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The coal cleat system: A new approach to its study

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A B S T R A C T

After a general analysis regarding the concept of coal "cleat system", its genetic origin and practical applications to coalbed methane (CBM) commercial production and to CO_2 geological sequestration projects, the authors have developed a method to answer, quickly and accurately in accordance with the industrial practice and needs, the following yet unanswered questions: (1) how to define the spatial orientation of the different classes of cleats presented in a coal seam and (2) how to determine the frequency of their connectivites. The new available and presented techniques to answer these questions have a strong computer based tool (geographic information system, GIS), able to build a complete georeferentiated database, which will allow to three-dimensionally locate the laboratory samples in the coalfield. It will also allow to better understand the coal cleat system and consequently to recognize the best pathways to gas flow through the coal seam. Such knowledge is considered crucial for understanding what is likely to be the most efficient opening of cleat network, then allowing the injection with the right spatial orientation, of pressurized fluids in order to directly drain the maximum amount of gas flow to a CBM exploitation well. The method is also applicable to the CO_2 geological sequestration technologies and operations corresponding to the injection of CO_2 sequestered from industrial plants in coal seams of abandoned coal mines or deep coal seams.

1. Introduction

The coal fracture system has been investigated since the earliest days of coal mining operations, and the first descriptions and speculations on fracture origin dated back to the late 19th century, aiming to determine the design of mine workings (Pattison et al., 1996). Such studies consisted in general descriptions of the appearance of the fractures and measurements confined to their orientation, which are considered important issues in designing coal mines so as to maximize extraction efficiency and to improve safety conditions.

In the past, coalbed gas was considered mostly as a hazard (Flores, 1998) due to the effect of both fire-damps and gas outbursts. Many studies were also carried out in the scope of mine safety related to these phenomena, i.e. coal fracturing and tectonics (Alpern, 1963, 1967, 1970). An account of more recent investigations was given by Cao et al. (2001), Jin et al. (2003), Ryan (2003), and Solano-Acosta et al. (2007, 2008), respectively.

Coalbed gas corresponds nowadays almost to a resource commodity through the commercial exploitation of CBM deposits, and the study of coal fracturing is again considered crucial. In fact, as stated by several different authors (Gamson, 1994; MacCarthy et al., 1996; Ayers, 2002; Durucan and Shi, 2009), the prerequisite to obtain economical and technical viable projects in coalbed gas recovery as well as in CO_2 injection is intimately related to coal permeability which, in turn, depends on coal fracturing.

Many terms were used over the years to designate the natural fracturing of coal. However, the term "cleat", used for the first time in 1925, was the one retained by the current miners, geologists, and engineers as the general designation for a variety of fractures commonly found in coal, usually as a result of the coalification process and basin regional tectonics. In fact, cleats in coal have been described as equivalent to joints in competent rocks or as closely spaced, pervasive fractures originated from an almost imperceptible movement associated with an extensional opening. After the

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work of Macrae and Lawson (1954), Nickelsen and Hough (1967), Ting (1977), Karacan and Okandan (2000), and Wolf et al. (2001), the formation of cleat appears to be influenced by shrinkage occurring during the process of coalification, stress release, and extensional strain. It was also documented that, in general terms, a cleat system is present in coal ranging from lignite to anthracite, being commonly well developed in low volatile bituminous coals. This is justified by the fact that the increases of heat and pressure, usually associated with metamorphism, produce plastic flow that destroys the original cleat structure. This fact was more recently confirmed by Su et al. (2001).

Many hypotheses exist concerning the origin of cleats in coal. However, authors like Ting (1977) and Close (1993) believed that cleat genesis can be effectively classified in three main processes: dehydration, devolatilization, and tectonics. The first process consists of dehydration caused by mechanical compaction of plant fragments when water is expelled from peat induced by overburden. This process is easily understandable since coal, at the very beginning of its formation, has a high moisture content, which progressively decreases as rank increases. Consequently, coal suffers considerable changes in volume that lead to fragments being rearranged due to inter-granular slippage, compaction, and the collapse of cellular cavities. As a result, coal fractures tend to increase as dehydration increases. The devolatilization effect consists in the loss of volatile matter during the coalification process and after the loss of moisture has already been completed. This mechanism also produces a decrease in coal volume which, once more, induces fracture formation.

Tectonics apparently controls cleat orientation in coal in a process somewhat similar to jointing observed in other rocks. It is common to relate the strike directions of cleats to major structures such as folds in many basins, although local and lateral disturbances, such as faults, folds, and stresses, induced by differential compaction and produced by underlying non-coal material, tend to complicate the coal cleat system. Another aspect that must be pointed out is that, locally, cleats can be rotated and deviated from the settings resulting from the stress field. In order to avoid this effect, it is necessary to study a set of samples strategically positioned, depending on the spatial basin geometry, in the coalfield to permit a real representative stress field study.

The cleat system, as it is currently understood, is theoretically characterized by two main sets of sub-parallel fractures (“face cleat” and “butt cleat”), both mostly orthogonal to bedding. Face cleats are usually dominant, with individual surfaces almost planar, persistent, laterally extensive, and widely spaced. Butt cleats constitute a poorly defined set of natural fractures, orthogonal or nearly orthogonal to face cleats. Face cleats are continuous throughout the coal seam, while butt cleats tend to be discontinuous, non-planar, commonly ending at the intersection with face cleats. However, in practical terms, detailed cleat characteristics of a coal seam are far more complex than the two main fracture sets as described above. This fact is on the basis of different detailed cleat classifications in literature, e.g. Ammosov and Eremin (1963), Tremain et al. (1991), and Gamson et al. (1993). In 1998, Laubach et al. (1998) defined the following detailed cleat characteristics: orientation, spacing, aperture, height, length, and connectivity as crucial indices to classify the cleat system in a coal basin.

2. The need for a new approach to study coal cleat system

Since the very first studies on the coal cleat system process, several authors have been interested in introducing a correct and adequate methodology to quantitatively characterize coal cleat networks. However, up to date, it was only possible to obtain quantitative results by a rather expensive and time-consuming method, similar to the one used in micro-tectonics which is a direct response of regional and local tectonic settings (Ting, 1977; Close, 1993; Levine, 1993; Pyrak-Nolte et al., 1993; van Krevelen, 1993; Laubach et al., 1998; Montemagno and Pyrak-Nolte, 1999; Morris et al., 1999; Mazumder et al., 2006).

