Tectonics and Geological Factors Controlling Cleat Development in the Barito Basin, Indonesia

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Abstract. Cleats are natural fractures within coal seams. This paper presents the results of regional cleat mapping and characterization in relation to coalbed methane (CBM) exploration and development in the Barito Basin, South Kalimantan, Indonesia involving two major coal layers, namely the Late Eocene Tanjung Formation and Early to Middle Miocene Warukin Formation with thicknesses ranging from 2 to 50 m. The coal is classified as lignite to subbituminous with calorific values ranging from 6000-8000 Cal/gr with ash content 0.68-17.42%. We applied two methods of cleat measurement, i.e. scanline and window sampling using a 100 x 100 cm grid. More than 20,000 cleats were measured from 65 scanline and 37 window sampling locations. The results revealed that face and butt cleats are predominantly oriented in the WNW-ESE and NNE-SSW directions, respectively. The results showed that cleat density increases related to structural position such as fold hinge and fault zone. The formation of the cleats may be influenced by several geological processes, where the cleats, which form during coalification, are superimposed by later processes such as fluid pressure and tectonic stresses and are seemingly also affected by the composition of the coal.

Keywords: *Barito Basin; coalbed methane; cleats; geology; tectonics.*

1 Introduction

Cleats, in general, are natural fractures that develop within coal seams during their formation (coalification process). There are two types of cleats that are often found in coal seams, generally termed ‘face cleats’ and ‘butt cleats’ [1], and are generally oriented almost perpendicular to each other and also nearly perpendicular to the bedding. Face cleats are planar, longer in length, more continuous and more predominant, which indicates that face cleats are formed first. Meanwhile, butt cleats are shorter in length, less continuous and often terminate at intersections with face cleats, which indicates that the butt cleats are formed later [2,3]. However, the mechanism of their formation and controlling factors are uncertain. Some authors have concluded that their formation is highly influenced by tectonic stress, for example due to higher density near fault zones [i.e. 2].

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Of special interest is the capability of cleats to act as permeable channels that allow the migration of coalbed methane (CBM) gas to production wells. Cleats contribute to permeability by providing migration pathways for gas and water flow to the well. The CBM gas is produced by diffusion from the coal matrix and Darcy flow through the cleat system [4], until it reaches the production well. Since cleats are responsible for the majority of fluid flow to the producing gas, they are considered to be one of the most important parameters that determine the permeability of CBM reservoirs. Therefore, the characterization of cleats is of considerable importance in view of CBM exploration and production, in particular in terms of implications for coal permeability and hence the deliverability of CBM gas reservoirs.

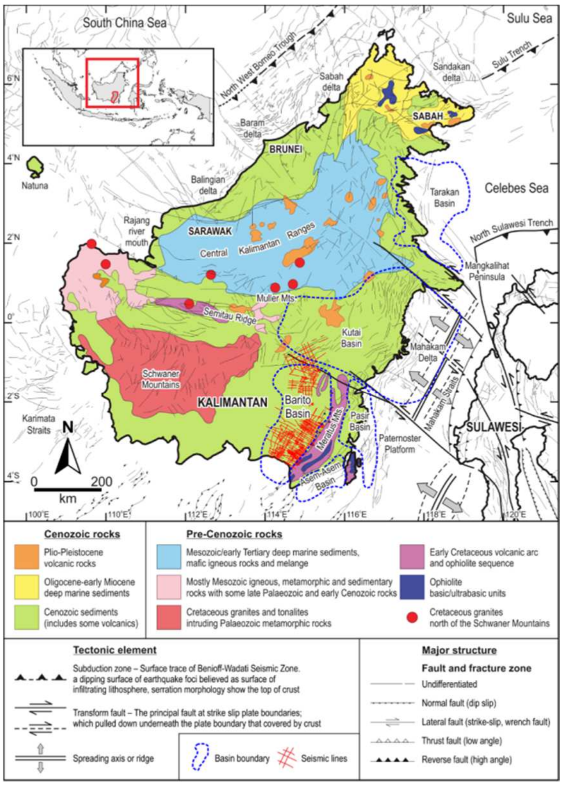


Figure 1 Simplified geological map of Borneo (compiled and modified from Moss and Wilson [5], Hall and Nichols[6]) showing the location of the study area within the Barito Basin.

The study area is located in the Barito Basin, South Kalimantan, Indonesia. Geographically, it lies between 114° 59' 50.000" - 115° 29' 50.000" E and 2° 33' 25.000" - 3° 17' 55.000" S. The Barito Basin, situated at the south-eastern margin of the Sundaland continent, is an asymmetric foreland basin lying on the western side of the Meratus Range, and thickens to the east towards the mountain front, with a platform area to the west and a foredeep to the east [7]. The basin is bounded to the west by the Schwaner Mountains, which represent a continental basement of Sundaland and to the east by the Meratus Mountains, which separate the Barito Basin from the Asem-Asem Basin (see Figure 1). To the north, the Adang Flexure separates the Barito Basin from the Kutai Basin. To the south, the border is less distinct, and seems to be extended and narrowed to the south into the Java Sea [7-11] because no structural features or lithofacies changes can be observed.

This paper presents the results of regional cleat mapping and characterization from a field-based study in the Barito Basin area supported by laboratory analysis. This study intends to provide a better understanding of the vertical and lateral distribution, and characteristics of the cleats as well as the mechanism of their formation. To accomplish these objectives, special attention was paid to evaluation of the role of tectonics in controlling cleat development. The outcome of this study will be used for conducting permeability modeling of CBM potential in the study area. Figure 2 shows the detailed observation points, seismic lines, well locations, and main geological units in the study area. Data were mainly collected in the Rantau, Binuang, and Tanjung Areas.

