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Coal Properties and Cleat Attributes at Tanjung Enim Coalfield in South Palembang Sub-basin, South Sumatra

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Abstract. Observation on the Tanjung Enim coal outcrops has been conducted to evaluate coal and cleat characteristics, particularly those occurring at Suban and Air Laya Putih (ALP) sites. Tectonically, the region is located in the South Palembang Sub-basin. In this region, there are four to five coal seams dipping to the SW direction. The dips of coal beds in ALP are commonly steeper than those in Suban, implying that the ALP seams had been more deformed tectonically and hence underwent more shortening. The samples analyzed reveal that the coals are medium in rank with the ash content relatively constant along strike, but distinctive vertically. Most seams have high values of inherent moisture, fixed carbon, and volatile matter. Deformation of the seams has resulted in two types of fractures known as face and butt cleats. The present study employed a scanline method to measure cleat attributes such as spacing, aperture, and bedding orientation. A total of 3,241 face and butt cleats were measured from 12 scanlines. The face cleats predominantly have NNE-SSW orientation, suggesting paleostress direction. The general trend of butt cleats is NW-SE, likely coincident with the releasing stresses. Face cleats have spacing and aperture more tightly than butt cleats. This suggests that face cleats developed in response to the maximum stresses, and butt cleats formed due to the minimum in situ stresses. Scanning Electron Microscope (SEM) analysis revealed that microcleats in seam show a number of apertures that were connected to form a network system within the analyzed samples.

INTRODUCTION

The nature, origin, and development of cleats have been investigated by numerous workers. Based on published review on cleat generation, [1] has assorted the existing theories into three fundamental concepts, a) intrinsic-induced coalification processes or "endogenetic", b) external influence related to tectonic events or "exogenetic", and c) combination of these controlling factors or "duogenetic". An overview of the genetic origin of brittle fracturing as well as the property of cleats has been comprehensively outlined [2]. Field measurements on lignite outcrops suggested that cleats were formed as a result of ductile deformation (folding) and salt intrusion [3]. Isotopic studies on dawsonite within coal measures suggested that the formation of cleats might have related to the invasion of carbonate-rich solutions [4]. There are different interpretations on controlling factors for cleat spacing in seam. The average of cleat spacing decreases as maturation increases, obviously from lignite up to high volatile bituminous, but likely scattered towards the higher-ranked coal [5]. Results of studies on cleat attributes suggest that the reduction of average cleat height may result in a decreasing density of fractures in seam [6].

The development of cleats in the Bowen Basin has been explain by [5] on basis of lithotype aspects. These authors have also inferred that vitrain rich or bright coal is likely to be more fractured than inertinite rich or dull seam. Importantly, the work provides evidence indicating that open-mode fractures within coal measures in the basin were formed mostly during burial of the overburden sequence, prior to an episode of post-depositional tectonic event. A computer-aided program called geographic information system (GIS) has been conducted by [7] in order to recognize the spatial orientation of cleats and the appearance of their network. More recent study has determined a relationship between cleat parameters and coal types from polished sections and seam blocks [8]. Their analytical results suggest that cleat aperture may become narrower as coal stress increases. Hence, a clearer understanding of

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coal properties and cleat systems, as well as the behavior may be gleaned from closer analysis of cleat aperture characteristics across different coal lithotypes, in conjunction with cleat orientation and spacing [9].

The present work aimed to determine coal properties and cleat attributes from outcrops around the study area. This study employed the practical procedures mentioned previously in the state-of-the art, which were considered to be appropriate for the current field survey and laboratory experiment. The focus of the fieldwork was to investigate coal exposures that have been described elsewhere and to observe cleats in the studied coals. A few sample were analyzed using Scanning Electron Microscope (SEM) to identify cleat apertures and networks, hence providing more constraints necessary for interpretation of the generated data. All of the yielded data were then combined to assess the general trend of characters between face and butt cleats in the coal seams within the study area.

