Cleats Analysis and CBM Potential of the Barito Basin, South Kalimantan, Indonesia*

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Abstract

The study area is located in the Barito Basin, South Kalimantan Province which is known as major coal producer in Indonesia. Cleats are described as natural fractures developed in coal seams and acted as the main parameters in controlling permeability performance in the coal bed methane development. Therefore, knowledge of the origin and character of cleats is very important due of their influence on recovery of methane, and the local and regional fluid flows. This article is presents results of integrated surface and subsurface data supported by regional cleats mapping, characterization and analysis in relation to Coal Bed Methane (CBM) exploration, and development in the basin.

There are two main coal seams in the study area, Late Eocene and Lower to Middle Miocene of the Warukin Formation with thicknesses ranging from 2 m up to 60 m. Subsurface data show three different coal zones from data from six wells. The occurrence of coal seams in each well is based on the value of RHOB with 1.75 as a cut-off value. Coal rank is classified as Lignite/Sub-Bituminous C with calorific values ranging 5000-8000 Cal/gr containing an ash content of 8%-17%. There are two methods of cleat and/or fracture measurements used in this study: scan-line and windows sampling (100 cm x 100 cm dimension). More than 20,000 cleats and/or fractures were measured from 60 scan-lines and 39 windows measurement locations. Cleats distribution and orientations indicates three major trends: WNW-ESE, NNW-SSE, and NE-SW. Coal parameters relationships are: an inverse linear is the best fit data for the bed thickness-density relationship, an exponential relationship between average density and cleats height, a power-law relationship between average density and average spacing, and cleats density increases related to regional structural position where they increase towards the main deformation zone (Meratus Mountain). Cleats spacing varies with coal type and ash content. The relationship between cleats spacing and coal rank indicates decreasing spacing from low to high coal rank. The relationship between cleats density with calorific value and ash contents shows high calorific values with low ash content tends to have higher density. Cleats origin may have resulted from several processes and formed during coalification, which may have been superimposed by later processes such as hydrostatic pressure and tectonic stresses, and also affected by the coal composition.

Introduction

The study area is located in South Kalimantan (known also as Borneo) Province, in the Barito Basin, and lies between 114° 59' 50.000" - 115° 29' 50.000" E and 2° 33' 25.000" - 3° 17' 55.000" S. Data were mainly collected in the Rantau, Binuang, and Tanjung areas, and cleat attributes (spacing, aperture, height, and orientation) were measured in the Tanjung and Warukin formations. The study area.

The Barito Basin is located along the southeastern edge of the stable Sundaland continent (Figure 1). To the west, the basin is bounded by the Schwaner Mountains, which consist of metamorphosed rocks of continental character; granitic and tonalitic plutons and volcanic rocks. To the east is bounded by the Meratus Range, a recently uplifted zone of highly folded and thrusted Pre-Tertiary rocks, presumably a suture or collision zone. To the north, the basin rises up into the Adang Flexure area. The southern boundary is unclear due to no structural features or facies changes observed, but may extend south into the Java Sea.

Objectives

The main objectives of this research are:

- To understand vertical and lateral cleats distribution and characteristics (spacing, aperture, orientation) in the Barito Basin.

- Integrating the compiled cleat characteristics with other structural information to examine variability in structural domains and thus enhance the understanding of the evolving stress regime during the Tertiary.

Regional Geology and Tectonic Setting

Kalimantan Island (Borneo) is considered the most stable island in Indonesia and is a continental area which has little or no seismicity (Figure 1). However, the island was subjected to multiple deformation events during the Tertiary, generating a complex structural and stratigraphic setting. Tectonic evolution of this island had become a growing debate among workers. Three major Tertiary basins were formed, caused by rifting along the Sundaland margin, including the Barito and Asem-Asem basins.

The stratigraphic successions of the area can be divided into four mega sequences: pre-rift, syn-rift, post-rift and syn-inversion sequences (Figure 2). The Pre-rift sequence of Barito Basin is presently represented by the basement complex which underlies the basin. Being located along the margin of continental Sundaland, the basement is composed of a variety of amalgamated terrains; those are continental basement in the west and accreted zones of Mesozoic and Early Paleogene rocks in the east. The distribution of rock types in the subsurface is not clear. It is notable, however, that at least in the east of Barito, the basement is evidently Meratus type rather than acidic-crystalline Barito Platform type.

Basin subsidence continued through the Oligocene and by Middle Miocene had resulted in sediments constituting the upper part of the sequence. The calcareous sediments of the Berai Formation fed the basin at that time. The lower part of the formation, below the massive limestone, consists of a condensed paralic and inner neritic sequence of shales and marls. This passes up into thick massive Late Oligocene limestone, which is succeeded by Early Miocene shale, marls and thin limestone.

The syn-inversion sequence of the Barito Basin consists of the Warukin and Dahor formations. The Upper-Early to Late Miocene Warukin sediments were deposited into the rapidly subsiding basin as the result of continental uplift in the west and the Meratus uplift in the east. The resulting sediments are up to several thousand meters thick in the central part of the basin. The Warukin Formation consists of shallow and marginal marine sand, shale, silts and coal (Figure 3). The last intense tectonics in the Plio-Pleistocene, which re-activated the Meratus Range against the rigid Barito Platform, resulted in the shedding of clastic sediments and tectonic molasses of the Plio-Pleistocene Dahor Formation westward filled, into the Barito Basin.

Methods of Study

The methods used in this study includes: field survey and field data acquisition, data sorting, data calculation, and statistical analysis and interpretation. The field survey and field data acquisition entailed two methods of measurement: scan-line method and windows sampling method (Figure 4). More than 20,000 cleats and/or fractures were measured from 60 scan-line and 39 windows measurement locations. Statistical data analysis was accomplished by placing all data into rose diagrams and stereographic projections. By applying an assumption, cleats originally formed sub-vertical in flat-lying bed, cleats and fractures in each coal seam were rotated to their original position (when the bed was horizontal). This sorting technique successfully infers the cleats and/or fractures which formed during or after coalification due to tectonic stress.

Results

60 scan-line and 39 windows measurement locations with a total of 19,738 cleats were measured. Field data presented in this study most likely corresponds to macrocleats. Most data were collected on mine walls (cross section view measurement). Cleats data were collected for several coals from the Tanjung and Warukin formations. Most data were collected from the Warukin Formation and subdivided into Lower, Middle and Upper Warukin. To better understand cleats development, cleats distribution and orientation were presented based on their formation.

Based on the distribution and orientation map, it can be summarized for each formation where the cleats were measured. From all data measured, there were three main orientations: WNW-ESE, NNW-SSE and NE-SW. Face cleats orientation within the Tanjung and Warukin formations have dominantly a WNW-ESE direction. Discrepancy is observed within the Warukin Formation where several locations have a face cleats direction of NE-SW which differs by ~90° from other locations in the same interval. The apparent discrepancy may have resulted from structural geology associated with strike-slip faults nearby which formed a secondary cleat system, or from improper identification of face versus butt cleats data in the field, or insufficient measurement that complicates interpretation.