In the present work, a new, semi-automatic, fast, accurate, and statistically based optical method, aiming to obtain more reliable results in order to satisfy the current industrial practice and needs, was developed. In this regard, it should be mentioned that, more recently, Alpern and Lemos de Sousa (2002) have proposed, to adapt to CBM problems, an alternative mechanical degradation test that was developed to study the outburst prediction (Alpern, 1963) through which it has been possible to define a “fracturability index” in correlation with gas circulation.

In fact, it is well known that the natural network of fractures presented in coal allows the drainage of CBM from coal seams to the production wells through the cleat system. Furthermore, in a classical approach, exploitation methods include additional fracture opening induced by stimulation with injection of various fluids. However, even when using more advanced technologies that are applied in several basins, such as open-hole cavity completion method, the gas production advantage revealed to be either successful or unsuccessful depending on the basins and/or the coal seams (see also Ayers (2002)). This means that only in very favorable cases it is possible to obtain advantageous economic levels of CBM production.

Therefore, what really matters in the authors’ opinion is, in each case, to know (i) the spatial orientation of the different classes of fractures (cleat) and (ii) the frequency of their connectivity, in order to make possible a right orientated hydraulic fracturing injection of fluids (water, gas, or combining both fluids) under pressure to open the cleat system, thus allowing the highest amount of gas release. In fact, the cleat families of highest connectivity frequency are those that define the gas circulation network to the production well, and are, therefore, the most favorable ones to be opened by fluids, although they must be injected in the correct direction. Taking this fact into account, drilling a higher number of holes does not solve *per se* the problem of gas production from coal seams. The method must be applied with extreme care, otherwise it may lead to misleading conclusions. One limitation in this method is related with the availability of the core samples needed to this kind of studies.

Other options, like the televiewer method, considered as the best solution to study *in situ* the cleat system mostly in terms of orientation, do not, in the authors’ opinion, allow to study the microfractures, only the meso and macrofractures. Additionally, the presented method is able to statistically describe in detail the characteristics of the studied samples, also in terms of spacing, aperture, height, length, filling, and connectivity.

It should also be noted that, although the coal cleat system also depends on the local and regional tectonics, the cleat network cannot be inferred using conventional regional micro-tectonics studies. Indeed, in terms of mechanical properties, coal has a very particular rheologic behavior; the deformation threshold is totally different from the other rocks presented in the local stratigraphic column, even considering strata directly contacting with coal seams, i.e. the roofs and floors. This particular rheologic behavior occurs due to its microlitotypes composition, i.e. if one is dealing with a rich liptite coal, one will certainly have difficulties in observing a pertinent fracture network, since liptite has a high elasticity behavior and this performance will be more complex when liptite is strongly interstratified with the other microlitotypes whose behaviors are totally different. Additionally, in most basins that correspond to CBM deposits, the ellipsoid of effective tectonic stress is more or less constant, i.e. there are no changes in amount or direction of the effective stress. What really changes with local tectonics is the deformation strength of the different rocks filling the basin, since coal does not have a standard behavior directly linked to tectonic stress, due to the above-mentioned aspects. Coal having very weak deformation strength is not able to resist minor changes of the effective tectonic stress. This is the reason that it is necessary to stimulate gas production by opening cleats and injecting fluids under pressure during CBM operational issues, and that statement agrees with the experimentally well-established fact that coalbed permeability is highly stress-dependent (Gamson et al., 1993; Ayers, 2002).

3. Development of the proposed methodology: the “coal core tectonics” (CCT) method

The necessity of a methodology able to produce accurate, reliable, and statistically significant three-dimensional (3D) data in an easy and semi-automated way, as well as allowing a correct representation of the stress system of the coal basin, has been conducted by the authors regarding the method described in detail in this section and entitled “coal core tectonics” (CCT) method, based on the work initially performed by Rodrigues (2002). A supplementary advantage of the method is its time-saving feature, since using the GIS tool is possible to perform a detailed analysis of a core sample in just a few hours. GeoMedia software provides GIS with advanced parameters that include improved display, performance, and spatial analysis. GIS has been adopted in many geological studies since it provides the opportunity to combine layers of information about a geographical area in order to produce a better understanding of different parameters involved, which will obviously depend on the purpose of the project.

Fig. 2. Image obtained with high-resolution scanner.

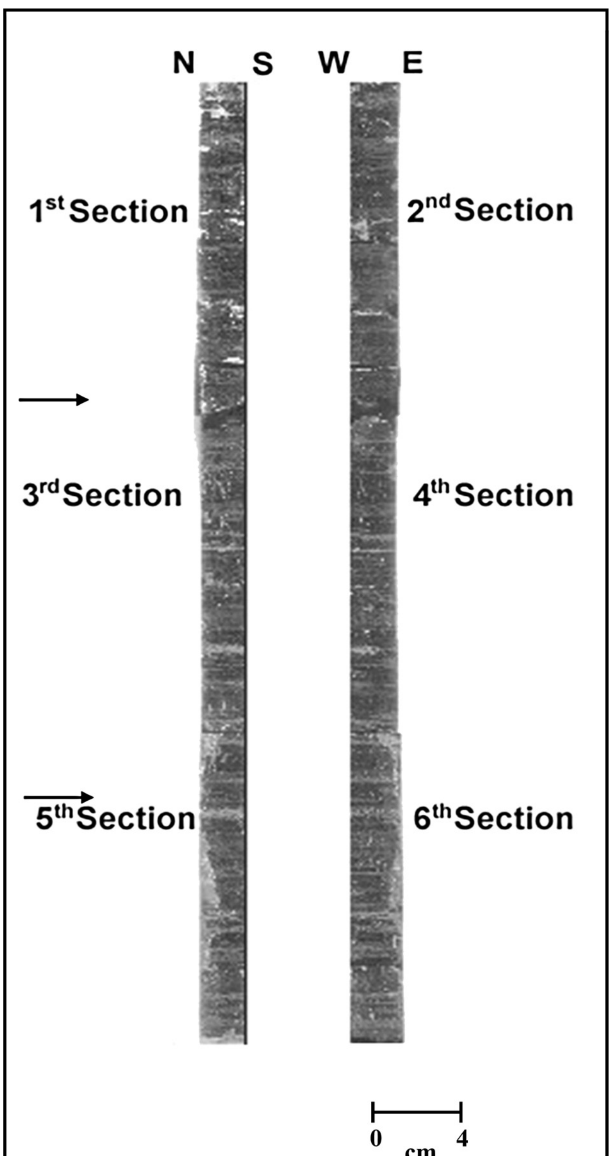

Fig. 1. Sample orientation in N–S and W–E planes.