METHOD AND ANALYSIS

The data discussed throughout the manuscript were principally generated from field observation and laboratory analysis. The ground survey was conducted on coal outcrops by using a hand magnifier, a vernier caliper, and other basic geologic equipment in order to identify the megascopic characteristics of individual seam, such as bedding direction, apparent thickness, coal type (lithotype), banding, relative hardness, and structural features. In addition, the fieldwork includes measurements on coal properties and cleat attributes, while the laboratory experiments include petrography, proximate, and SEM analysis. Fractures were identified from all measures, while cleat attributes were measured at wherever such structures were macroscopically identifiable. Investigation on seam structures focused on two commonly recognizable face and butt cleats.

Field description and data acquisitions were conducted by applying scanline method is applicable to collect cleat attribute (such as cleat orientation, apertures, and spacing) of each cleat that intersects the measure line. The function of scanline is to avoid duplicate cleat data and can be used to calculate the linear cleat intensity (number of cleats per unit length). Scanline direction is also important as it relates to the appearance of face and butt cleats. So, the scanline would be ideal if the azimuth line toward the diagonal or ±45o from strike of coal seam. Implementation of scanline in this study provides length followed average coal thickness (8 m), resulting a total 3,241 cleat intensity. Cleat length was not measured, as we could not see in to the coal outcrop. Statistical analysis was applied to all cleat orientations and they were plotted in rose diagram for each coal seam.

DESCRIPTION OF THE STUDY AREA

This work was conducted in the Air Laya Coalfield that has been mined since 1919, and nowadays the mine concession is under the management of the state-owned company of PT. Bukit Asam (PTBA). The region is administratively included within Tanjung Enim District of Muara Enim Regency of South Sumatra Province. The open pit mine covers an area of about 66,414 ha with total mineable reserves of approximately 1.6 billion tons [10]. The present field observation was undertaken in two different localities around the Air Laya Mine, namely Suban and Air Laya Putih (ALP).

Regionally, the South Palembang Sub-basin of South Sumatra Basin is situated in the southern portion of Sumatra. The South Sumatra Basin is one of coal producing areas in Sumatra, tectonically located in a back arc setting that extends NW-SE along the eastern side of the island. Reviews on the general geology and the regional stratigraphy of the region [11] has been widely cited for depositional history of the basin. The basin structural architecture formed due to tensional and compressional tectonics during Tertiary time, suggesting that these stress fields have strongly controlled the evolution of regional structures. The studied region is locally part of the Muaraenim Anticlinorium, generally striking along WNW-ESE direction. This interpretation is principally to follow the previously proposed surface structural model [12]. Structurally, the Suban coalfield is situated in the northern flank of a syncline, whereas the ALP site is located in the southern limb of an anticline. Four major seams are exposed in Suban, and five main coals outcrop in ALP. **Fig. 1** shows structural patterns exposed in the Muara Enim and surrounding areas, including the currently studied region at Tanjung Enim.

Numerous workers have investigated the geology of the study area for a wide range of aims. Stratigraphic column for the Muara Enim Region contains coal strata that have been devided into four groups from lower to upper levels [13], M1 comprising of Kladi and Merapi seams; M2 consisting of Petai, Suban and Mangus seams; M3 containing Burung and Benuang seams; and M4 including Kebon, Enim, Jelawatan, and Niru seams (**Fig. 2**). Amongst these seam groups, the M2 and M4 units are inferred to consist of the largest amount of coal deposits, consequently the most economic coal measures within the region [10]. In the Suban site, there exists an exposure of andesitic intrusive body outcropping in contact with the lowest coal bed belonging to the Suban unit. Hence, there appear a variety of coal maturities in the mine area. Studies on maceral revealed that there are significance changes along strike in the coal seams, particularly those have experienced different heating paths from the Suban andesite. This suggests coal rank along strike gradually increases towards the igneous rock. The occurrence of coal metamorphism has also been reported by [14]. It is a speculative view that the presence of magmatic liquid might have in some way provided the controlling factors for cleat generation in the Suban coals. This requires more constraints especially on mineral impurities filling in the seam fractures in order to figure out such a relationship [4].