The regional maps of cleat orientation have distinguished domains and variable cleat strike, where the face cleats in the Tanjung and Warukin formations have a general WNW-ESE orientation (Figure 5). Uniformity of cleat strikes within domains indicates that fractures responded to regionally coherent stress patterns, which could reflect plate-scale stress or stresses related to uplift or basin geometry (Laubach et al., 1998).

This means the origin and evolution of coal cleats (as an opening-mode fracture) can be attributed to compression, extension and other manifestations of tectonism. The control of the tectonic stresses on the cleat formation is based on the intrinsic tensile forces and fluid pressure in coal beds. The formation of cleats within the Tanjung Formation might be related to the NW-SE trending rift basins thate were formed and followed by a prolonged period of subsidence and sedimentation extending into the Late Miocene. The formation of cleats in the Warukin Formation is related to transpression along the Meratus Range which produced NW-SE compressive stress. The face cleats extend along the SH direction and the butt cleats along the direction of horizontal minimum compressive principal stress (SHmin), so the regular reticular cleat pattern is formed in the basin.

The face cleat represents the direction of horizontal maximum in situ stress (SHmax), and butt cleat along the direction of horizontal minimum in situ stress (SHmin), so the regular reticular cleat is formed (ie. Su et al., 2001). When the preferred fracture orientation is consistent with the principal stress over wide areas (Olson and Pollard, 1989; Laubach et al., 1998), cleat formation is mostly controlled and superimposed by tectonic stress.

With the assumptions that cleats were formed subvertically in flat-lying beds, we tried to distinguished the cleats origin and formation from the first cleats formed to the latest cleats. From this assumption all data were rotated back to the original coal bed, this was done by rotating the bed including the cleats for each location and summarized in Figure 6. From data distribution on the crossplot charts we can interpret that the cleats with subvertical dip (in this case above 75°) formed in the first stage, while the cleats and/or fractures which have dips less than 75° are interpret to have formed in the later or secondary stages.

Another approach used to analyze cleat development is plotting the face cleats into a stereographic projection. Based on the stereogram and orientation analysis the data are subgrouped into several domains. For the Tanjung, Lower Warukin, and Middle Warukin formations plots showing at least three domains of the face cleats data set, while the Upper Warukin Formation shows at least two domains of the face cleats data set. These results indicate the complexity of data sets which could not be seen clearly from rose and strike vs. dip analysis. This asserts the cleats origin where subjected to several processes, where the cleats which formed during coalification were superimposed by later processes such as hydrostatic pressure and tectonic stresses and also can be affected by the coal composition.

Cleat Attributes Analysis

Cleat Size

Apertures of cleat data observed at an interval of 0.01 to 0.3 cm, where most data ranges between 0.01 - 0.05 cm. The height or length of the cleats range from centimeters to meters, and bear in mind the limitation to the height/length where the measured length is restricted to the limited scan-line and windows sampling dimension, so the height/length data are not completely reliable. Variability in cleat size (aperture and height) in coal beds has been summarized by Laubach et al. (1998) where the cumulative frequency of cleat aperture follows a power law and cleats with large apertures tend to have large heights. The summary chart of aperture and height of all scan-line locations shows the general trend where large apertures tend to have large heights (Figure 7A).

Cleat Spacing

Measurement on mine highwalls shows that spacing between individual cleats ranges from microns to meters. Average spacing of all scan-line locations vary over the study area. Average cleat spacing has been used to characterize the cleat relationship with the frequency. Average spacing and frequency from all measurement locations in the study area and are plotted in the chart and follows a power law distribution trend line (Figure 7B).

Cleat Density

The measure of cleat/fracture density used in this study is the summed length of all fractures within a square area divided by the area of the rectangle. The fracture density is expressed in units of length/area (e.g. ft/ft^2, cm/cm^2, m/m^2, and km/km^2). In practice, the values of fracture density are converted to the reciprocal form (ft^{-1}, cm^{-1}, m^{-1}, and km^{-1}) (Davis and Reynolds, 1996).

For development of coalbed methane, important natural fracture attributes contribute to permeability pathways for gas and water flow to wells (Laubach et al., 1998). Cleat density can affect the coal stability and thus success of cavity stimulation. Therefore, the relationship of the cleats attributes with their density is important in order to understand cleat origin and development. The density is related to the cleat network geometry and connectivity, where higher density will probably have a good network and connectivity.

The average density has been used to understand the relationship with other attributes: bed thickness, average spacing, average aperture, and average height. The crossplot chart between bed thickness and density shows that in thinner the coal beds the cleat density is higher (Figure 8A). There are several discrepancies on the chart where it might be related to the structural position. Further analysis was carried out to find best fit data without the data possibly induced by structure. The first fit data experiment with a power law gives R^2= 0.8123 (Figure 8B) while the second experiment with an inverse linear gives R^2= 0.8569 (Figure 8C). From the goodness-of-fit (R2) values that represent the quality of the relationships, suggested an inverse linear is the best fit data for the bed thickness-density relationship. From the measurement in the same coal bed indicates a mechanical layering within the same coal bed where measurement taken in the bottom, middle, and top of same coal bed showing different average density.

The same approach was taken for the relationship between average density and average spacing in order to avoid the discrepancies due to structure or tectonic induced (Figure 8D). The crossplots show a power law distribution trend line (Figure 8E). The average density from all location shows the average spacing range from 2.28 to 13.34 cm. Another attribute analyzed is the cleat height, and although the data were not very representative, there is an indication of the relationship with the average density. The crossplots chart between average density and cleat height shows an exponential relationship (Figure 8F). Surprisingly, we can observe at least two exponential trend lines for the Middle and Upper Warukin Formation. The overall representative data also shows an exponential equation (Figure 8G).

The last attribute analyzed is the aperture; the average aperture ranges from 0.01 to 0.3 cm. Apertures were measured in the outcrops are larger than apertures measured from cores, which range from 0.01 to 0.2 mm. This can occur because the coal seams in the outcrops are fully exposed and/or the accuracy of tools used in the field. However, cleat aperture from outcrops studies do not represent current confining pressure conditions.

The distribution of fracture density in the study area, particularly in areas with numerous observation locations, shows an increase of fractures to the north and to the east towards the Meratus Range. This evidence shows cleat density might be related to the structural position. Several NW-SE cross sections were made to show density variation towards the Meratus Range. Density contours on the adjacent area of scan-line location shows density increases northwards and eastwards. Density increases northward most likely due to diachronous uplift of the Meratus Mountains where the northern Meratus Range is more uplifted than the southern part.

