity test of the model includes the *loading factor method*, *square root of the average variance extracted* (AVE), and *goodness of fit* (GoF). On the other hand, the reliability test is conducted to measure the degree to which an assessment tool produces stable and consistent results by looking at the *composite reliability value* (CR) of the indicator block that measures the constructs and Cronbach's *alpha methods* (CA). The results of the goodness-of-fit test are presented in Table 5:

Based on the threshold value and the model matching index shown in Table 5, all model matching criteria have been met, so the proposed model can be expressed as a structural model and fits the data.

The results of this test show that the model as a whole fits the data or is able to reflect the reality and phenomena that exist in the field. The results of this study can be declared to be valid and reliable.

Table 5. Summary of Validity and Reliability Tests of Outer Model

Goodness of Fit Index	Threshold Value	Test Result Value	Remarks
Loading Factor	≥ 0.50	0.722754 - 0.988543	Fit
AVE	≥ 0.50	0.7149 - 1.0000	Fit
GoF	≥ 0.90	0.924 - 0.970	Fit
CR	≥ 0.70	0.9088 - 1.0000	Fit
CA	≥ 0.60	0.8642 - 1.0000	Fit

Conclusion

Two cleat system sets, face and butt cleat, were identified in the macro-, meso-, and microcleat modes in the Berau Basin. These cleat sets are perpendicular to each other, and the face cleat direction is NE-SW, while the butt cleat is NW-SE. The angle between the two cleats is nearly 90°.

The cleat formation in the Sajau Formation was mainly controlled by mechanical stresses in response to tectonic stresses of both regional and local origin.

Acknowledgments

The authors are deeply grateful to Equator Energy Group for the permission to use the coal exploration data. Our gratitude is extended to two anonymous reviewers for their thoughtful reviews of this manuscript.

References

Ammosov, I.I. and Eremin, I.V., 1963. *Fracturing in Coal*. IZDAT Publishers, Moscow. Office of Technical Services, U.S. Department of Commerce, Washington, DC. 109pp.

ARII (Advanced Resources International Inc.), 2003. Indonesia CBM Data Package, Advanced Resources International, Inc. *Migas and ADB Report*: www.adv-res.com.

Ayers, W. B., 2002. Coalbed gas system, resources, and production and a review of contrasting cases from the San Juan and Powder River basins. *American Association of Petroleum Geologists Bulletin,* 86 (11), p.1853-1890. DOI: 10.1306/61eeddaa-173e-11d7-8645000102c1865d

Close, J., 1993. Natural fractures in coal. *In*: Law, B.E., Rice, D.D. (eds), Hydrocarbons from Coal. *AAPG Studies in Geology,* 38, p. 119-132.

Flores, R.M., 2013. *Coal and Coalbed gas: Fueling the Future*. Elsevier, Waltham, MA. 697pp.

Hamdani, A.H., 2015. X-ray Computed Tomography Analysis of Sajau Coals, Berau Basin, Indonesia: 3D Imaging of Cleat and Microcleat Characteristics. *International Journal of Geophysics,* p.1-8. DOI: 10.1155/2015/415769

Karacan, C.Ö. and Okandan, E., 2000. Fracture/cleat analysis of coals from Zonguldak Basin (northwestern Turkey) relative to the potential of coalbed methane production. *International Journal of Coal Geol*ogy, 44, p.109-125. DOI: 10.1016/s0166-5162(00)00004-5

Ketcham, R.A., Slottke, D.T., and Sharp, M., 2010. Three-dimensional measurement of fractures in heterogeneous materials using high-resolution X-ray computed tomography. *Geosphere*, 6 (5), p.499-514. DOI: 10.1130/ges00552.1

Laubach, S.E., 1991. Fracture patterns in low-permeability sandstone gas reservoir rocks in the Rocky Mountain region. *Proceedings, Joint Society of Petroleum Engineers Rocky Mountain Regional Meeting. Low-Permeability Reservoir Symposium SPE Paper,* 21853, Society of Petroleum Engineers, Richardson, Tex. DOI: 10.2118/21853-ms

Laubach, S.E., Tyler, R., Ambrose, W.A., Tremain, C.M., and Grout, M.A., 1992. Preliminary map of fracture patterns in coal in the western United States. *Geological Association, Wyoming*, 43, p.253-267.