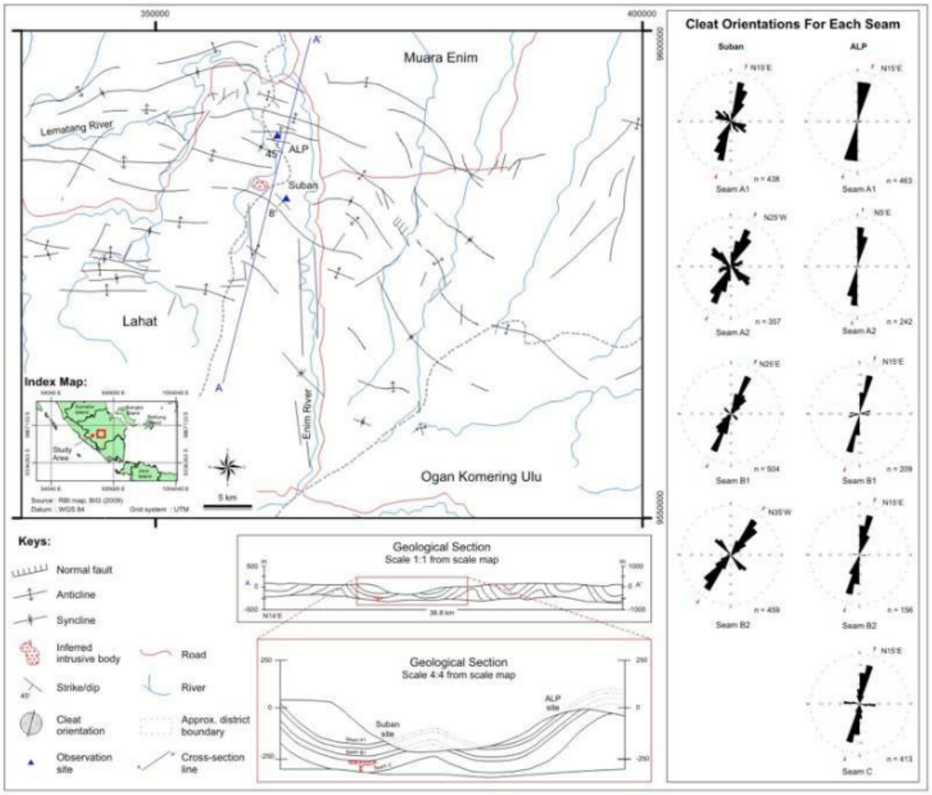

FIGURE 1. This map displays geological structures in the Tanjung Enim region and the vicinity. It also shows are the schematic structural sections and the rose diagrams representing the general orientation of coal fractures in individual seams (right) and in each locality observed (inside the map).

RESULT AND DISCUSSION

Coal Properties

The analytical results of this study are presented in **Tab. 1**. Coals at two locations within the Air Laya Mine postulate that they are different in geometry. The coals apparently have distinct orientations, but they are relatively consistent in strike with the NW-SE direction, approximating the general trend of regional structures. The Suban coal beds have dips of <10º, whereas the ALP coal beds have dips of ~45º, respectively. With respect to the dip data, the seams might have been subjected to different degrees of tilting. By comparison, the coal bed in ALP appeared to have been steeply tilted and consequently more shortening, implying that compressional folding seemed to be more intense in this site. In a regional context, a tilting episode of sedimentary sequences in the South Sumatra basin occurred as a result of compression peaked at the Late Neogene Barisan orogeny [15].