Coal Rank and Composition Effects on Cleats Development

Several studies indicate the relationship between cleat spacing and coal rank, that from lignite through medium volatile bituminous coal the cleat spacing is decreasing (Ammosov and Eremin, 1963; Ting, 1977; Law, 1993), and increasing through anthracite coals. Laubach et al. (1998) noted Law (1993) found that face cleat spacing ranges from approximately 22 cm in lignites (Ro (vitrinite reflectance) values of 0.25-0.38%) to 0.2 cm in anthracites (Ro values more than 2.6%). This relationship is represented by an inverse exponential equation:

$$S = 0.473 \text{ X } 100.398/Ro \qquad (1)$$

where S is cleat spacing in centimeters; this equation is derived from Laubach et al. (1998). The results of coal sample analysis were plotted to Law's chart, the available data have vitrinite reflectance ranging from 0.25 to 0.49% and classified as lignite to sub-bituminous C. The crossplots give a spacing range of 2.84 to 17.08 cm. This result is comparable with the scan-line results in the same interval: 2.28 to 13.34 cm. Many authors have noted that coal type and ash content affect cleat spacing (Spears and Caswell, 1986; Tremain et al., 1991; Law, 1993). Coals with low ash content tend to have smaller cleat spacing than coals with high ash content (Laubach et al., 1998).

The lateral coal samples from several scan-line locations indicate varies calorific value (dry, ash free) and ash content (air-dried basis) related to the density value along the scan-line. These laboratory results also show that coal composition not only varies vertically but also horizontally. The summary chart of density with coal samples along the scan-line shows the general relationship where high calorific value with low ash content tends to have a high density (Figure 9).

Cleats and Permeability

Development of fracture porosity/permeability is one of the most important parameters for effective and economical coal bed methane production. Abundant cleats increase permeability and correspond with highly fractured reservoirs. Scott (1999) used the relation proposed by Lucia (1983) to model permeability in coal. Lucia (1983) proposed an equation which represents the relationship between permeability, abundance of fractures and fracture aperture. Although Lucia's study is based on carbonates, Scott (1999) suggested a similar approach where the matrix between fractures is considered impermeable in carbonates and coals, so the permeability occurs mainly through fractures. Lucia's relation indicates that permeability increases with the cube of the fracture aperture and varies with the inverse of the fracture spacing:

$k = [84.4 \text{ X } 105]\ w3 / z$ (2)

where k is permeability (darcys), w is fracture aperture (cm), and z is fracture spacing (cm). The equation of Lucia (1983) is a modification of the standard definition of fracture permeability according to the cubic law, but simplified to account for only two variables (fracture aperture and spacing). Another solution to estimate fracture permeability through open fractures is by following a development similar to the one presented for solution vugs (Aguilera, 1995). The relationship for fracture permeability attached to single point properties (kf) is as follows (combined with Darcy's law):

$kf = 8.35 \text{ X } 106w2$ darcys (3)

Fracture permeability from equation 3 is attached to single point properties. It can be developed to fracture permeability ($k2$) attached to bulk properties of the system for one set of parallel fractures by using the equation:

$k2 = kf\ w / z$ (4)

Equation 4 assumes one set of parallel fractures. It can be extended for calculations of fracture permeability $k2$, in the case of cubes and match stick models by using the following equations:

Cubes, $k2 = (2/3)\ (kf\ w2/ z)$ (5)

Match sticks, $k2 = (1/2)\ (kfw2/ z)$ (6)

In general, some of the coals of the Barito Basin have permeability in the range of 20 to 2000 md, but for some coals which have cleats with large apertures (>0.04 cm), the permeability can reach more than 2000 md. Figure 10 gives ranges of permeability of coal where active CBM projects exist. The tabulation implies a diversity of permeability in commercial projects. The figure shows that the cleat permeability of Barito Basin can be analogous to the coal permeability of Powder River Basin and Forest City Basin, USA.

Conclusions

- Cleats distribution and orientation indicates three major orientations WNW-ESE, NNW-SSE and NE-SW trending.

- This study summarizes the relationship between cleat attributes and cleat density. They are: an inverse linear is the best fit data for the bed thickness-density relationship, an exponential relationship between average density and cleats height, a power-law relationship between average density and average spacing, and cleat density increases related to regional structural position where they increase towards the main deformation zone.

● Cleat spacing varies with coal type and ash content. Cleat spacing decreases from low to high coal rank. High calorific value with low ash content tends to have high cleat density.

● Cleats which formed during coalification may be superimposed by later processes such as hydrostatic pressure and tectonic stresses and also can be affected by the coal composition.

● Some of the coals of the Barito Basin have permeability in the range of 20 to 2000 md, but for some coals which have cleats with large apertures (>0.04 cm), the permeability can reach more than 2000 md. The cleat permeability of the Barito Basin may be analogous to the coal permeability of the Powder River Basin and Forest City Basin, USA.

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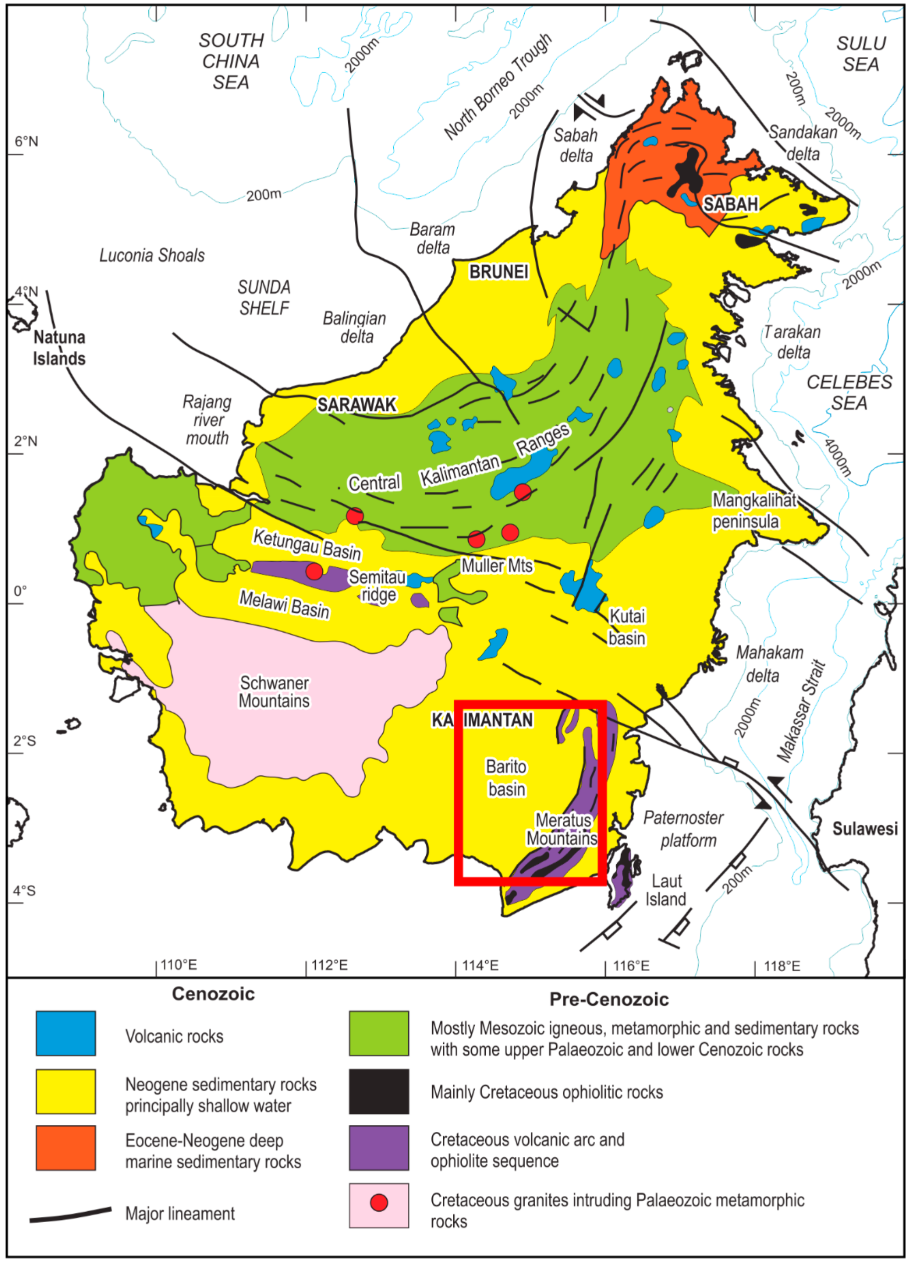