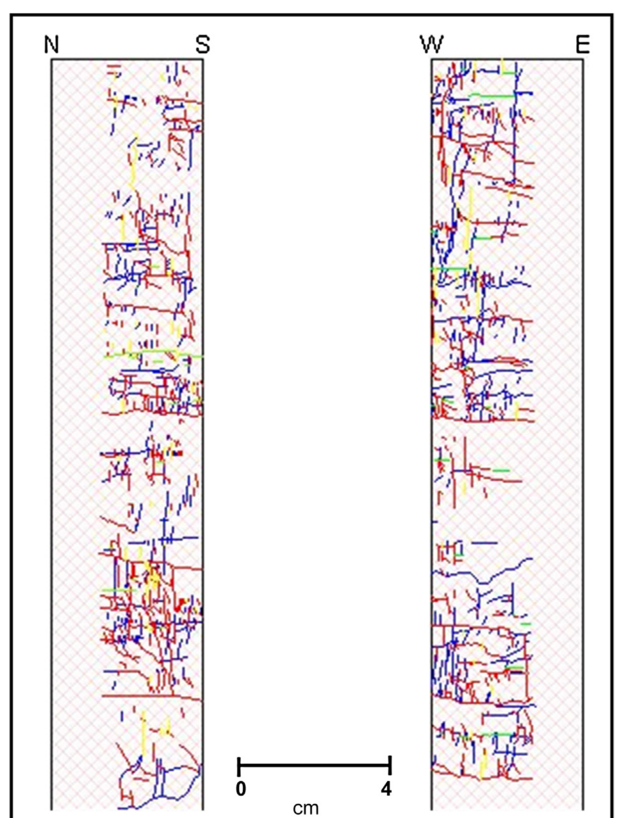

Fig. 3. Representation of the cleat plunging lineation.

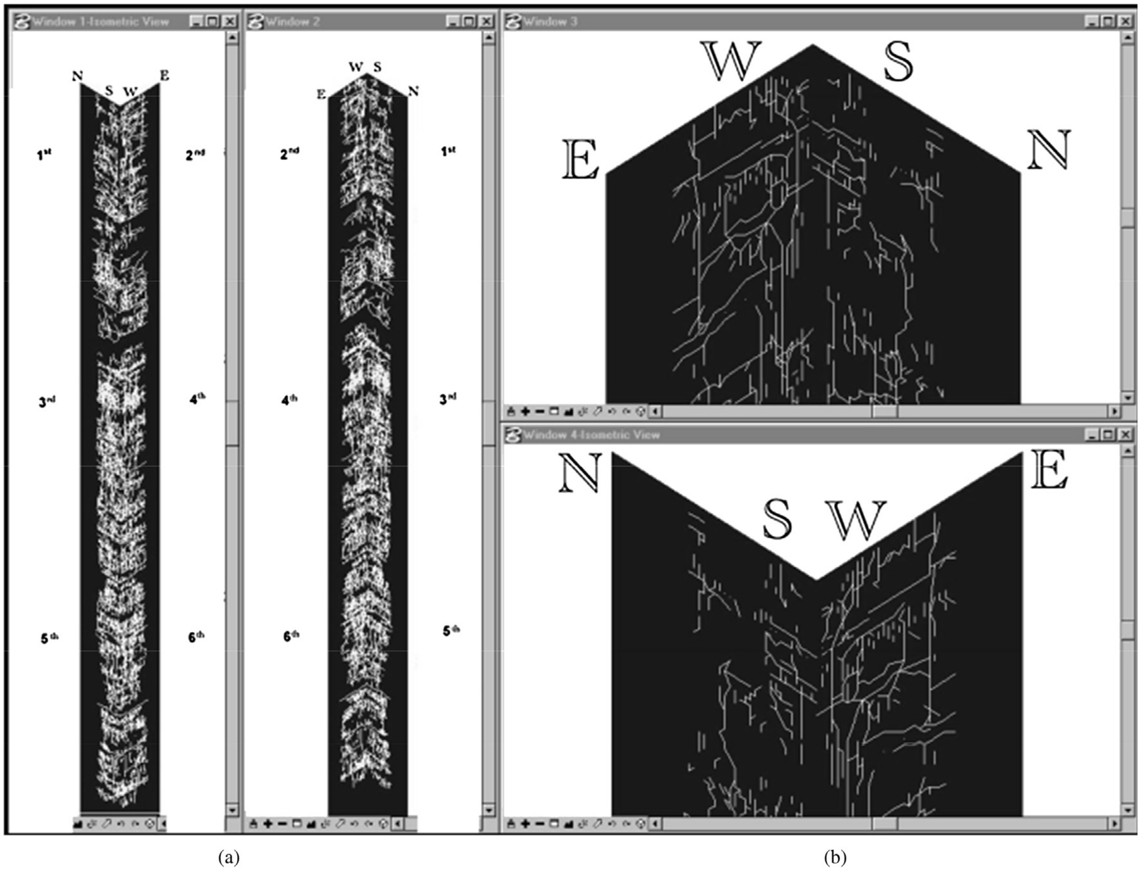

Fig. 4. (a) Cleat elements identified on the sample used in the example given and (b) detail of the image represented in Fig. 4a.