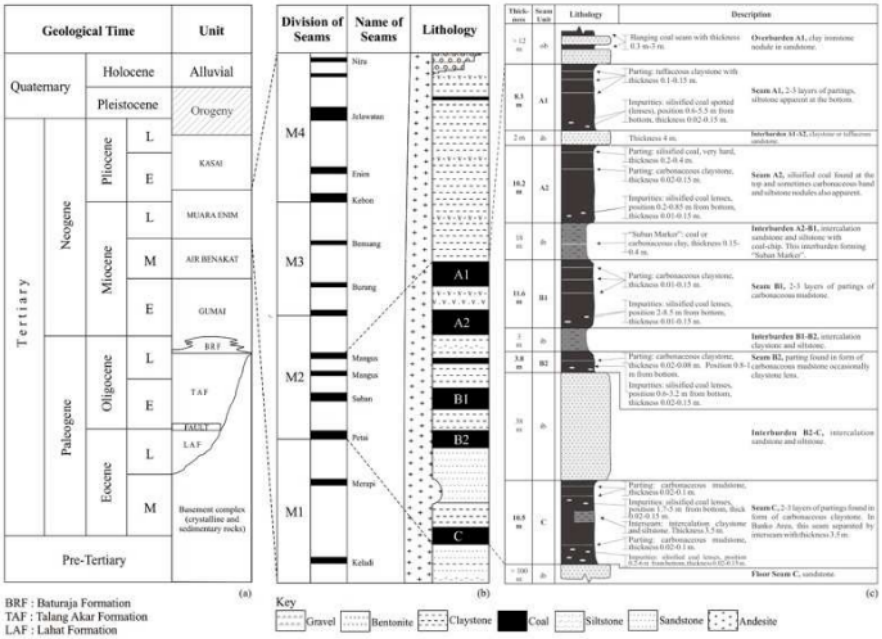

FIGURE 2. The composite diagram showing (a) stratigraphy of South Sumatra Basin, (b) the Muaraenim coal division [13], and (c) the measured section of the M2 group in the study area.

TABLE 1. Results of field work and laboratory analysis of the Air Laya mine.

Obser-vation	Parameters (unit)		Coal Seams										Remarks and keys
			A1		A2		B1		B2		C		
			Yields	Mean	Yields	Mean	Yields	Mean	Yields	Mean	Yields	Mean	
Labo-ratory	Micro-cleat (μm)	Face	9-20	11	2-30	9	1-13	2	2-23	8	3-21	5	SEM analysis.
		Butt	3-25	13	5-24	14	3-7	5	1-37	8	18-19	18	
	Vitrinite (vol. %)		63.4		71		73.4		73		68		Petrographic analysis. VR: vitrinite reflectance.
	Liptinite (vol. %)		8.2		10.4		3.6		7.4		10.6		
	Inertinite (vol. %)		17		12.8		12.2		11.4		13.2		
	Minerals (vol. %)		11.4		5.8		10.8		8.2		8.2		
	VR (%)		0.49		0.53		0.43		0.57		0.53		
	Ash (adb. %)		2.96		3.98		1.68		1.77		5.65		Proximate analysis. FC: fixed carbon. VM: volatile matter. adb.: air dried basis.
	Moisture (adb. %)		12.98		12.4		10.64		13.12		14.42		
	FC (adb. %)		42.60		44.69		42.53		44.55		42.59		
	VM (adb. %)		41.46		38.93		45.15		40.67		37.34		
Field	Strike (NºE)		156 (S), 145 (A)		151 (S), 149 (A)		155 (S), 144 (A)		158 (S), 147 (A)		144 (A)		Each seam SE-NW.
	Dip (º)		8 (S), 45 (A)		5 (S), 43 (A)		7 (S), 46 (A)		9 (S), 47 (A)		44 (A)		Areas investigated: Suban (S) and ALP (A). MH: medium hard.
	Thickness (m)		7.5 (S), 9.5 (A)		9 (S), 11.5 (A)		10 (S), 12 (A)		3.5 (S and A)		10 (A)		
	Fractures		Face & butt		Face & butt		Face & butt		Face & butt		Face & butt		
	Mineral impurities		Pyrite, amber, clay mineral, iron oxide		Pyrite, clay mineral, iron oxide		Pyrite, amber, clay mineral, iron oxide		Pyrite, clay mineral, iron oxide		Pyrite, clay mineral, iron oxide		
	Banding features		Vitrain (S), fusain (A)		Vitrain (S), fusain (A)		Vitrain (S), fusain (A)		Vitrain (S), fusain (A)		Vitrain (S), fusain (A)		
	Partings (m)		3 layers tuffaceous claystone (0.1-0.15)		Silisified coal (0.2), carbonaceous claystone (0.1)		3 layers carbonaceous claystone (0.01-0.15)		Carbonaceous claystone (0.02-0.08)		3 layers carbonaceous mudstone (0.02-0.1)		
	Hardness		Brittle (S), MH (A)		Brittle (S), MH (A)		Brittle (S), MH (A)		Brittle (S), MH (A)		Brittle (S), MH (A)		

Individual seam shows a variety of thickness with average ranging from 3.5-12 m but B2 seam is the thinnest layer. Overall, the Suban coals are commonly brittle and vitrain, while in ALP coals are medium hard and most likely fusain in banding. Each measure here is characterized by the presence of thin partings. Mineral impurities such as pyrite and iron oxides are common in all seams, but amber occurs particularly in units A1 and B1. The exposures appear to have extensively fractured; face and butt cleats are present in every stratum.

