

A NEW CHARACTERIZATION METHOD FOR COAL BED METHANE

Dan BOSSIE-CODREANU¹, Karl-Heinz A.A. WOLF² & Rudy EPHRAIM²

1: Institut Français du Pétrole, 1-4 Avenue du Bois-Préau, BP 311 – 92506 Rueil-Malmaison Cedex, France
<Dan.Bossie-Codreanu@ifp.fr>

2: Delft University of Technology, Department of Applied earth Sciences, Dietz Laboratory, Mijnbouwstraat 120, 2628 RX Delft, the Netherlands. <k.h.a.a.wolf@ta.tudelft.nl>

(17 Figures, 2 Tables)

ABSTRACT. Coal bed methane reservoirs are hard to characterize due to their small scale heterogeneities which often vary from seam to seam. Based on recent developments in image analysis techniques and fracture generation software, we propose a methodology aiming at a better quantitative characterization of the macro-cleat system of coal, for better prediction of petro-physical properties.

The methodology is based on four main steps:

- Image analysis aiming at identifying to the best of the CT scan resolution, the macro-cleat system for large cores.
- A statistical analysis of the main features characterizing the network: orientation, length distribution, frequency, density, aperture distributions and average distance between fractures. Different families are then identified and their respective statistics recorded.
- Generation of realistic images at a large scale (10m*10m*10m), from the statistics of one core, using a dedicated software developed at IFP.
- Calculation of porosity and permeability values for up to 30 block of 1m*1m*1m, selected randomly from the large block.

The generation of such a petro-physical data-base allowing the development of K-PHI plots can improve log analysis performed in CBM fields leading to flow-unit identification, since permeability attributes are considered along with porosity. Problems encountered and use of those statistics for other purposes than characterization are discussed. Examples of applications and of the results leading to this characterization are shown, using coals from France.

Keywords : coal, fractal, fracture distribution, K vs. PHI expression, image analysis

1. Introduction

Characterization of coal is essential for the simulation of CH₄ production or CO₂ injection. Most characterization methods routinely performed use bulk measurements of reservoir properties such as porosity or permeability, performed on limited support volumes such as plugs or cores (mega scale). An important aspect is the representative nature of the cores used when results are extrapolated to the field. This question, certainly valid for coal fields, is a recurrent one when attempting to characterize hydrocarbon systems, requiring in principle an extensive sampling program. For coal, this would imply a coring program which explores most coal seams, and that in several wells. Furthermore, the practical problem of recovering long cores and plugs for petro-physical properties measurements can be time consuming (4 to 5 days for each plug permeability measurement) and thus costly. When looking at coal, the different scales pertinent to CH₄ production or CO₂ injection are the Darcy scale, the diffusion scale and the sorption scale (Fig. 1).

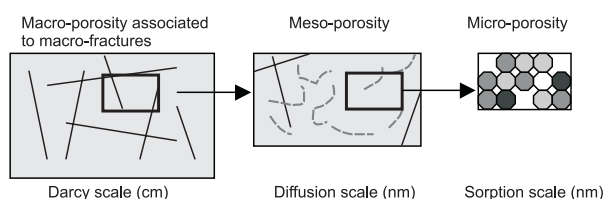


Figure 1. Different scales found in coal.

Analyzing these different scales are important for CBM and ECBM operations because diffusion and Darcy flow are phenomena which have to be accounted for simultaneously. Specialized numerical models (KING, 1985 and KING et al., 1986) consider a Darcy flow at the macro-scale while diffusion (Fick's law) at the meso and micro scale. This distinction between micro, meso and macro fracture is not so easy to distinguish. Nevertheless an analysis of the coal using CT (Computerized Tomography) thin-sections allows the recognition of at least two of the scales described above, namely the macro and

meso scale, of which the Darcy scale leads itself to quantification of porosity, permeability, anisotropy, macro-cleat orientations and estimation of the characteristic time of the de-sorption/adsorption term.