GIS was chosen for three different reasons: (i) A GIS project permits to link data sets by common location of the data, such as geographical position (e.g. detailed coalfield geographical location), which helps numerous different institutions to share their data. By creating a shared database, one institution can benefit from the work of another and that will also improve organizational integration. (ii) A GIS project is not just an automated decision-making system but a tool to query, analyze, and map data as a support in the decision-making process. GIS can then be used to decide where is the best location to exploit a new coal deposit—for coal mining or

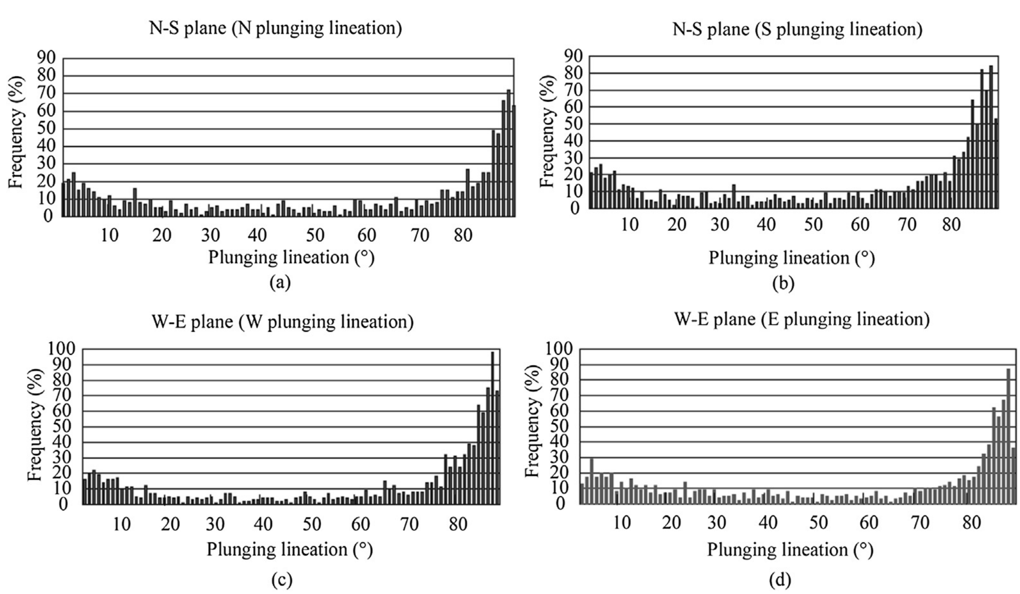

Fig. 5. Frequency of plunging lineation determined on different planes: (a) N–S plane (N plunging lineation); (b) N–S plane (S plunging lineation); (c) W–E plane (W plunging lineation); and (d) W–E plane (E plunging lineation).

Table 1
Data of the most frequent cleats on each plane.

Classes of cleat frequency (in decreasing order) (%)	N–S plane (N plunging lineation) (°)	N–S plane (S plunging lineation) (°)	W–E plane (W plunging lineation) (°)	W–E plane (E plunging lineation) (°)
7.7	88	88	88	88
6.5	89	86	87	87
6.1	87	87	89	85
5.1	85	84	85	86
4.2	86	89	86	84
3.1	80	85	83	89
2.7	83, 84, and 3	83	84	83
2.4	2	82	78 and 82	3
2.1	5	80	80	82
1.9	82	81	79 and 81	5 and 7

underground direct utilization such as in the case of CBM production—in order to minimize the potential environmental impact—if it is localized in a low risk area or if it is close to a population center—and to maximize the economic profit. The information can be presented concisely and clearly in the form of a map and an accompanying report, allowing the project manager to focus on the real issues, rather than trying to understand isolated data. Since GIS products can be quickly produced, multiple scenarios can be evaluated efficiently and effectively. That will allow the making of better decisions. (iii) GIS creates maps from the data collected from databases. Mapping with this method is much more flexible than by the traditional manual or automated cartography approaches. It is also possible to digitalize existing paper maps and to translate them into the GIS environment. The GIS cartographic database can be both continuous and scale free. Map products can then be created centered on any location, on any scale, and showing previously selected information, effectively symbolized to highlight specific characteristics.

The new methodology in the paper was developed as follows:

(1) The use of samples that correspond to non-damaged borehole core samples, in which it is possible to macroscopically observe the cleats. Cores are then cut into two orthogonal planes and the two surfaces are roughly polished to clearly identify the cleat characteristics. Prior to the cut, if the cores have the tendency to break in small pieces, a previous treatment with polymer resin as a binder becomes necessary. Samples with these characteristics will be considered as cleat representative samples of the basin, allowing statistical inference.
(2) The choice of the coal cleat characteristics indicated in the literature (Laubach et al., 1998) that are considered to be more directly related to gas production (cleat directions, measured as a reference, preferably an correctly orientated core during drilling or to measure the borehole direction in small intervals with accuracy; cleat frequency, taking into account different types of cleats; cleat height; cleat length; cleat spacing; number of cleat connectivity/intersections; and cleat aperture and number of cleats filled with minerals).
(3) The use of GIS combined with appropriate software, as a tool to quantitatively develop the following items: borehole geographical location; sample orientation; scanning of core samples; the adopted model; georeferentiation of core sample images, cleat digitalization and cleat characterization; statistical analyses from georeferentiatiated data; and connectivity frequency.

3.1. Borehole geographical location

The first stage comprises registering all pertinent local geological information, and collecting all relevant data, such as cartographic parameters, as well as the geographical coordinates of the system in use. It is absolutely indispensable to create specific databases since all data will be georeferentiated through local geographical coordinates.

3.2. Sample orientation

The second stage is the most difficult to be systematically investigated due to high costs and time-consuming procedures needed to obtain orientated samples during drilling. However, the sample orientation is considered to be an indispensable tool in CBM prospection, because it is the only way to have an accurate knowledge of sample cleat network in field, in terms of the coal basin stress field. In the absence of orientated data it is always possible, at least, to obtain the orientation of the borehole axis from the televiewer data.

In the example presented and for simplification, the core length plane as a reference plane was used, in which the orthogonal planes of the core drilled correspond to north–south (N–S) and west–east (W–E) planes, wherein all measurements were made (Fig. 1).

3.3. Core samples scanning

It is very difficult to obtain an acceptable optical image to be used for a visual interpretation, particularly in the case of the lack of contrasts in the examined surface, as it is always the case in coal. However, using a high-resolution scanner, with proper scanning parameter adjustments, it is possible to obtain reliable images in

Table 2
Cleat lines measured in N–S plane (N plunging lineation) and W–E plane (E plunging lineation).