Petrographic analysis revealed that the Air Laya coals contain predominantly vitrinite or huminite >60%, but individual seam varies in huminite content, commonly ranging from 63-73%. Other constituents, including liptinite <10%, inertinite <20%, and mineral matters <10% are apparently minor. These results are similar to the previous works reported by several workers [14], [16], [17]. The recent maceral analysis suggests that the studied coals likely belong to a *humodetrinite* assemblage [18]. Vitrinite reflectance (VR) measurements yielded low values with average mostly ±0.50%, concordant with the previous studies reported by [19]. The VR yield suggests that the samples analyzed are mostly the limit between low and medium rank coals, which can be categorized into subbituminous and high volatile bituminous.

The proximate parameters discussed throughout this study were analyzed on air-dried basis (adb). These include ash content, total moisture, fixed carbon (FC), and volatile matter (VM). In order to better understand the coal properties in the region, each parameter here is compared to the results of proximate analysis reported elsewhere in the published studies [16], [17], [19].

The ash content for all samples varies slightly, with average ranging from 1.77-3.98 adb.%. In general, the ash constituent for the Air Laya coal tends to be similar laterally along strike, varies vertically at different stratigraphic levels, and increases towards the intrusion [17]. Inherent moisture varies slightly among the sampled coals, but tends to be relatively high with average ranging from 10.64-14.42 adb.%, similar to the studied results of [16], [17]. However, the yields are different, showing lower moisture content for most given samples [17].

Individual seam in this area contains fixed carbon (FC) >40% with average ranging from 42.53-44.69 adb.%. The measured values are mostly concordant with the analytical results, but lower than those reported by [17]. The highest average of volatile matter (VM) resulted from seam B1 (45.15 adb.%), while the lowest yield came from seam C (37.34 adb.%), consistent with the VM analytical results reported by [16]. Based on the published work [14], the VM measurements for the upper A1 and A2 seams yielded >40 adb.%, whereas analysis of the lower B1 and B2 coals, excluding the bottom B2 bed, resulted in <15 adb.%, suggesting an upward-increasing VM component.

Cleat System

A comprehensive characterization of cleats should be conducted first in order to better understand cleat occurrence, orientation patterns, and distribution. The face cleats are perpendicular to the strike of bedding, whereas the butt cleats tend to be parallel to the strike of bedding. Since several authors have noted that cleats typically have a uniform orientation over wide areas [2], [3], measurements of cleat orientation within coal seams in the Air Laya Mine yielded values essential for determining the cleat trends. Cleat distribution and orientation indicated two major orientations i.e. NNE-SSW and NE-SW directions for the face cleats, and NW-SE and WNW-ESE directions for the butt cleats (see **Fig. 1**).

The structural pattern map of cleat orientations measured in the study area clearly shows gradual to abrupt strike variations in cleat trends over short distances. This indicates that cleat was influenced by multiple episodes of cleat development. The cleats might have generated during coalification, subsequently superimposed by later processes such as overpressure and changing of tectonic stress regimes, and been affected by the differences of coal composition [20], [21]. Given the different processes involved in cleat development, it is essential to apply statistical methods in order to differentiate the cleat formation and trends, hence progressive history of cleat can be described [21]. In addition, the cleat orientation may be represented using stereographic diagrams to show the general trends.