The basis of the approach is the assumption that the geometry of the cleat system (described statistically) at the small scale can be used to generate a realistic network of cleat features at a numerical size scale (ex. 10m to 50m), linking for instance the core scale and the log scale. Once that done, one can generate within this unitary volume a series of petrophysical values (typically K and PHI) using sub-volumes within this unitary volume, thus generating a $\ln K$ vs. PHI relationship, which is considered to be field representative. This implies that ideally, statistics of the macro-cleat are collected from several long cores at very distinct locations within the field, preferably far away from each other.

Formation evaluation has used image analysis techniques for quite some time (ex. Lattice-Boltzmann methods, CHEN & DOOLEN, 1998 or network models, FATT, 1956). Coal fracture characteristics (macro and meso cleat systems) leads particularly itself to this kind of analysis, since fracture features are relatively easy to recognize, given a high enough resolution. Classically, two methods have been used so-far for image reconstruction: process (OREN et al, 1998) and statistics (HAZLETT, 1997) oriented. In the first case, images are analyzed and grain diameter classes are determined. Sedimentation, compaction, quartz overgrowth and clay coating is then simulated and then properties measured. In the statistics based approach certain "object" statistics from 2D CT scans are recorded either by applying a filter or simply by eye inspection and then the reconstruction step allows a generated 3D medium which reproduces those statistics. Once generated, one can use them to assert for example the degree of continuity of the cleat system or for calculation of certain petrophysical properties at large scale. The key challenge for the statistical based methods is the selection of appropriate statistical properties or functions which can capture representative features of the porous media (ex. representative cleat distribution function). Research studies concerning fracture distributions in porous media have recognized either power, fractal distributions of fractures or sometimes exponential distributions (NUR, 1982, CARBOTTE & Mc DONALD., 1994, CRUDEN 1977). In this study calculation of the fractal number corresponding to the cleat distribution was analyzed from the 2D slices of the coal scanned (FRIESEN & MIKULA, 1995, RONG et al., 1998).

2. Methodology

The methodology used consisted of four distinct steps:

STEP 1: CT acquisition and visual recognition of fracture lineaments.

STEP 2: Characterize the "core"

This step consists of the quantification of the statistical geometry of the macro-cleat system:

*Length distribution

*Density distribution

*Frequency distribution

*Aperture distribution

*Average distance between cleat systems *Orientation of the different cleat classes.

This quantification is done in 3D, meaning the image analysis acquisition is taken in the three Cartesian planes, leading to three plane statistical characterization. This analysis concerns the macro-fracture system (closed or "mineralized" fractures along with open ones), due to the image resolution, which cannot discriminate between macro and micro scale. The quantification of both open and closed cleats is done because we consider that prior to mineralization, cleats were open, participating to the overall network, and thus important within the geometrical characterization method used. In petrophysical terms "mineralization" is only a "corrective" term of porosity or permeability, since it affects fully or partially the aperture of the fracture. The two approaches leading to this quantification are: *hand and eye quantification and *image reconstruction. Along with the image reconstruction, an analysis of cleat orientation, based on cutting analysis is also done. This work was performed at Delft University. Details of the method is shown in an application example provided below.

STEP 3: Fracture geometry generation

From the statistics above one generates a given number of fractures (given by the recorded frequency at a small scale) within a large volume (ex. a cell of 10m lattice) which we will call Unitary Cell, using the length distribution obtained above. The software used for this purpose is FRACA™ (BOURBIAUX et al. 1998), developed at IFP, allowing the generation of fractal distributions, power distributions and log-normal distributions of fractures. The procedure is to first generate (place) all fractures or a set of fractures in a given volume according to a distribution and an orientation and then assign to that set an aperture (from the above statistics). During the fracture generation step, all fractures (open and closed) are considered when determining which distribution function to use. Nevertheless, closed fractures are considered as one family, as are the open ones. To both the same distribution function is applied and then during the aperture assignment the open ones are assigned a random draw from a maximum to a minimum aperture distribution. Apertures are not considered as correlated.