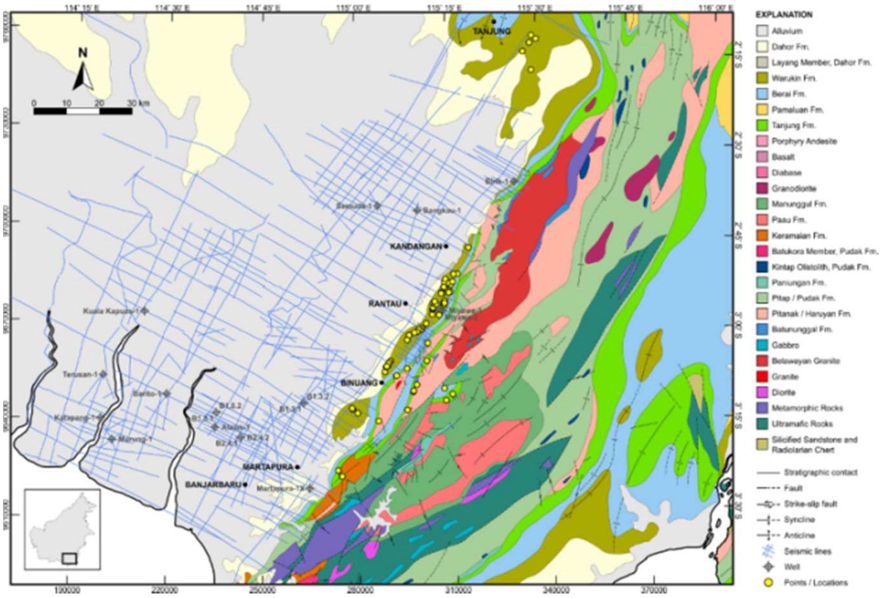


Figure 2 Location of the study area, including 2D seismic and well logs, geological map at scale 1:250,000 [12-15]. The yellow circles indicate measurement locations.

2 Regional Geology and Tectonic Setting

The structural framework and tectonic evolution of the Barito Basin are constrained by several regional tectonic events (Figure 3). The complex tectonic evolution of the Barito Basin in the framework of the evolution of Gondwanaland began in the Late Jurassic-Early Cretaceous era. By Eocene times, India began to collide with the southern Eurasian margin [16]. The Eocene India-Eurasia collision was likely responsible for the Cenozoic tectonic events in most of Southeast Asia [17,18]. However, the tectonic evolution in Borneo is less likely to be related directly to the collision of India with Eurasia [19,20].

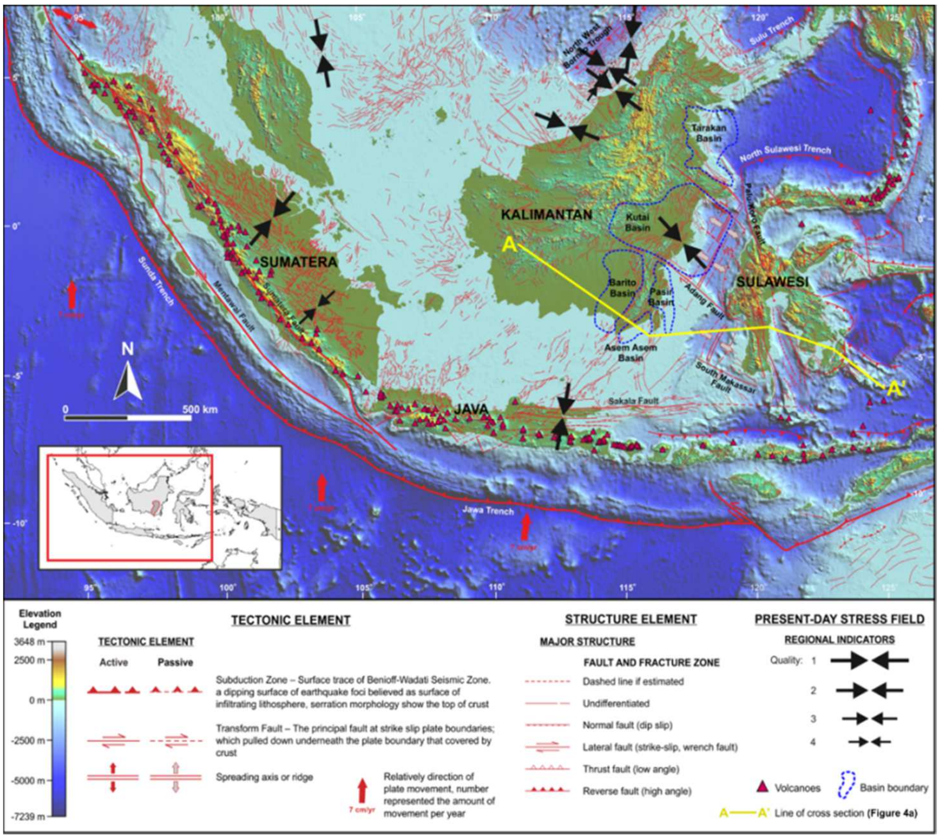


Figure 3 Regional tectonic framework of Western Indonesia showing tectonic boundary forces including the present-day maximum horizontal stress direction (S_{Hmax}). Stress data are from Heidbach, *et al.* [21]. A cross-section of yellow line A-A' is given in Figure 4(a). The study area is located in the Barito Basin.

During the Middle and Late Eocene, rifting appears to have been predominant in many areas of Sundaland [18]. The development of the Barito Basin was initiated by the opening and extension of the Makassar Straits in the Middle Eocene [e.g. 19, 22], which separate eastern Borneo from western Sulawesi to the east [20]. This extension in the Strait of Makassar resulted in the NW-SE aligned horst and graben structures developed along a series of NW-SE trending strike-slip faults related to the opening of the Makassar Strait [7]. At the end of the Lower Oligocene rifting ceased in the Barito Basin [18].