The cleat elements such as spacing and aperture were measured in both face and butt fractures present in outcrops. Spacing represents a distance measured orthogonal between two adjacent coal joints. This attribute determines the cleat intensity that reflects fracture abundance along a given scanline. The face cleat spacing mostly varies in all seams studied, but spacing tends to face increasing towards butt cleat (**Fig. 3**), mainly in Suban the spacing value on the face and butt has a large margin is ~0.76 cm in face and ~1.66 cm in butt. Face cleats in ALP also tend to have more dense spacing than butt cleats, with an average of 1.05 cm of analysis yield versus 1.53 cm. The average result after tested geostatistic and embodied in the boxplot model. **Fig. 3** shows the overall distribution of spacing cleat data, that there is also a data outlier (dotted line). Statistically feasible data is in the box, assuming that the data has uniformity of data. The spacing cleat pattern in this study area is due face fractures developed in response to the maximum stresses, and butt cleats formed due to the minimum in situ stresses. The interpretation agrees with a scenario on spacing-paleostress relationship [6].

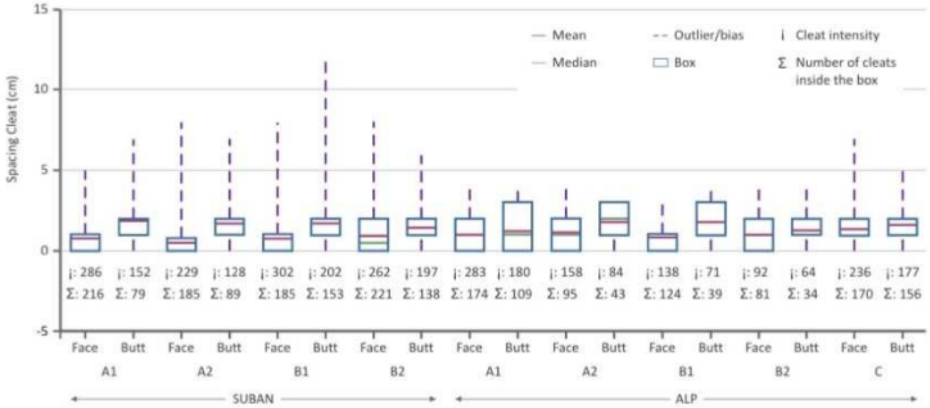

FIGURE 3. The spacing cleat feature using boxplot model. Face cleats have spacing more tightly than butt cleats.

The coal cleats in this area are commonly opening-mode fractures with average face cleat aperture mostly similar amongst the M2 seam units. The yielded average of face cleat openness at the Suban and ALP areas are about 0.24-0.67 mm (**Fig. 4**), respectively. Such elements in face cleat are generally narrower than those in butt cleats, with difference of amount 0.13 mm in Suban and 0.21 mm in ALP. However, the SEM analysis of core samples resulted in even smaller-sized opening mode attributes. **Fig. 5** presents the aperture data generated from the microscopic analysis. The SEM analysis yielded an average of micro-apertures ranging from 2-11 μm in face cleats and 5-18 μm in butt cleats. These data indicate that butt tends to have larger apertures than do face microcleat.

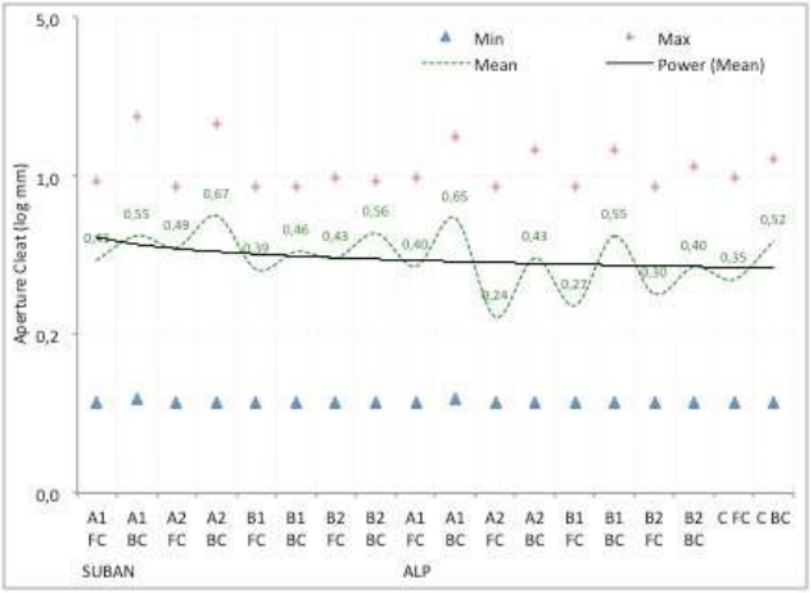

FIGURE 4. This diagram shows the comparison of aperture on face and butt. Generally, obtained by the pattern of aperture trend tends to decrease toward the deeper bed.