Classes of cleat frequency (in decreasing order) (%)	Cleat lines measured in N–S plane (N plunging lineation) (°)	Cleat lines measured in W–E plane (E plunging lineation) (°)
7.7	88→0	88→90
6.5	89→0	87→90
6.1	87→0	85→90
5.1	85→0	86→90
4.2	86→0	84→90
3.1	80→0	89→90
2.7	3→0; 83→0; and 84→0	83→90
2.4	2→0	3→90
2.1	5→0	82→90
1.9	82→0	7→90 and 5→90

Table 3
Cleat lines measured in N–S plane (S plunging lineation) and W–E plane (W plunging lineation).

Classes of cleat frequency (in decreasing order) (%)	Cleat lines measured in N–S plane (S plunging lineation) (°)	Cleat lines measured in W–E plane (W plunging lineation) (°)
7.7	88→180	88→270
6.5	86→180	87→270
6.1	87→180	89→270
5.1	84→180	85→270
4.2	89→180	86→270
3.1	85→180	83→270
2.7	83→180	84→270
2.4	82→180	78→270 and 82→270
2.1	80→180	80→270
1.9	81→180	79→270 and 81→270

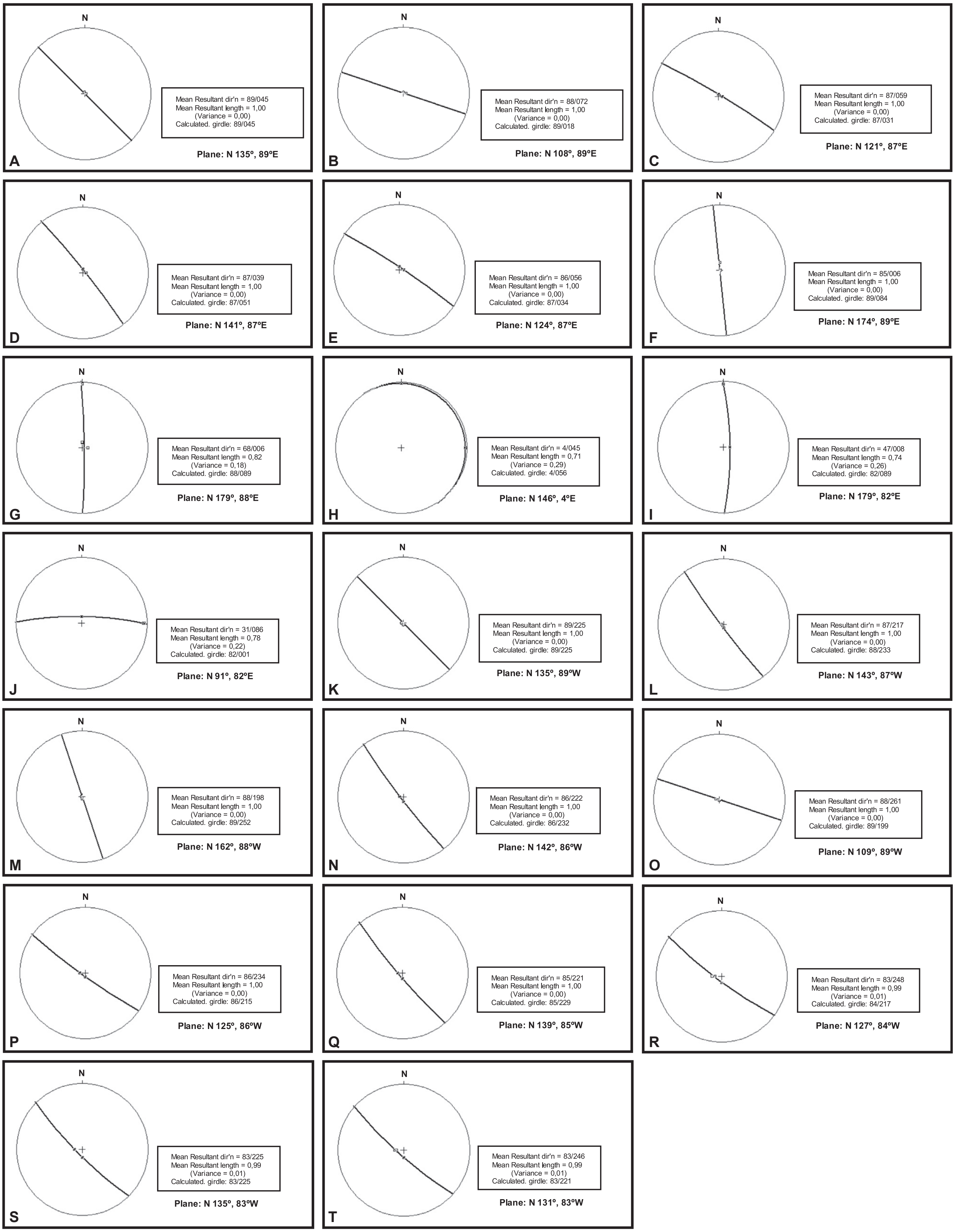

Fig. 6. Cleat frequencies determined from N–S plane (N plunging lineation) and W–E plane (E plunging lineation): letters A–J indicate cleat frequencies 1–10. Cleat frequencies determined from N–S plane (S plunging lineation) and W–E plane (W plunging lineation): letters K–T indicate cleat frequencies 1–10.

Table 4
Calculated planes by combining N–S plane (N plunging lineation) with W–E plane (E plunging lineation) and N–S plane (S plunging lineation) with W–E (W plunging lineation).

Classes of cleat frequency (in decreasing order) (%)	Cleat planes calculated from combining N–S (N) to W–E (E) planes	Cleat planes calculated from combining N–S (S) to W–E (W) planes
7.7	N135°, 89°E	N135°, 89°W
6.5	N108°, 89°E	N143°, 87°W
6.1	N121°, 87°E	N162°, 88°W
5.1	N141°, 87°E	N142°, 86°W
4.2	N124°, 87°E	N109°, 89°W
3.1	N174°, 89°E	N125°, 86°W
2.7	N179°, 88°E	N139°, 85°W
2.4	N146°, 4°E	N127°, 84°W
2.1	N179°, 82°E	N135°, 83°W
11.9	N91°, 82°E	N131°, 83°W

which discontinuities can be identified (Fig. 2). With a high quality image it is also possible, in "GIS environment", to improve the image, with specific parameters which allow to introduce changes in brightness and contrast, as well as the assembly of a negative image. Besides the already mentioned feature to create collections of databases, which will allow to georeferentiate data observed in the core sample, the high-resolution scanner also allows to improve the captured images.