Laubach, S.E., Marrett, R.A., Olson, J.E., and Scott, A.R., 1998. Characteristics and origins of coal cleat: a review. *International Journal of Coal Geol*ogy, 35, p.175-207.

Lentini, M.R. and Darman, H., 1996. Aspects of the Neogene Tectonic History and Hydrocarbon Geology of the Tarakan Basin, *Proceedings, Indonesian Petroleum Association, 27th Annual Convention*, p.241-25.

Lohmőller, J.B., 1989. LVPLS 1.6 program manual: Latent variables path analysis with partial-least square estimation. Munich, Germany: University of the Federal Armed Forces.

Lubis, L.A., Harith, T., Zahir, Z., Noh, M., and Ariffin, K., 2011. Workflow to Reconstruct 3D Pore Space from 2D CT-Scan Image of Berea

Sandstone. *In: National Geoscience Conference 2011*, Johor Bahru, Malaysia

Mardon, S.M., Cortland, F.E., Hower, J.C., Takacs, K., Mastalerz, M., and Bustin, R.M., 2014. Organic petrology, geochemistry, gas content and gas composition of Middle Pennsylvanian age coal beds in the Eastern Interior (Illinois) Basin: implications for CBM development and carbon sequestration. *International Journal of Coal Geol*ogy, 127, p.56-74. DOI: 10.1016/j.coal.2014.02.002

Mazumder S, Wolf K, A.A., Elewaut K., and Ephraim, R., 2006. Application of X-ray computed tomography for analyzing cleat spacing and cleat aperture in coal samples, *International Journal of Coal Geol*ogy, 68, p.205-222. DOI: 10.1016/j.coal.2006.02.005

McCulloch, C.M., Deul, M., and Jeran, P.W., 1974. Cleats in bituminous coalbeds. *U.S. Bureau of Mines Report of Investigations,* 7910, 23pp.

McCulloch, C.M., Lambert, S.W., and White, J.R., 1976. Determining cleat orientations of deeper coalbeds from overlying coals. *U.S. Bureau of Mines Report of Investigations,* 8116, 24pp.

Moore, T. A., 2012. Coalbed Methane-A Review. *International Journal of Coal Geol*ogy, 101, p.36-81.

Nelson, W.J., 1983. Geologic disturbances in Illinois coal seams. *Illinois State Geological Survey Circula*r, 530, 50pp.

Nelson, R.A., 1985. *Geologic analysis of naturally fractured reservoirs*. Gulf Pub. Co., Houston, 320 pp.

Noon, S., Harrington,J., and Darman, H., 2003. The Tarakan Basin, East Kalimantan: Proven Neogene Fluvio-Deltaic, Prospective Deep-Water and Paleogene Plays in A regional Stratigraphic Context. *Proceedings, Indonesian Petroleum Association*, *29th Annual Convention*, 16pp.

Olson, J.E. and Pollard, D.D., 1989. Inferring paleostresses from natural fracture patterns: A new method. *Geology,* 17, p.345-348.

Pahl, P.J., 1981. Estimating the mean length of discontinuity traces. *Internation Journal of Rock Mechanics and Mining Sciences,* 18, p.221-228.

Paul, S. and Chatterjee, R., 2011. Determination of in-situ stress direction from cleat orientation mapping for coal bed methane exploration in south-eastern part of Jharia coalfield, India, *International Journal of Coal Geol*ogy, 87(2), p.87-96. DOI: 10.1016/j.coal.2011.05.003

Pollard, D. D. and Aydin, A., 1988. Progress in understanding jointing over the past century. *Geological Society of America, Bulletin,* 100, p.1181-120.