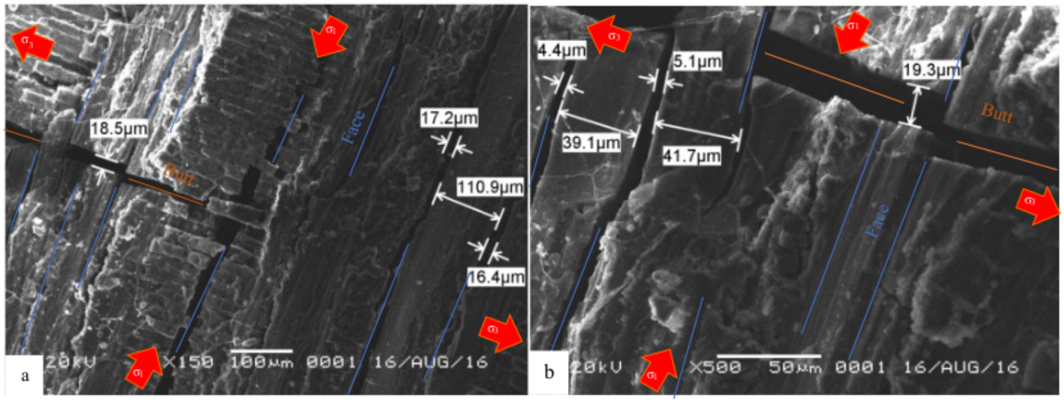

FIGURE 5. SEM show microcleat spacing and network pattern sorted isolated linetype. Red arrows is paleostress, $\sigma_1 > \sigma_3$ max and min stress; (a) Suban sample with 150x magnification have been clearly; (b) from ALP must be up to zoom in 500x.

Referring to the fractures occurrence, the face cleats oriented parallel to the paleostress, can be compared with tension joint and tension due to open mode [9]. Face cleats are relatively smooth, planar planes, continuous, and elongated, present at regular distances, while butt cleats are coarse surface and terminate on face cleats and tend to open wider. To conclude that face cleats is comparable with the systematic planar openness while butt cleats are open and linked to release joints, which are filled by minerals impurities in the aperture [22]. Thus the aperture of face cleat is smaller than that of butt cleat, possibly due to the releasing stress at the time of deformation. The results of SEM analysis indicate a network pattern belonging to isolated linetype, suggesting that cleat aperture might have been controlled by deformation (see **Fig. 5**). According to [23] the isolated linetype formed by the stress is compressive in one direction, and the tensile in another direction. Due to tensile in another direction, butt cleat aperture is opening wider.

CONCLUSIONS

The experimental data set on coal properties and cleat system for the Air Laya Mine has been discussed for a better understanding, and the following conclusions were obtained:

1. The Air Laya mine situated in the Paleogene South Sumatra Basin holds a vast amount of coal sources belonging to the Mio-Pliocene sequence, in which four to five seams are outcropped and have different geometry and properties. The coal thickness varies between ~4 m and ~11 m. The seam beds generally strike to NW-SE and are dipping more steeply towards the ALP area.
2. The coals are of subbituminous-high volatile bituminous in rank with a predominant maceral composition of vitrinite (>70 vol.%). The mineral and ash contents in coal are mostly low, and other proximate constituents appear to vary in each measure.
3. Face cleat has spacing more tight than butt cleat. From SEM analysis shows that cleat pattern is classified isolated linetype. So, the origins of the cleat this pattern are controlled by tectonic stresses. Isolated linetype formed by the stress is compressive in one direction, and tensile in another direction. It is due to tensile in another direction, butt cleat aperture is opening wider.
4. Cleat orientation varies in NNE-SSW is matches with compressive stress. Preferred fracture orientation is consistent with the principal stresses over wide areas which suggests that the genesis cleat is nearly controlled by tectonic.

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