3.4. The adopted model

The next step consists in creating a database comprising all measured and interpreted data, all related to sample images, such as the images themselves, the cleat digitalization, and some eventual complementary information. Due to the fact that when one is dealing with apparent measurements, it is indispensable to develop a new modified terminology to characterize the cleat system. Note that the main objective is to relate the cleat system to the gas circulation, the relevant information will be: the description of the plane where the data were collected; the azimuth of the cleat, expressed in the dip direction; the cleat direction; the cleat length; the cleat aperture (open or closed); the cleat filling (by secondary mineralization, as referred to by Faraj et al. (1996)); and any eventual additional information.

3.5. Georeferentiation of core sample images, cleat digitalization, and cleat characterization

The scanned images are georeferentiated in the GIS program, which directly allows cleat digitalization and cleat characterization of each interpreted line on the basis of the above described model. It is also pertinent to focus the attention on the adopted scale, since it could influence the digitalization process, as well as its interpretation. Since the average cleat length in the example presented in Fig. 2 is less than 1 mm, the best scale corresponds to enlarging the original image up to 10,000 times. Fig. 3 shows the cleats, which were digitalized in the selected sample taking into account the following direction of dip: light green lines correspond to the intersection of horizontal cleat—W–E plane; black lines correspond to intersection of vertical cleat—W–E plane; red lines correspond to W cleat plunging lineation—W–E plane; light blue lines correspond to E cleat plunging lineation—W–E plane; dark blue lines correspond to intersection of horizontal cleat—N–S plane; dark green lines correspond to intersection of vertical cleat—N–S plane; brown lines correspond to cleat N cleat plunging lineation—N–S plane; and purple lines correspond to S cleat plunging lineation—N–S plane.

3.6. Statistical analyses from georeferentiated data

This stage consists in converting georeferentiated data into the form of text and statistical parameters in order to allow a correct and suitable statistical interpretation as well as optimum stereographic projection. Data must then be processed by specific software able to produce reliable statistical results and to plot lines and planes determined in GIS. There are a different number of powerful commercial computerized applications available for that purpose.

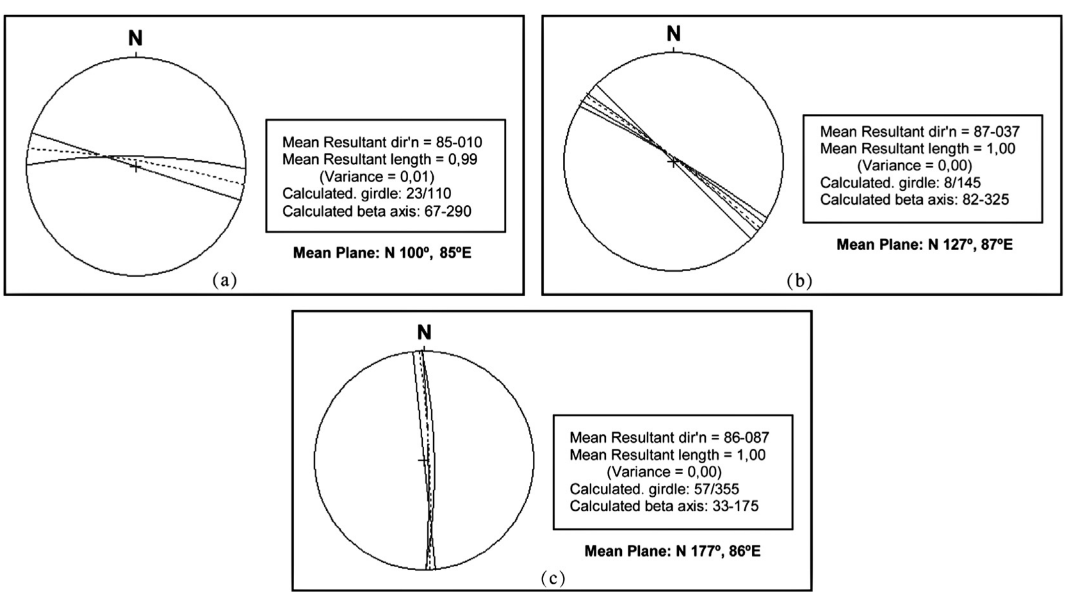

Fig. 7. (a) Mean plane (sketched line) determined for 90°–120° plunging lineation interval in N–S plane (N plunging lineation); (b) mean plane (sketched line) determined for 120°–150° plunging lineation interval in N–S plane (N plunging lineation); and (c) mean plane (sketched line) determined for 150°–180° plunging lineation interval in N–S plane (N plunging lineation).

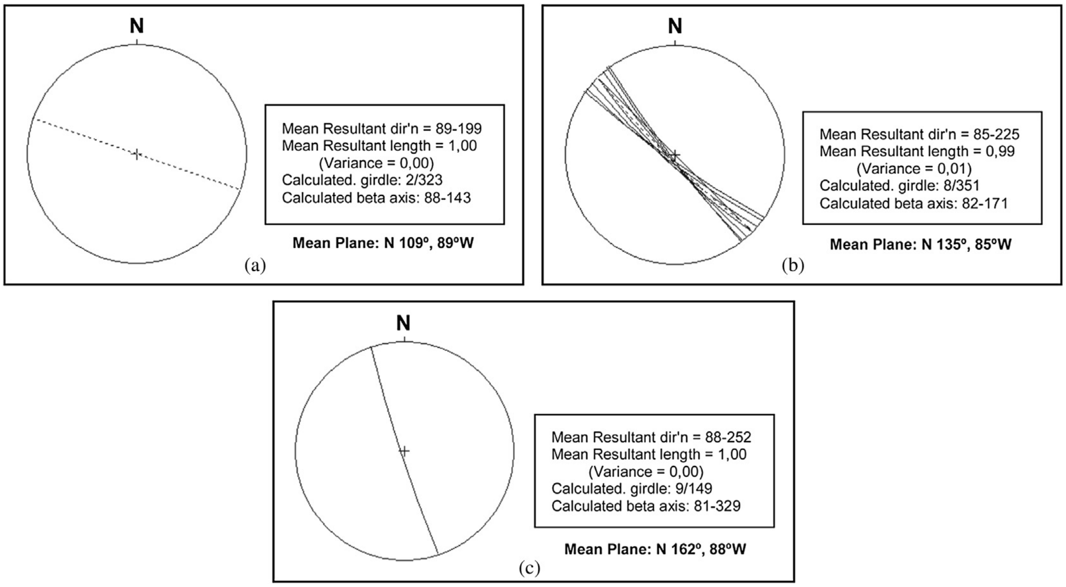

Fig. 8. (a) Mean plane (sketched line) determined for 90°–120° plunging lineation interval in N–S plane (S plunging lineation); (b) mean plane (sketched line) determined for 120°–150° plunging lineation interval in N–S plane (S plunging lineation); and (c) mean plane (sketched line) determined for 150°–180° plunging lineation interval in N–S plane (S plunging lineation).