The Early Miocene is inferred to mark the time of significant tectonic changes in the basin development within Sundaland. A regional uplift and contractional regime took place around Middle Miocene times, which led to the uplift and emergence of the Meratus Range and generated the inversion of pre-existing extensional faults in the Barito Basin [7-9]. This contractional regime still persists to the present day with the convergence and collision between the Australian and the SE Sunda Plate [18,22]. The present-day maximum

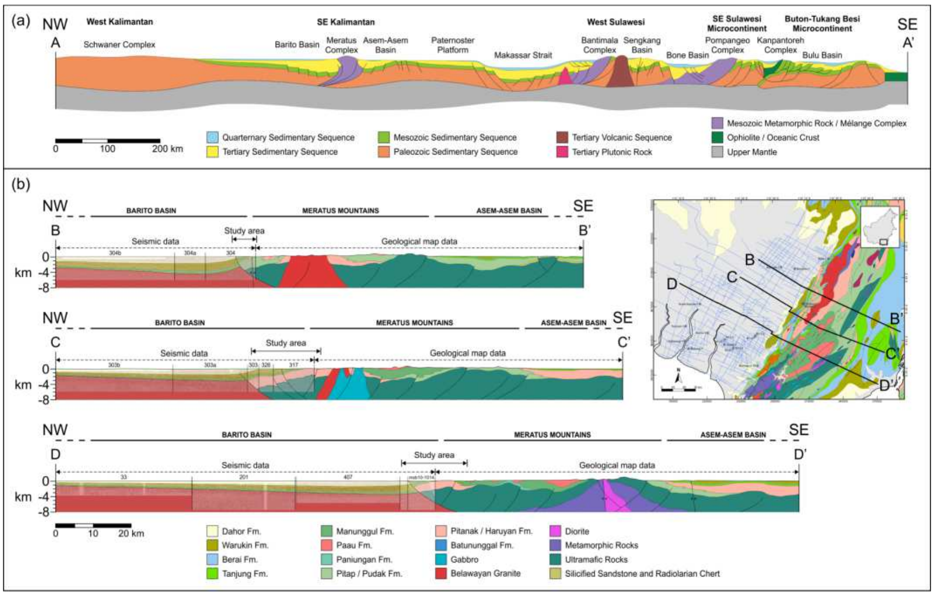


Figure 4 (a) Schematic regional cross-section extending from West Kalimantan (Schwaner Complex), Barito Basin (study area) into Southeastern Sulawesi (Buton-Tukang Besi microcontinent). The location of cross-section A-A' is shown in Figure 3. (b) NW-SE cross-sections (B-B', C-C', and D-D') to illustrate structural style variations around Barito Basin, SE Kalimantan. The cross-sections are based on geological maps, seismic data, and well data.

horizontal stress (S_{Hmax}) in Borneo is primarily oriented NW-SE [17] (see Figure 3 for details). This NW-SE maximum horizontal stress orientation in Borneo has long been postulated to have been caused by the orientation of geologically recent lineaments and the NW-SE oriented inversion of many major structures [23]. The NW-SE present-day stress direction is similar to the ESE absolute plate motion and thus the stress orientation may result from a combination of multiple plate boundary forces. Figure 4 shows regional cross-sections to illustrate the regional structural (deformation) and stratigraphic configurations of the Barito Basin and adjacent areas that may provide a better understanding of the characteristics of the basin, with a specific emphasis on their relationship to the Meratus Mountains.

3 Method of Study and Analysis

A method integrating all cleat data collected directly from the field (coal mines, road cuts, and rivers) and laboratory study was used in this study to investigate and evaluate the characteristics of cleats that are assumed to control the permeability of the coal and hence the deliverability of CBM gas reservoirs.

Field description and field data acquisition were conducted by employing two sampling methods of measurement, i.e. scanline sampling and window sampling. The cleat attributes (such as cleat apertures, height/length, spacing, distribution, and orientation) were measured in the Tanjung and Warukin Formations. The scanline sampling method is applicable to collect cleat attribute data of each cleat that intersects the sampling line (Figure 5(a)). The length of the sampling line was set parallel to the individual coal bed, oriented perpendicular to the face cleats and butt cleats. The scanline sampling method can be used to calculate the linear cleat intensity (number of cleats per unit length of scanline). The windows sampling method is able to collect cleat attribute data of all cleats that are present within a specified sampling area (Figure 5(b)). The geometry of the sampling areas was designed to be rectangular, where the area of each as was usually 1 square meter. The window sampling method can be used to calculate the cleat density (summed traces of all cleats in the area).

For this study, more than 24,000 cleat orientation data from 66 locations and a total of 16,106 cleat attribute data from 65 scanline and 37 window sampling measurement stations were collected for several coal seams of the Tanjung and Warukin Formations throughout the study area. Statistical analysis was applied to all cleat orientations from each location. They were plotted in stereograms and Rose diagrams for each formation.

Coal samples were collected to represent variations in coal composition and coal rank, including proximate analysis, maceral analysis, and vitrinite reflectance measurement. Proximate analysis was conducted on 31 coal samples using the ASTM and ISO standard methods to calculate the air-dried (ad basis) and dry, ash-free (daf basis) results. Maceral analysis and vitrinite measurement were carried out on 30 coal samples following the Australian Standard.

4 Geology of Barito Basin

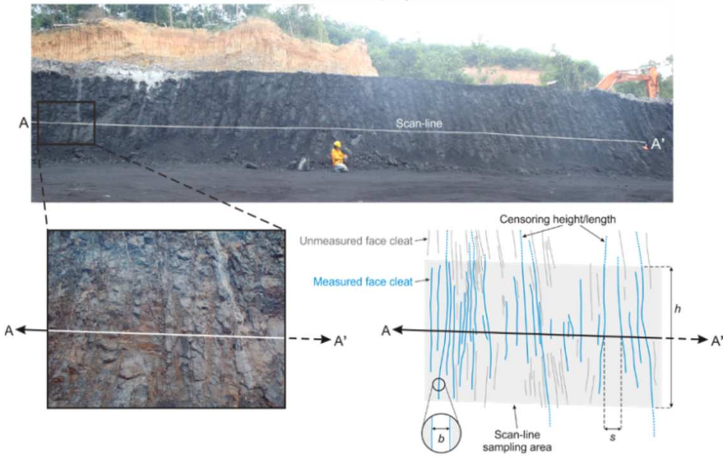
The Barito Basin consists of thick Cenozoic sedimentary sequences. The sequences are well exposed along the eastern margin of the basin and comprise four formations, i.e. (from oldest to youngest) the Tanjung, Berai, Warukin, and Dahor Formations, that range in age from the Middle Eocene to the Pleistocene eras (Figure 6). The deposition processes of these sequences occurred in transgressive-regressive cycles influenced by the basement's topography and the uplift of the Meratus Range [8, 9, 24].