Figure 1. Location of study area (red box) showing tectonic and structural elements of Kalimantan Island (adapted from Hall and Nichols, 2002).

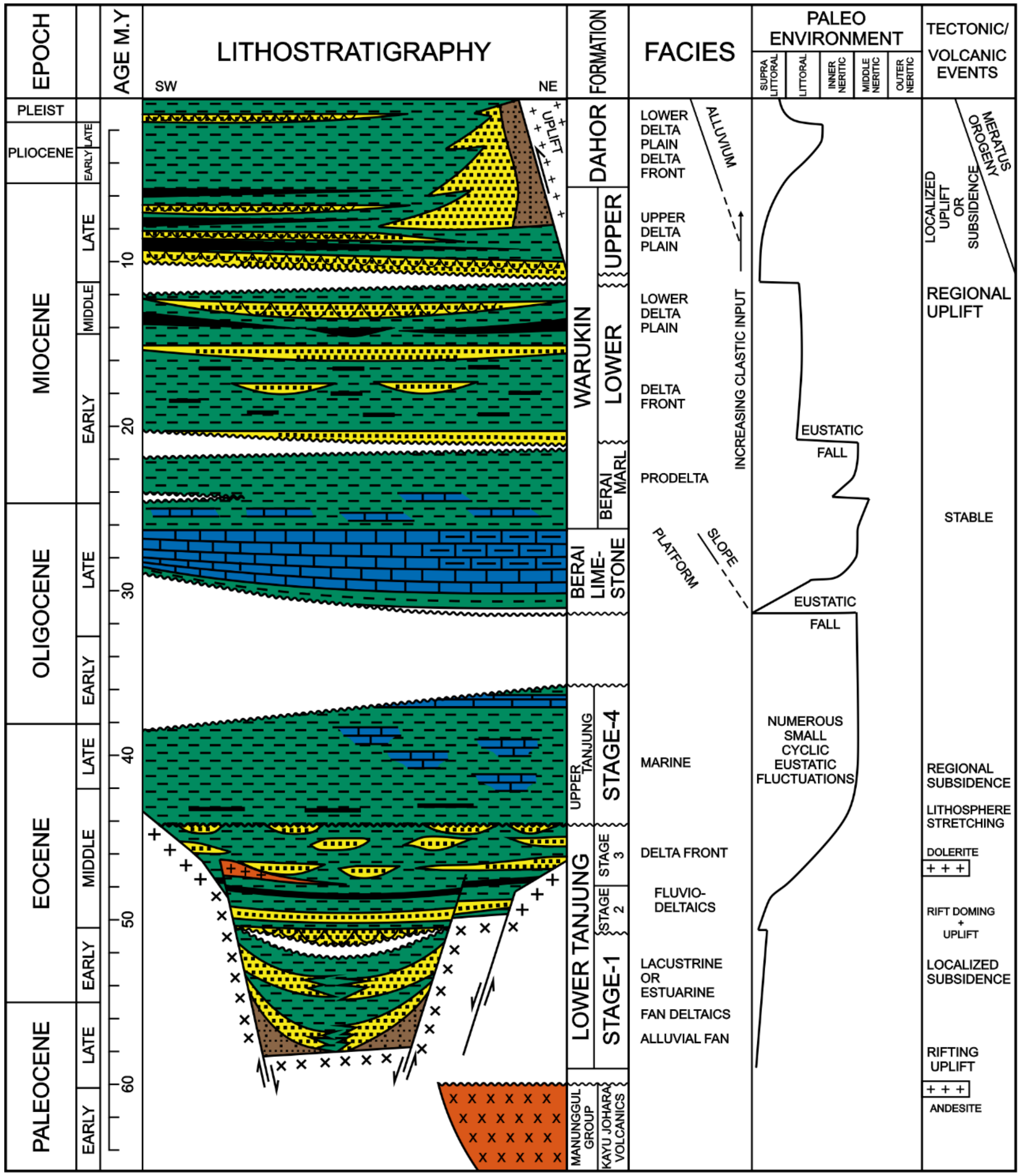

Figure 2. Regional stratigraphic column of Barito Basin (Kusuma and Darin, 1989) showing two major coal formations: Tanjung and Warukin formations.

Figure 3. Coal outcrops of the Warukin Formation showing steeply dipping thick coals (>50 m).