Priest, S.D., 1993. *Discontinuity Analysis for Rock Engineering*. Chapman & Hall, London, United Kingdom.

Rodrigues C. F., Laiginhas, C., Fernandes, M., Lemos de Sousa, M.J., and Dinis, M.A.P., 2014. The coal cleat system: A new approach to its study. *Journal of Rock Mechanics and Geotechnical Engineering,* 6, p.208-218. DOI: 10.1016/j.jrmge.2014.03.005

Salahuddin , Setianto A., Rakhmadi A, and Jonathan, 2011. Geological Evolution of the Berau sub-Basin, East Kalimantan.

Scott, S., Anderson, B., Crosdale, P., Dingwal, J., and Leblang, C., 2007. Coal petrology and coal seam gas contents of the Walloon Subgroup- Surat Basin, Queensland, Australia. *International Journal of Coal Geol*ogy, 70, p.209-222. DOI: 10.1016/j.coal.2006.04.010

Situmorang, R.L. and Burhan, G., 1995. *Geological Map of the Tanjungredeb Quadrangle, Kalimantan, scale 1:250.000*. Geological Research and Development Centre, Bandung.

Songhang, Z., Shuheng, T., Dazhen, T., Zhejun P., and Fang, Y., 2010, The characteristics of coal reservoir pores and coal facies in Liulin district, Hedong coal field of China. *International Journal of Coal Geol*ogy, 83, p.117-127. DOI: 10.1016/j.coal.2009.11.007

Solano-Acosta, W., Mastalerz, M., and Schimmelmann, A., 2007. Cleats and their relation to geologic lineaments and coalbed methane potential in Pennsylvanian coals in Indiana.

*International Journal of Coal Geol*ogy, 72, p.187-208. DOI: 10.1016/j.coal.2007.02.004

Su, X., Feng, Y., Chen, J., and Pan, J., 2001. The characteristics and origins of cleat in coal from Western North China. *International Journal of Coal Geol*ogy, 47, p.51-62. DOI: 10.1016/S0166-5162(01)00026-X

Ting, F.T.C., 1977. Origin and spacing of cleats in coal beds. *Journal of Pressure Vessel Technology Transaction. ASME,* 99, p.624-626.

Tremain, C.M, Laubach, S.E., and Whitehead, III N.H., 1991. Coal fracture (cleat) patterns in Upper Cretaceous Fruitland formation, San Juan Basin, Colorado and New Mexico-implications for coalbed methane exploration and development. *In*: Schwochow, S, Murray D.K., and Fahy M.F. (eds.), *Coalbed Methane of Western North America*. Rocky Mountain Association of Geologists, p.49-59. DOI: 10.23867/ri2018d

Wellington, S.L. and Vinegar, H.J., 1987. X-ray computerized tomography. *Journal of Petroleum Technology,* 39, p.885-898.

Wold, H., 1982. Soft modeling: the basic design and some extensions. *In*: Jöreskog K.G. and Wold, H. (eds.), *Systems under Indirect Observation*, Part 2. North-Holland, p.1-5.

Wold, H., 1985. "Partial Least Squares", *In*: Kotz, S. and Johnson, N. L. (eds.), *Encyclopedia of Statistical Sciences* (6)*,* New York, Wiley, p.581-591.

Xu, H., Tang, D. Z., Liu, D.M., Tang, S.H., Yang, F., Chen, X.Z., He, W., and Deng, C.M., 2012. Study on coalbed methane accumulation characteristics and favorable areas in the Binchang area, southwestern Ordos Basin, China. *International Journal of Coal Geol*ogy, 95, p.1-11. DOI: 10.1016/j.coal.2012.02.001

Yanbin, Y., Dameng, L., and Yongkai, Q., 2013, Variable gas content, saturation, and accumulation characteristics of Weibei coalbed methane pilot-production field in the southeastern Ordos Basin, China. *American Association of Petroleum Geologist, Bulletin,* 97 (8), p.1371-1393. DOI: 10.1306/02131312123