In the Middle Eocene [5, 11, 24, 25], the Barito Basin received rift sediments eroded from the Paleocene horsts [7, 9, 19], which form the clastic sedimentary rocks of the Tanjung Formation. The Tanjung Formation is widely exposed in the northern part of the Barito Basin and along the western flank of the Meratus Range. The thickness of the Tanjung Formation varies from 450 m around the Barito Platform in the west to 1300 m on the foredeep in the east [10].

Following a phase of regression in the Middle Oligocene, as the marine influence increased, the extensive shallow water platform carbonates of the Berai Formation were deposited from the Late Oligocene through the Early Miocene [7,24,26]. Carbonate development in the Barito Basin ceased in the Early Miocene coinciding with an increase in pro-deltaic clastic input from the west [7,24].

The Early Miocene marked the initiation phase of Meratus uplift [10,25], which changed the setting from transgressive to regressive, resulting in the deposition of the prograding deltaic sediments of the Warukin Formation [7,9]. The Warukin Formation is widely exposed in the northern part of the Barito Basin and along the western flanks of the Meratus Range. The Warukin Formation consists of fluvial sandstone, intertidal siltstone and mudstone, shale, and coal beds. The coal-bearing sedimentary rocks thicken to the east towards the Meratus Range, whereas the coal seams have significant variation in thickness, ranging from 0.5 m to ~50 m. This formation has a total thickness of sediments of up to several thousands of meters [9], was deposited in a shallow marine to fluvio-deltaic environment [26], and comprises the syn-inversion sequence of the basin [9].

(a) Scan-line sampling method



(b) Windows sampling method

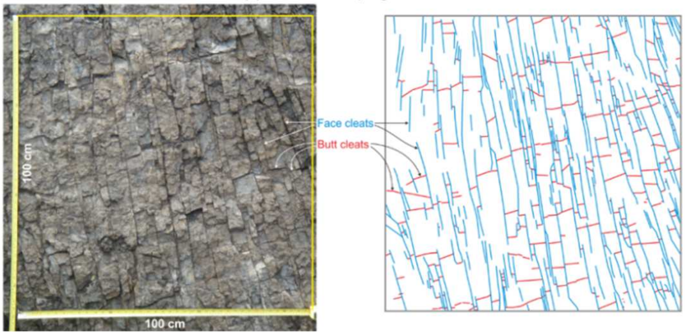


Figure 5 (a) Schematic illustration of scanline sampling carried out on the outcrop. Cleat attribute data were collected only from cleats intersecting the sampling line. A-A' is the length of scanline measurement; *b* is the aperture size of the cleat; *s* is the spacing between adjacent cleats; *h* is the trace height/length of the cleat. (b) Schematic illustration of the window sampling carried out on the outcrop. Cleat attributes data were collected only from cleats present within the specified sampling area.

The Meratus uplift continued from the Pliocene through the Plio-Pleistocene [7,10] and resulted in the deposition of polymict alluvial, shallow marine sediment and tectonic molasse of the Dahor Formation, which comprise the syn-inversion sequence of the basin [25,26]. The Dahor Formation consists mostly of reddish sandstone, polymict conglomerate and siltstone with an indication of kaolinitic features. This formation has a thickness that reaches up to 3000 m near the Meratus front [24]. Structurally the basin inversion during the Neogene contractional deformation period created the predominantly NE-SW trending thrust blocks, folds and inverted structures, which are commonly observed within the Tanjung Formation. This structural trend tends to be nearly parallel to the Meratus trends. The thrust faults observed in the Barito Basin indicate an apparent vergence to the northwest.

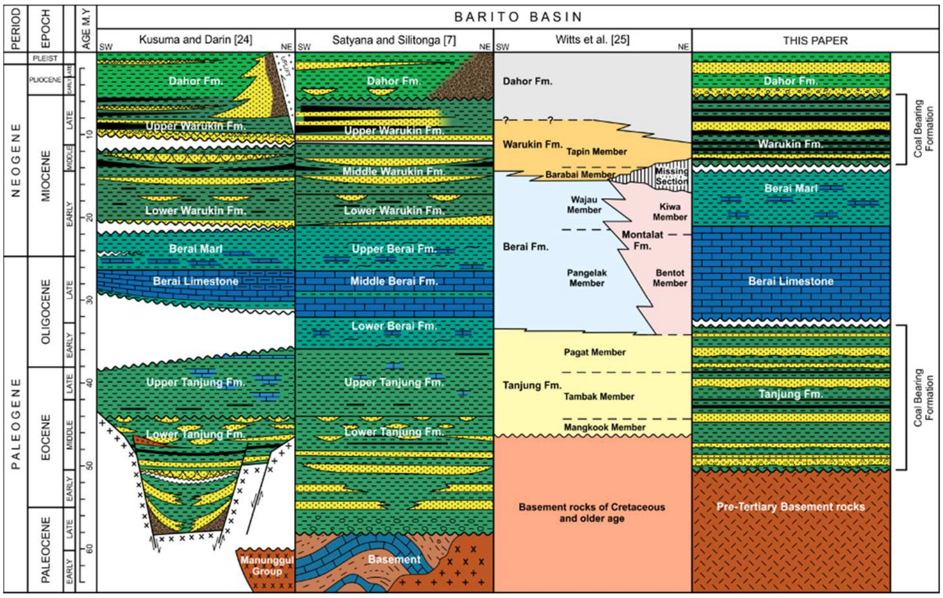


Figure 6 Comparison of stratigraphic columns and nomenclature for the Barito Basin showing the thick coal-bearing Lower Tanjung and Warukin Formations.