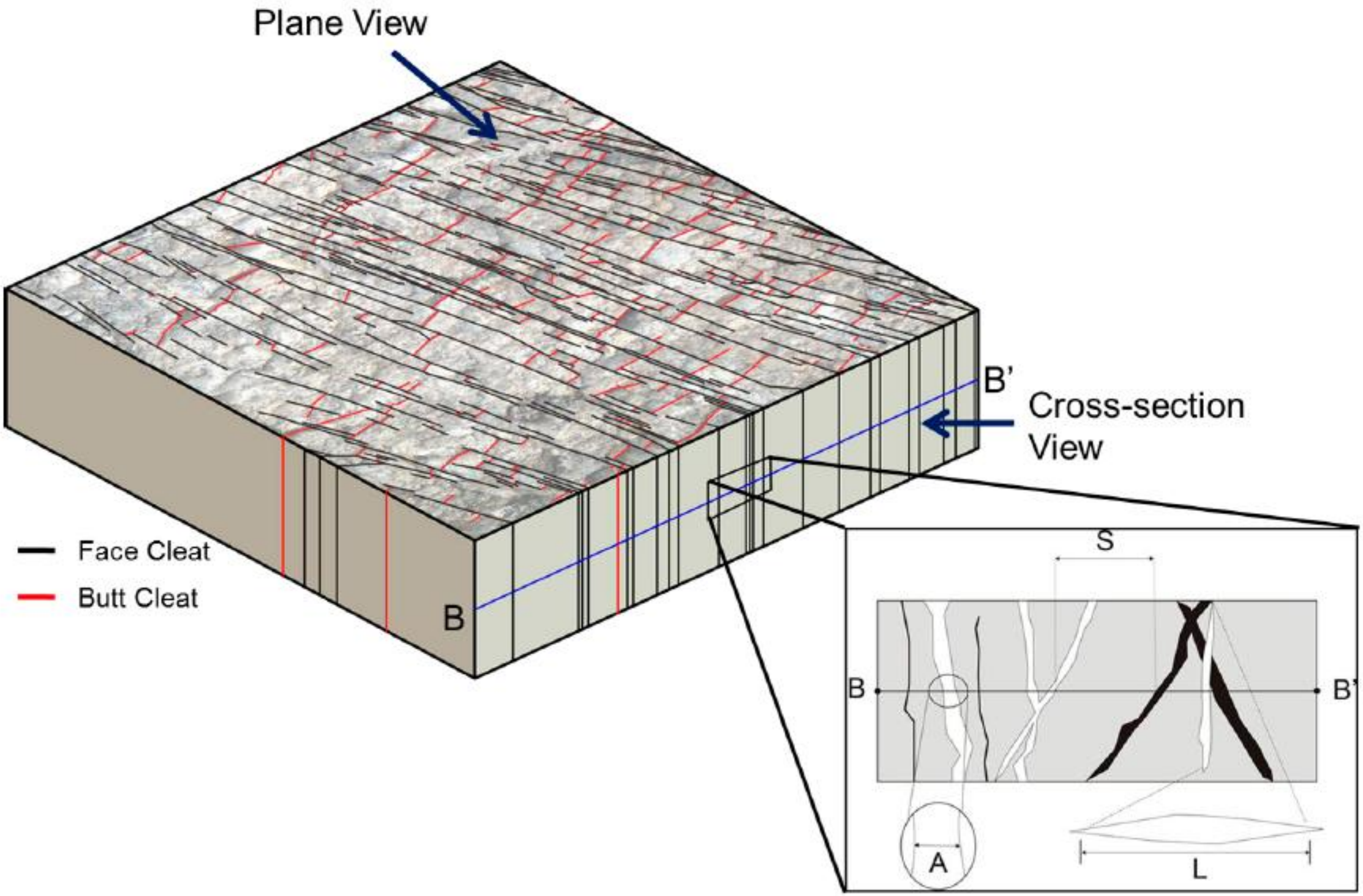

Figure 4. Schematic diagram showing the cleat/fracture attributes that were measured: A is aperture; B-B' is the length of measurement; S is spacing between fracture/cleat; and L is the height/length of fracture/cleat (modified from Sapiie, 1998).

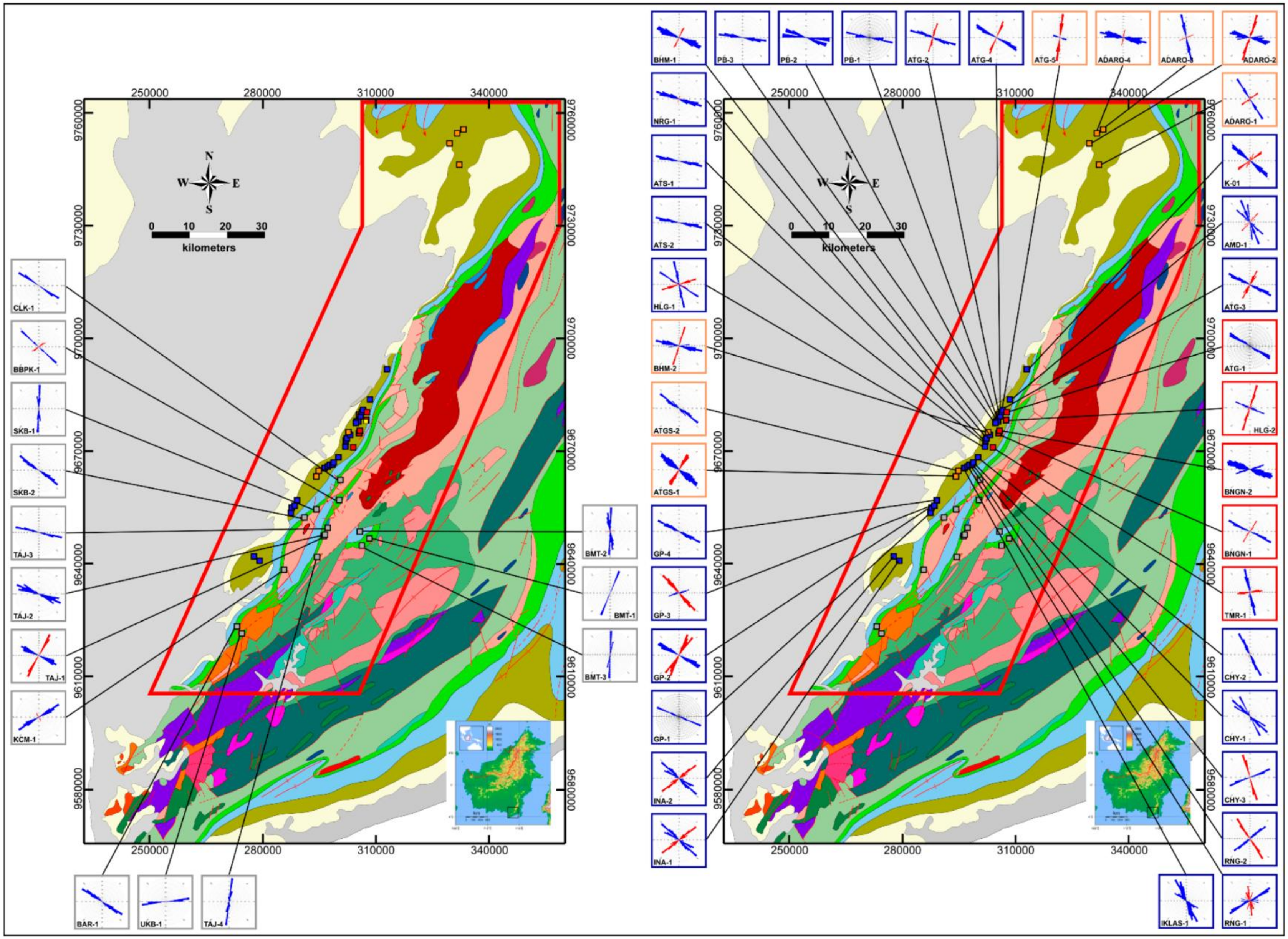

Figure 5. Cleats distribution and orientation map in Tanjung Formation (left) and Warukin Formation (right). Observation locations in Tanjung, and Lower, Middle and Upper Warukin Formation shown by grey, red, blue and orange boxes, respectively. Face cleats orientation shown in blue in rose diagram, whereas butt cleats orientation shown in red.