3.7. Connectivity frequency

The connectivity frequency is one of the most important parameters to be taken into account due to its relevant role in gas circulation. Based on the digitalized values and statistical data, it is possible to establish a global connectivity frequency, which is determined by calculating the total cleat connection. In order to filter the huge set of data (e.g. 5072 cleats), three intervals of cleat plunging lineation were considered (i.e. 0°–30°, 30°–60°, and 60°–90°).

4. Results and discussion

The example given before to demonstrate the proposed methodology refers to a coal core of approximately 1 m in length that the authors collected. It belongs to a coalfield in the exploration stage.

After the implementation of all the above-mentioned steps, necessary for the application of the GIS, a total of 5072 elements were accounted in the present exercise. Fig. 4a represents a block-diagram of the 3D data obtained from the whole core, and Fig. 4b shows a detail of the image represented in Fig. 4a. It is possible to verify that some cleats can be followed from the N–S plane to the W–E plane, which is possibly due to the effects induced by the regional stress identified on the coalfield. Fig. 4 also allows concluding that all data obtained with the GIS analysis consist of lines, which will be combined afterwards and used to determine the primary stress planes presented in coal seams.

Table 5
Mean planes frequencies in N–S plane (N plunging lineation)/W–E plane (E plunging lineation) and N–S plane (S plunging lineation)/W–E plane (W plunging lineation).

Plane intersection	Plunging lineation interval (°)	Mean planes	Frequency (%)	
N–S (N)/ W–E (E)	90–120	N100°, 85°E	8.4 N–S (N)	10.1 W–E (E)
	120–150	N127°, 87°E	23.4 N–S (N)	22.6 W–E (E)
	150–180	N177°, 86°E	12.1 N–S (N)	8.6 W–E (E)
N–S (S)/ W–E (W)	90–120	N109°, 89°W	4.2 N–S (S)	5.2 W–E (W)
	120–150	N135°, 85°W	30.5 N–S (S)	40.2 W–E (W)
	150–180	N162°, 88°W	5.6 N–S (S)	6.5 W–E (W)

The statistical treatment and interpretation of data were carried out according to the following three sequential procedures:

(1) Initially, the two different planes were analyzed individually, in order to produce a suitable filtering of the large number of elements collected, as follows:
 (i) To calculate the frequencies of the cleat intersections in N–S and W–E planes, and the plunging lineation of each element was taken into account. Since the measured cleats have a large variety of lengths, the best option consisted in determining frequencies on the basis of cleat length standardization classes. As a result the following data were obtained:
  N–S plane:
  North plunging lineation = 37.6%
  South plunging lineation = 60.0%
  Intersection of vertical cleat = 2.2%
  Intersection of horizontal cleat = 0.2%
  W–E plane:
  West plunging lineation = 52.9%
  East plunging lineation = 45.0%
  Intersection of vertical cleat = 1.8%
  Intersection of horizontal cleat = 0.3%
 (ii) To determine, on both N–S and W–E planes, the cleat frequencies of each plunging lineation in each direction, histograms were drawn. As the vertical and horizontal cleats on both planes correspond to plunges of 90° and 0°, respectively, the statistical analysis has focused on the north and south plunges of lineations on N–S plane, and west and east plunging lineations on W–E plane. Histograms in Fig. 5 show that the plunges of lineation around 85° and 89° are the most frequent in both planes, followed by the ones around 3° and 5°. All the other measurements, although less frequent, can yet be relevant to defining the stress field.
 (iii) To point out the frequency of the cleat intersection in N–S and W–E planes, it is necessary to select at least 50% of the

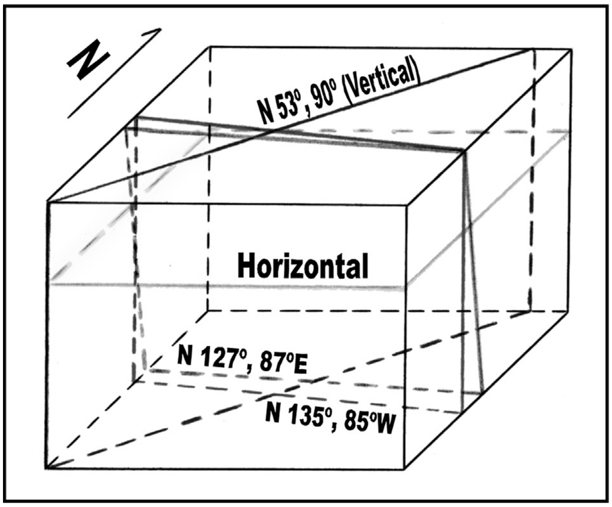

Fig. 9. Schematic representation of the four dominant planes determined in the present case study.

Table 6
Classes of plunging lineation defined on sample WTB 5/30.

Class designation	Plunging lineation interval (°)
Class 0	0
Class 1	>0 and ≤30
Class 2	>30 and ≤60
Class 3	>60 and <90
Class 4	90

measured cleats in order to obtain a statistical sampling representation. The frequency of cleat plunging lineation between 20° and 60° is too low and it will not produce a major effect on gas circulation stage. Table 1 presents the most frequent cleat plunging lineation, which conforms to the minimum of 50% mentioned above.