5 Coal Characterization

The Tertiary sediments in the Barito Basin contain the thick coal-bearing Tanjung (Eocene/Oligocene age) and Warukin (Miocene age) Formations. The Tanjung Formation is represented by pervasive thin coal seams (typically less than 3 m thick) that are fairly constant in thickness (Figure 7(a)). The Warukin Formation, based on variation in coal thickness and the presence or absence of marine and tidal facies, can be informally divided into three parts: the lower, middle, and upper Warukin Formations.

The lower Warukin Formation is characterized by relatively thin coal seams (commonly less than 2 m thick) with much more tidal and marginal marine influence (Figure 7(b)). The middle Warukin Formation is characterized by varying coal seam thicknesses (~10 m on average), interbedded with fluvial facies, where the channel geometries can be observed from the main coal-bearing strata (Figures 7(c)-7(e)). In some areas, the coal layer in this formation reaches a maximum thickness of 50 m (Figure 7(c)). The upper Warukin Formation is represented by a general reduction in abundance and thickness of the coal seams and an increase in fluvial facies such as channel sandstone (Figure 7(f)). The coal seams are commonly less than 12 m thick.

Figure 7 Representative photographs of coal outcrops in the Barito Basin. Photographs are from: (a) Tanjung Formation, located at BMT-3 station; (b) lower Warukin Formation, located at ATG-1 station; (c, d, and e) steeply dipping middle Warukin Formation, located at IKLAS-1 (c), RNG-2 (d), and NRG-1 (e) stations; and (f) steeply dipping upper Warukin Formation, located at Adaro coal mine (ADARO station). Trucks, security post, and people for scale.

Coal beds within the Tanjung and Warukin Formations have a wide range of dip angles varying from 10° to 90° to the northwest and southeast, striking NE-SW. Steeply dipping to vertical coal beds represent moderately strong thrust and folded strata, which appear to be related to the uplift of the Meratus Range. Proximate analysis indicates that the coals in the Tanjung and Warukin Formations contain 2.19-9.83% moisture, 0.68-17.42% ash content, 0.11-2.55%

total sulphur, 46.92-59.92 volatile matter and 40.08-53.08% fixed carbon (daf basis).

Coal from the Tanjung Formation generally has higher quality with high calorific value on a dry, ash-free (daf) basis, varying in a narrow range, from 8065 to 8549 Cal/gr. The lower Warukin coal has a calorific value ranging from 7136 to 7224 Cal/gr. The middle Warukin coal has a varied calorific value ranging from 6364 to 7434 Cal/gr, while the upper Warukin coal has a calorific value ranging from 6215 to 7055 Cal/gr. Maceral analysis showed that the coals from the Tanjung and Warukin Formations are dominated by vitrinite macerals with much smaller amounts of liptinite and inertinite. The coals are classified into the category of lignite to subbituminous according to the ISO 11760:2005 coal classification standard.

6 Cleat Characterization

A comprehensive characterization of cleats should be conducted first in order to better understand cleat occurrence, distribution, and orientation patterns, and to assess its contribution to the cleat density and hence the permeability of the coal. A method integrating cleat data collected directly from the field and laboratory study was used in this study to describe and characterize the cleats.

Identification and measurement of cleat orientation were conducted for several coal seams in the Tanjung and Warukin Formations. 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 [e.g. 2,3,27], many measurements of cleat orientation within coal seams in the Barito Basin tended to provide valid information needed to determine the regional cleat trends. Cleat distribution and orientation indicated three major orientations [27], i.e. WNW-ESE, NNW-SSE, and NE-SW directions for the face cleats, and NNE-SSW, ENE-WSW, and NW-SE directions for the butt cleats (Figure 8).

Measurements within the same coal bed indicated that cleat density can differ vertically and laterally within the same coal bed. This variation in cleat density can be expected due to the influence of mechanical layering within the same coal bed. The density distribution of cleat heights/lengths in the study area, notably in the area with numerous observation locations, indicated an increase in cleat density related to the regional structural position, where they increase to the north and east towards the main deformation zone (Figure 9). The increased cleat density towards the north is most likely subjected to the diachronous uplift of the Meratus Range, where the northern part of the Meratus Range is more uplifted than the southern part. This evidence implies that the cleat density is attributable to the structural position.

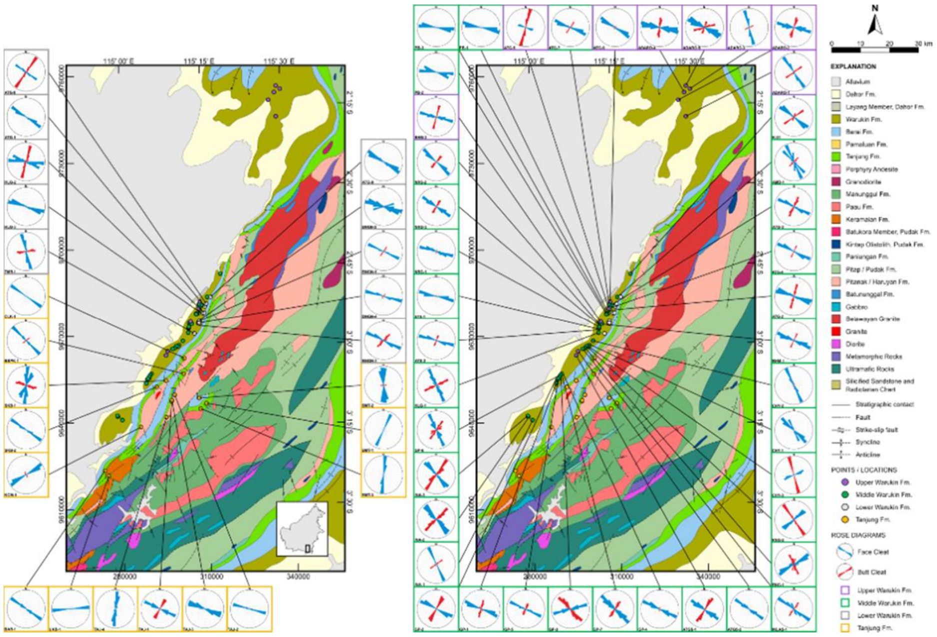


Figure 8 Map of the study area showing the cleat distribution and orientation of face (blue) and butt (red) cleats in the study area from all formations.