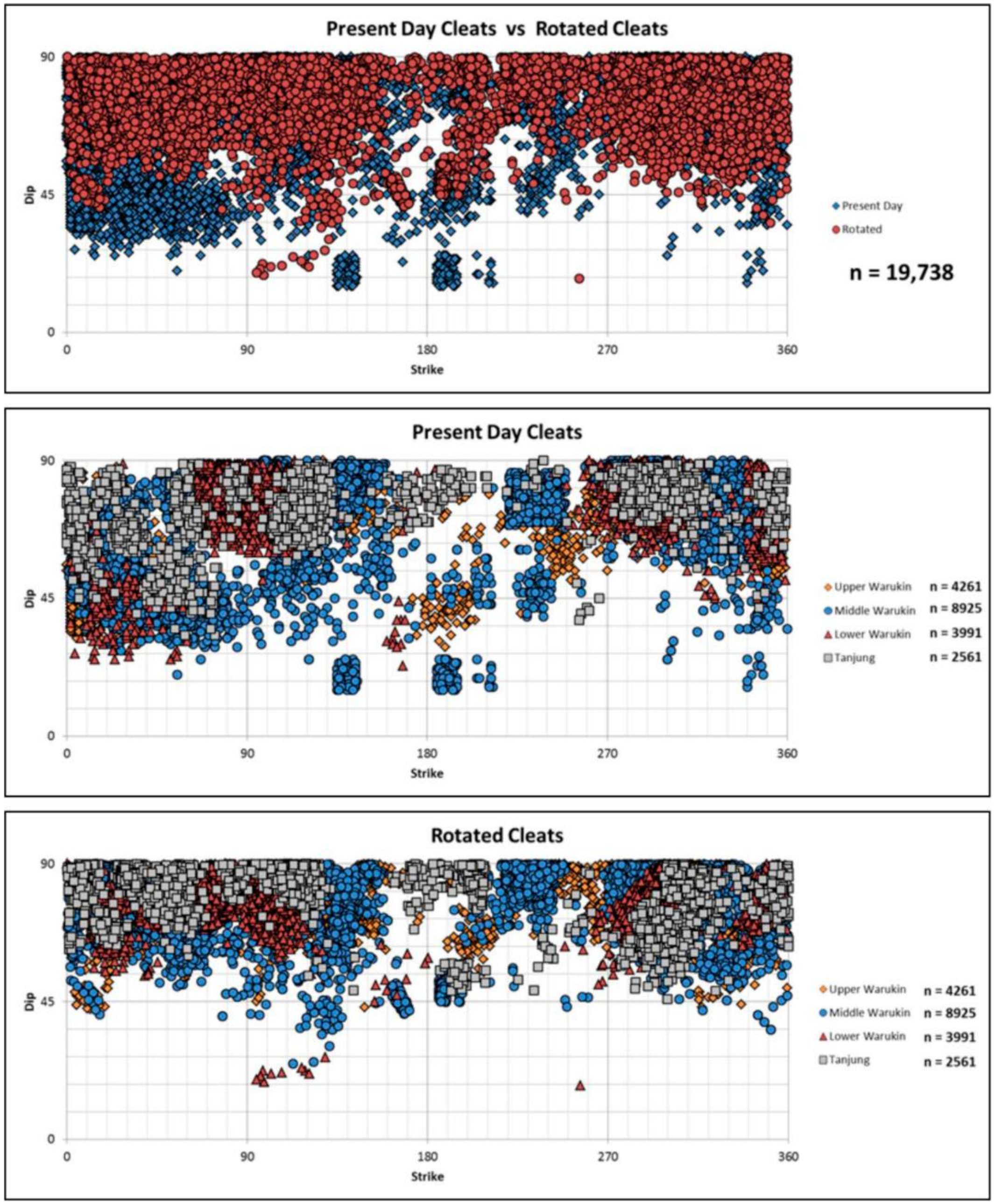

Figure 6. Crossplot charts showing the distribution of all cleats data before and after being rotated to their original bedding (n = 19,738).