(2) The second stage consists of linking intersections of the two N–S and W–E planes on the basis of the structural theoretical fundaments, which consider that two lines collected from two different planes will allow the determination of the plane that goes through those lines. From Table 1 it is possible to conclude that any set of lines is capable of producing different planes, which implies the need to establish criteria to define which planes should be considered as the most important ones. The question was bypassed by applying statistical data presented in term from (1) above. In fact, these statistical results will allow to combine data from N–S plane (N plunging lineation) to data from W–E plane (E plunging lineation), which corresponds to plunging lineation planes with the lowest cleat frequency, and will also allow to combine data from N–S plane (S plunging lineation) to data from W–E plane (W plunging lineation), corresponding to plunging lineation planes with the highest cleat frequency. The results obtained from such combinations are presented in Tables 2 and 3.

In this second stage, further procedures are necessary and consist in:

(i) Projecting lines using stereographic projection.
In the example given, Fig. 6 presents the main planes for each cleat frequency as well as the basic statistical parameters obtained with stereographic projections.

(ii) Determining the most representative planes.
Structural principles allow dividing cleat plunging lineation data into intervals, since it is possible to consider the calculated cleat planes of the same family if plunging lineation changes between an acceptable variation degree. In fact, planes determined from cleat lines projection shown in Table 4 allow us to consider that the best option is to create intervals of 30°. Consequently, it is possible to calculate three different planes from N–S plane (N plunging lineation) combining with W–E plane (E plunging lineation), and from N–S (N plunging lineation) combining with W–E (W plunging lineation). Fig. 7 shows the three mean planes in N–S (N plunging lineation)/W–E plane (E plunging lineation) planes, calculated by combining planes corresponding to cleat frequencies 2 and 10 (Table 4 and Fig. 7a), planes corresponding to cleat frequencies 1, 3, 4, and 5 (Table 4 and Fig. 7b) and planes from cleat frequencies 6, 7, and 9 (Table 4 and Fig. 7c). Fig. 8 shows the three other mean planes in N–S plane (S plunging lineation)/W–E (W plunging lineation) planes, calculated by combining planes corresponding to cleat frequencies 1, 2, 4, 6, 7, 8, 9, and 10 (Table 4 and

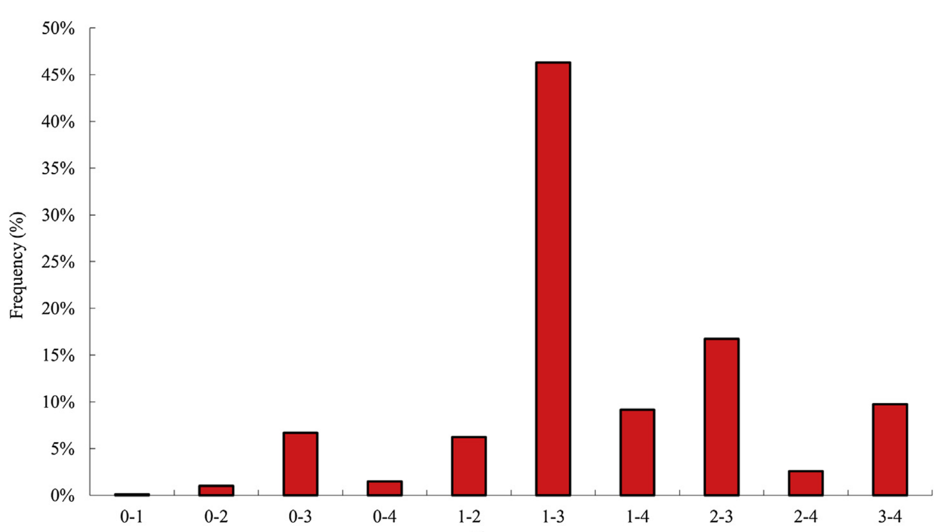

Fig. 10. Histogram of connectivity frequency from different classes of plunging lineation.

Fig. 8b). The two other mean planes correspond to planes that fall into the other specific interval conditions, i.e. the mean plane defined in 90°–120° plunging lineation interval is represented by the cleat frequency 5 (Table 4 and Fig. 8a), and the one defined in the 150°–180° plunging lineation interval is represented by cleat frequency 3 (Table 4 and Fig. 8c).

(iii) Selecting the dominant planes on the basis of cleat frequency criterion and on the data presented in item (ii) above.

Table 5 shows that in the first set of three planes interception, the most frequent plane corresponds to N127°, 87°E, and in the second set of three planes interception, the most frequent is N135°, 85°W.

Besides the two main planes mentioned above, it is obvious that vertical and horizontal planes should also be considered (item (i) from (1) above). In what concerns the vertical plane, and due to the highest frequency detected in N–S plane, it should be concluded that this plane strikes at 53°N.

The four dominant planes are represented in the solid model diagram presented in Fig. 9.

(3) In what concerns cleat connectivity in direct relation with gas release from the seam, the presented method considers a new parameter, the "global connectivity frequency, *Gcf*", calculated by the ratio between the total length of cleat intersection and the total length of cleat detected. In the present example a value of $Gcf = 85.77\%$ is obtained.

Finally, it is also important to study the interception between some specific cleat plunging lineation. Taking into account classes of plunging lineation of 30°, as well as vertical and horizontal cleats (see Table 6), it is possible to obtain important results. The ten possible combinations are presented in Fig. 10. The most frequent ones consist, in decreasing order, in interceptions between classes 1 and 3, followed by interceptions between classes 2 and 3, and between classes 3 and 4. This will allow to conclude that the cleat planes included in these classes of plunging lineation are the dominant ones in terms of gas release. In fact, this conclusion is also strongly supported by the high frequency determined for the planes N127°, 87°E and N135°, 85°W (see Table 2), also sustained by sub-horizontal to horizontal planes (item (i) from (1) above).

5. Conclusions

The present study allows concluding that whenever the parameters referred to above in (2) and (3) in Section 4 are defined, it is therefore possible to inject, in the right space orientation, pressurized fluids in order to open the coal cleat system, and directly drain the maximum amount of gas flow to CBM exploitation wells or even to inject CO_2, as it is the case of CO_2 geological sequestration projects. In the specific case study herein presented, the best direction to induce the fluid injection falls into the planes N127°, 87°E and N135°, 85°W, which is strongly supported by their high frequency. The present approach to best define the coal cleat system was developed as a contribution to the selection of the completion method for coalbed exploration wells in terms of design, and therefore cost estimates. Moreover, the method is applicable to the primary investigation steps of any potential CBM reservoir, i.e. prospecting and exploring phases, thus contributing to best estimate of its economic potentiality since the very beginning.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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