The regional 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 formation was influenced by multiple episodes of cleat development. The potentiality exists that cleats, once formed during coalification, may have beeen superimposed by later processes, such as overpressure and changing of tectonic stress regimes, and may also have been affected by the variability of coal composition. Given that different processes may have occurred since the initial cleat development until now, statistical treatment of the face cleat strike variability was further taken into account for the distinction between the differing generations of cleats. Admittedly, all face cleat orientation data in each formation represented stereographically were selectively resolved into several domains of uniform face cleats trends. This examination clearly identified and distinguished different domains of face cleat trends. These results indicate the complexity of the face cleat data sets and describe a progressive history of cleat development.

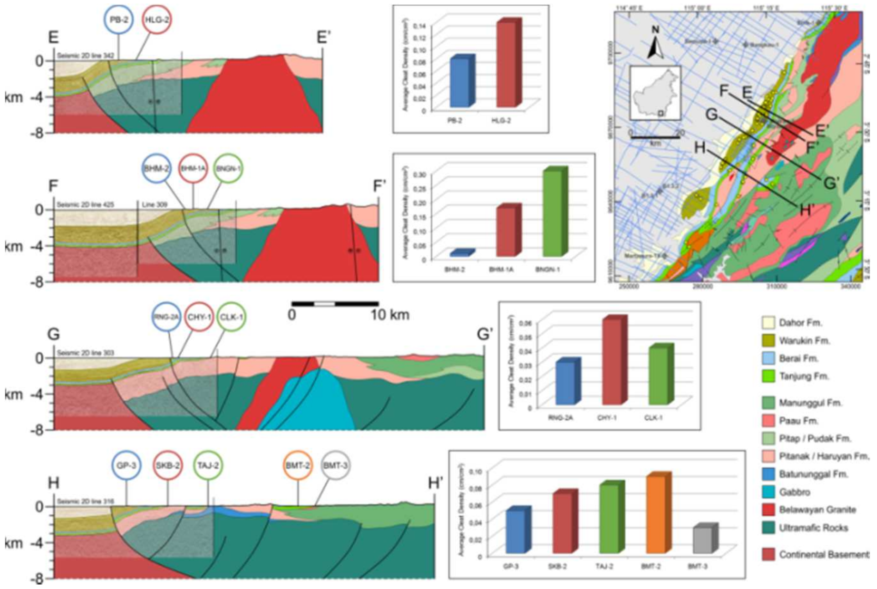


Figure 9 Density comparison from scanline stations on several NW-SE cross sections towards the Meratus Complex, showing an increase in cleat density related to the regional structural position, where they increase towards the main deformation zone (fold hinge and fault zone).

Furthermore, by applying the observation that the cleats occur vertically to subvertically within the coal seam in a flat-lying bed during burial, an attempt was made here to distinguish the origins and formation of the cleats from the early formed cleat set to the latest cleat set (second or superimposed cleat set) in the Tanjung and Warukin coals (Figure 10).

All cleats for individual coal seams were rotated back to their initial positions. This approach was done by rotating the bedding of individual coal seams back to their original positions (horizontal plane) prior to uplift and compressional deformation of the Barito Basin, including all cleats within a given coal bed.

According to the distribution of all data before and after being rotated to their original positions, we postulated that the early formed cleat sets should have occurred vertically to subvertically within the flat-lying coal seam, while the second or superimposed cleat sets will have a gentler dip (Figure 11).

Although not entirely conclusive, at least it can be suggested that when the coal beds are horizontal, the cleat sets dipping at high angles (in this case dip more than 75°) to the bedding are interpreted to be formed early on during coalification, whereas the cleat sets with low to moderate dip angles (less than 75°) were formed after coalification due to tectonic stress.