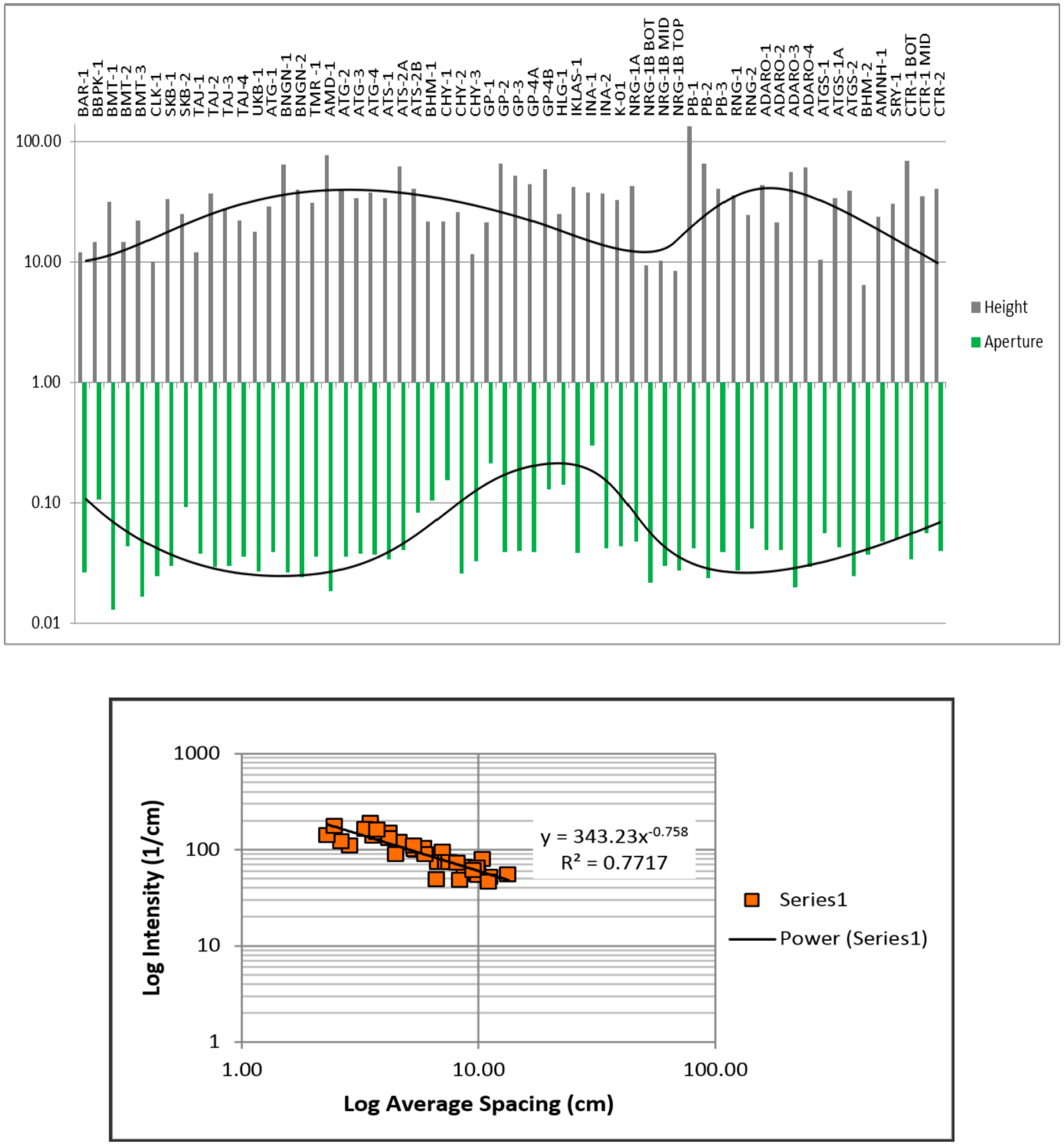

Figure 7. (A) Chart of aperture and height of all scan-line locations showing the relationship between them where large apertures tend to have large heights. (B) Chart shows the relationship between spacing and frequency of cleats follows a power law.

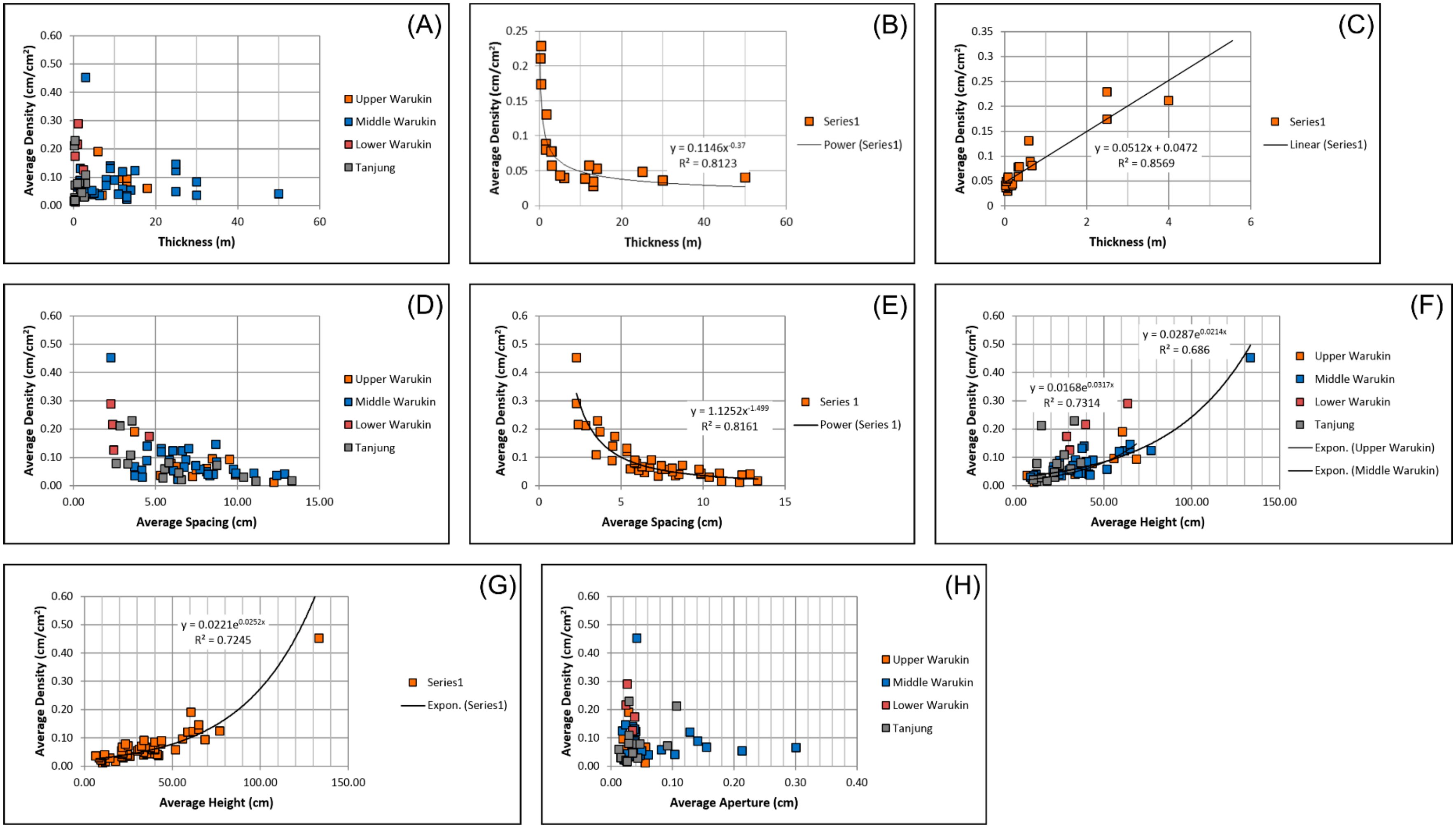

Figure 8. (A) Chart showing the crossplots between bed thickness and average density from all scan-line locations.
(B) Chart of bed thickness versus average density with a power law trend line.
(C) Chart of bed thickness versus average density with an inverse linear trend line.
(D) Chart showing the crossplots between average spacing and average density from all scan-line locations.
(E) Chart of average spacing versus average density with a power law trend line.
(F) Chart showing the crossplots between average height and average density with different exponential trend lines for Middle and Upper Warukin Formation.
(G) Chart of average height versus average density with an exponential trend line.
(H) Chart showing the crossplots between average aperture and average density from all scan-line locations.