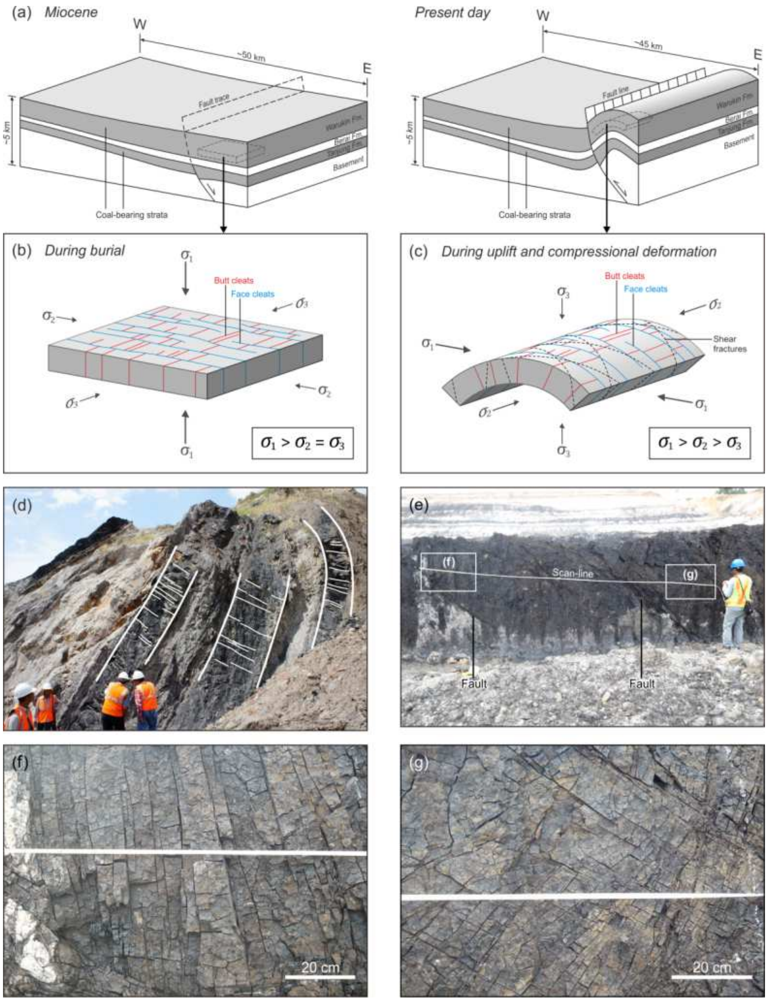


Figure 10 (a) Idealized block diagrams showing 3D geometry of the coal seam in the Barito Basin before (left) and after thrusting. (b) Model of block diagram illustrating the cleat sets formed vertically to subvertically within the coal seam in flat-lying bed during burial. (c) Block diagram illustrating the fracture sets formed during uplift and compressional deformation of the Barito Basin. (d) Photograph of Warukin coal outcrop, depicting cleats oriented at right angles to the bedding of the seams when the strata are folded. (e) Faults recognized in the Warukin coal outcrop located at GP-1 station. (f and g) Magnification of the area within the white frame represented in (e), showing the changes in cleat orientation near the fault planes. The cleats are locally superimposed on the regional cleat sets.

The results suggest that most cleats (≈70%) in coal outcrops of the Tanjung and Warukin Formations were formed during burial and before folding and thrusting (see Figure 11). These numbers are very important for controlling parameters used in 3D CBM reservoir modeling, particularly permeability within the Barito Basin area. In addition, comparison between regional cleat distributions of the Barito, Asem-Asem, and Kutai Basins shows that face cleat patterns and orientations suggest them to be strongly controlled by tectonics and local structures. All this evidence suggests that cleat development within the basin is controlled by various geological parameters, particularly tectonic parameters, which need to be considered in estimating true permeability values of the CBM system.

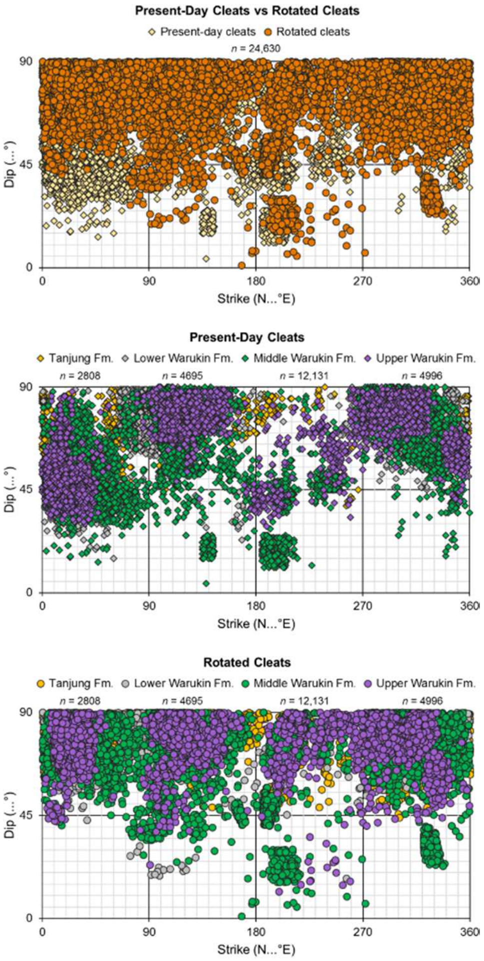


Figure 11 Diagram of strike vs. dip showing distributions of all cleat data sets before and after being rotated to their original positions.

7 Conclusions

All cleat orientation data of Tanjung and Warukin Formations from this study plotted on stereograms and Rose diagrams revealed that the dominant face and butt cleat orientations are in the WNW-ESE and NNE-SSW directions, respectively.

Field analyis indicated that the cleat density distribution in the study area shows a prominent increasing trend to the north and east towards the main deformation zone (tectonic influence). In additon, the knowledge of the distribution of cleat density can be used to predict the most permeable areas in the study area. Based on structural restoration, more than 70% cleats can be considered as originally formed during coalification and before folding and thrusting. This number will contribute to the overall permeability of the CBM prospect in the Barito Basin.

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References

[1] Laubach, S.E., Marrett, R.A., Olson, J.E. & Scott, A.R., *Characteristics and Origins of Coal Cleat: A Review*, International Journal of Coal Geology, **35**(1), pp. 175-207, 1998.

[2] Laubach, S.E. & Tremain, C.M., *Regional Coal Fracture Patterns and Coalbed Methane Development*, Proceedings of the 32nd U.S. Symposium on Rock Mechanics, Balkema, Rotterdam, Roegiers, J-C. (ed(s).), pp. 851-859, 1991.

[3] Kulander, B.R. & Dean, S.L., *Coal-Cleat Domains and Domain Boundaries in The Allegheny Plateau of West Virginia*, American Association of Petroleum Geologists Bulletin, **77**(8), pp. 1374-1388, 1993.

[4] Harpalani, S. & Schraufnagel, R.A., *Shrinkage of Coal Matrix with Release of Gas and Its Impacts on Permeability of Coal*, Fuel, **69**(5), pp. 551-556, 1990.

[5] Moss, S.J. & Wilson, M.E.J., *Biogeographic Implications of The Tertiary Palaeogeographic Evolution of Sulawesi and Borneo*, Biogeography and

Geological Evolution of SE Asia, Hall, R. & Holloway, J.D. (ed(s).), Leiden: Backhuys Publishers, pp. 133-163, 1998.

[6] Hall, R. & Nichols, G, *Cenozoic Sedimentation and Tectonics in Borneo Climatic Influences on Orogenesis*, Sediment Flux to Basins: Causes, Controls and Consequences, Jones, S.J. & Frostick, L. (ed(s).), Geological Society, London, Special Publication, **191**, pp. 5-22, 2002.

[7] Satyana, A.H., Nugroho, D. & Surantoko, I., *Tectonic Controls on The Hydrocarbon Habitats of The Barito, Kutei, and Tarakan Basins, Eastern Kalimantan, Indonesia: major dissimilarities in adjoining basins*, Journal of Asian Earth Sciences, **17**(1), pp. 99-122, 1999.

[8] Siregar, M.S. & Sunaryo, R., *Depositional Environment and Hydrocarbon Prospects, Tanjung Formation, Barito Basin, Kalimantan*, Proceedings Indonesian Petroleum Association, 9th Annual Convention, pp. 379-400, 1980.

[9] Satyana, A.H. & Silitonga, P.D., *Tectonic Reversal in East Barito Basin, South Kalimantan: Consideration of The Types of Inversion Structures and Petroleum System Significance*, Proceedings Indonesian Petroleum Association, 23rd Annual Convention, pp. 57-74, 1994.

[10] Satyana, A.H., *Paleogene Unconformities in The Barito Basin, Southeast Kalimantan: A Concept for The Solution of The "Barito Dilemma" and A Key to The Search for Paleogene Structures*, Proceedings Indonesian Petroleum Association, 24th Annual Convention, pp. 263-275, 1995.

[11] Witts, D., Hall, R., Nichols, G. & Morley, R.J., *A New Depositional and Provenance Model for The Tanjung Formation, Barito Basin, SE Kalimantan, Indonesia*, Journal of Asian Earth Sciences, **56**, pp. 77-104, 2012.

[12] Heryanto, R. & Sanyoto, P., *Geological Map of the Amuntai Quadrangle, Kalimantan*, *Scale 1:250,000*, Geological Research and Development Centre, Bandung, 1994.

[13] Heryanto, R., Supriatna, S., Rustandi, E. & Baharuddin, *Geological Map of The Sampanahan Quadrangle, Kalimantan*, *Scale 1:250,000*, Geological Research and Development Centre, Bandung, 1994.

[14] Sikumbang, N. & Heryanto, R., *Geological Map of The Banjarmasin Sheet, Kalimantan*, *Scale 1:250,000*, Geological Research and Development Centre, Bandung, 1994.

[15] Rustandi, E., Nila, E.S., Sanyoto, P. & Margono, U., *Geological Map of The Kotabaru Sheet, Kalimantan*, *Scale 1:250,000*, Geological Research and Development Centre, Bandung, 1995.

[16] Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S. & Chandler, M., *Global Continental and Ocean Basin Reconstructions Since 200 Ma*, Earth-Science Reviews, **113(**3-4), pp. 212-270, 2012.

[17] Tingay, M., Morley, C., King, R., Hillis, R., Coblentz, D. & Hall, R., *Present-Day Stress Field of Southeast Asia*, Frontiers of Stress Research, Heidbach, O., Tingay, M. & Wenzel, F. (ed(s).), Tectonophysics, **482**, pp. 92-104, 2010.

[18] Pubellier, M. & Morley, C.K., *The Basins of Sundaland (SE Asia): Evolution and Boundary Conditions*, Marine and Petroleum Geology, **58**, pp. 555-578, 2014.

[19] Daly, M.C., Cooper, M.A., Wilson, I., Smith, D.G. & Hooper, B.G.D., *Cenozoic Plate Tectonics and Basin Evolution in Indonesia*, Marine and Petroleum Geology **8**, 1991.

[20] Hall, R., van Hattum, M.W.A. & Spakman, W., *Impact of India-Asia Collision on SE Asia: The record in Borneo*, Tectonophysics, **451**, pp. 366-389, 2008.

[21] Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. & Müller, B., *The World Stress Map Database Release 2008*, 2008. doi:10.1594/GFZ.WSM.Rel2008.

[22] Zahirovic, S., Seton, M. & Müller, R.D., *The Cretaceous and Cenozoic Tectonic Evolution of Southeast Asia*, Solid Earth, **5**(1), pp. 227-273, 2014.

[23] Morley, C.K., Back, S., van Rensbergen, P., Crevello, P. & Lambiase, J.J., *Characteristics of Repeated, Detached, Miocene-Pliocene Tectonic Inversion Events, in A Large Delta Province on An Active Margin, Brunei Darussalam, Borneo*, Journal of Structural Geology, **25**(7), pp. 1147-1169, 2003.

[24] Kusuma, I. & Darin, T., *The Hydrocarbon Potential of The Lower Tanjung Formation, Barito Basin, S.E. Kalimantan*, Proceedings Indonesian Petroleum Association, 18th Annual Convention, pp. 107-138, 1989.

[25] Witts, D., Davies, L. & Morley, R., *Uplift of The Meratus Complex: Sedimentology, Biostratigraphy, Provenance and Structure*, Proceedings Indonesian Petroleum Association, 38th Annual Convention, IPA14-G-082, 2014.

[26] Witts, D., Hall, R., Morley, R.J. & BouDagher-Fadel, M.K., *Stratigraphy and Sediment Provenance, Barito Basin, Southeast Kalimantan*, Proceedings Indonesian Petroleum Association, 35th Annual Convention, IPA11-G-054, 2011.

[27] Sapiie, B., Riyanto, A. & Suryanugraha, A. M., *Tectonic controlled of cleats development as implication of coal bed methane (CBM) Prospect in the Barito Basin, South Borneo, Indonesia*, 76th EAGE Conference and Exhibition 2014, Workshops.