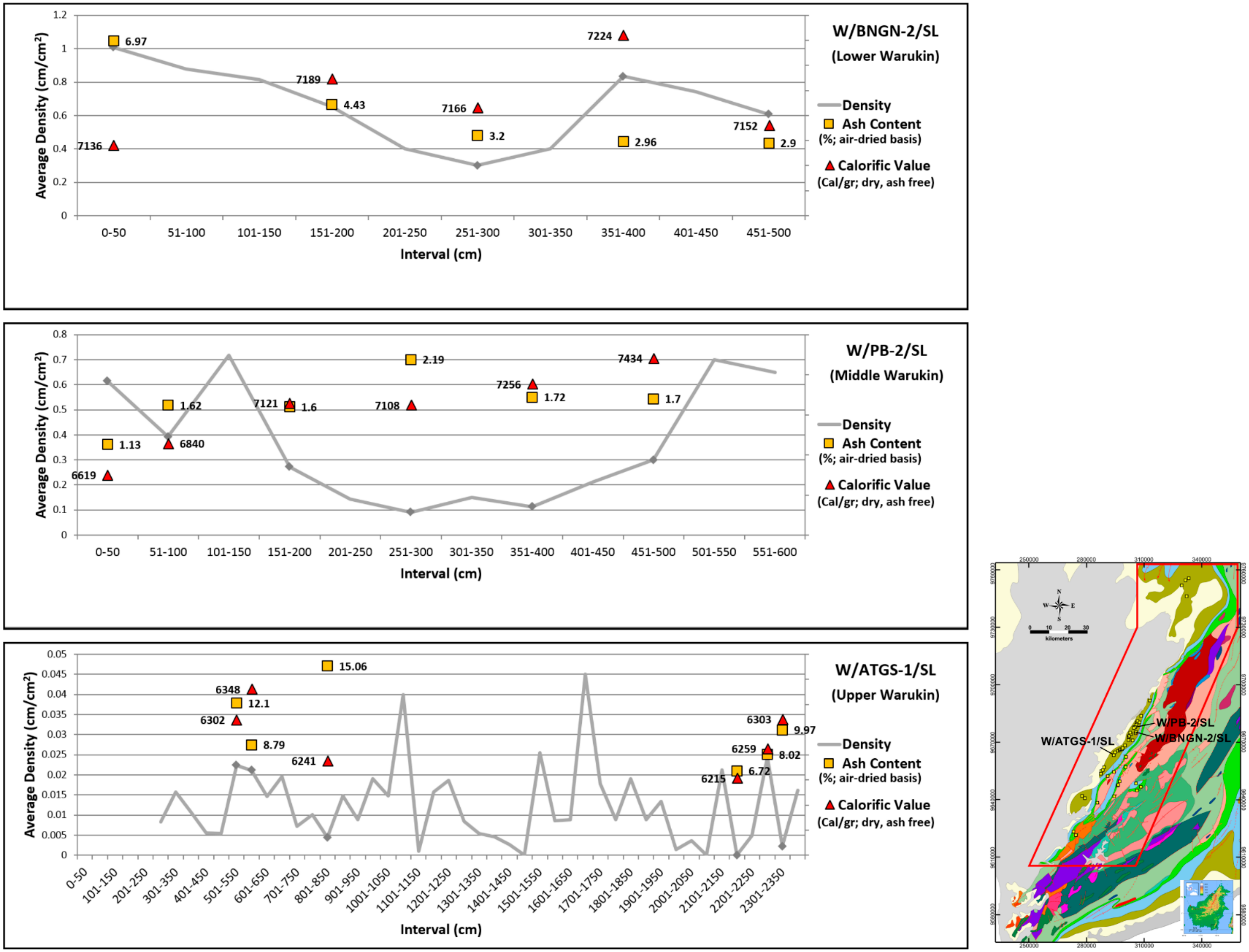

Figure 9. Charts shows the density along the measured scan-line with the calorific value and ash content in several intervals of scan-line.

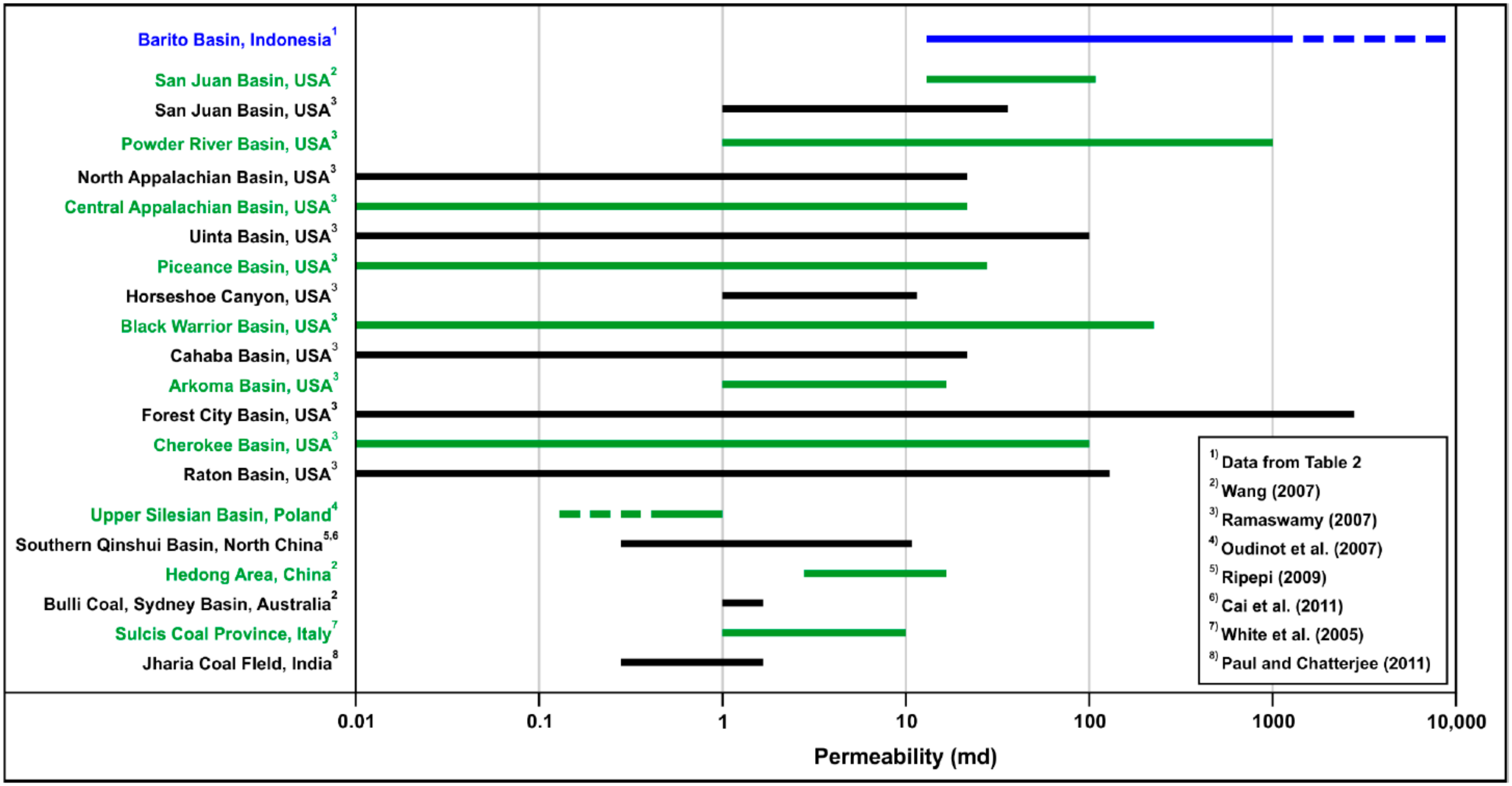

Figure 10. Barito Basin coal permeability compare to the range of coal permeability from various location around the world.