STEP 4: Porosity- Permeability calculation

During this step one can, either on the entire volume of generated fractures, or only on part of it, calculate porosity and permeability. By choosing within the Unitary Cell several volumes on which porosity and permeability

are calculated, a relationship $\ln K$ vs. PHI can thus be obtained. The entire procedure is summarized in Fig. 2. Detailed procedure:

- a) Scan the coal and geologically interpret it.
- b) Orient the coal pictures issued from the scanning procedure along the bedding plane.
- c) Select several slices in several directions out of which statistics will be compiled.
- d) Proceed to an interpretation stage, done manually, of the cleat system (the entire cleat system; open and closed cleats alike).
- e) Based on this interpretation, proceed to the fractal number determination by slice (2D fractal number). This, in our case is performed using a freeware (called HARFA)
- f) From all slices determine the 3D fractal number.
- g) Count the number of fractures per slice (all fracture features; closed and open alike)
- h) Determine the cumulative fracture length per slice.
- i) Count the individual length calculation of each fracture.
- j) Determine the cleat orientation. This step consists also of studying cleat orientations using cuttings (see below).
- k) Calculate the aperture distribution.
- l) Determine the average spacing between cleats.
- m) Perform image re-construction using the AMIRA™ software (reconstruction from cleat characterization performed on individual images (EPHRAIM et al., 2002).
- n) Perform FRACA fracture generation simulations along with permeability and porosity calculations.

As stated above in Step m, an image reconstruction was performed using cleat interpretation from scanned data in 3 different planes – X/Y, Y/Z and X/Z, leading to a 3D image (see Fig. 11). This was performed in order to compare cleat orientations from this type of reconstruction and a cutting analysis leading also to a cleat orientation distribution. Theoretical and practical reasons for such analysis are given in the Discussion section.

The “cuttings” or particle methodology is described here-below.

3. Angles obtained using cuttings

A representative “cutting” sample of about 2000 particles, ranging in size from 0.2 - 2 cm were scanned using a Leica Qwin image Analysis system. Multiple-particle images of randomly orientated coal particles were scanned and split up into single-particle images. Large and small particles were then separated and treated at two different magnifications. For each particle, the area, perimeter, particle face angles, length and width were measured. Then each single particle was analyzed in terms of its outline, which consists of line segments. The outline is then rotated, using 5° steps, and measured on segment lengths and

orientations. During rotation, parts of the outline which cross an overlying horizontal grid are measured. This information, forming the basis for the definition of cleat angles and widths, is first sorted, per angle and then related to the cumulative cleat length. Thereafter, for each particle, the five maximum length/angle values give four cleat angles. The results of all particles are summed and gathered in an unbiased histogram. A geometrical filter, which compares geometrical characteristics emphasizes the relation between particle shape and its cleat angles. Based on regular cleat systems, the filter has two main parameters:

- Low angularity bias. All particles with minimum area/perimeter ratios (spherical grains) are disregarded.
- Quadrangle definition. The grains usually are square or rhomboidal shaped, so parallelograms at various angles are defined so as to fit to the existing shapes. Angles ranging from 30° to 90° are used to define area/perimeter ratios or geometrical factors. Since we know the angles, the other shapes can be disregarded.

The geometrical filter is used to find the relation between the cleat angle and the shape (parallelogram) of the coal particle. All grains are measured and plotted in distribution graphs of the cleat angles of the coal particles that fall within a certain range of geometrical filter. For each parallelogram angle the optimum cleat angle is determined by its frequency distribution. The method is extensively described in EPHRAIM et al., 2002.

4. Defining cleat angles by using CT scans

From solid samples of three French coal types (No. 495), CT scans were provided in RAW and JPEG format, in 256 gray levels images. Based on density differences, open cleats represent the lowest gray level values (0) and mineral matter the highest, (up to 255). The number of slices (z stacks), 1 mm apart, varied per sample from 330 to 50. The 3D visualization and modeling software AMIRA reconstructed images from the XY-direction information, in the XZ- and YZ-direction. From all images open and mineral filled cleats have been detected in Qwin. Based on the picture quality (resolution, poor gray level segmentation, interfering distortions) manual editing is used to enhance the resultant binary images. After noise reduction, four binary images were produced - the envelope, open cleats, chemical minerals and original sedimentary minerals. These binary images are then analyzed in Qwin; cleats being reduced to lines (skeletonizing), cut on their intersections and measured on their lengths and orientations. Open cleats and mineral filled cleats are processed separately and then combined, making possible a distinction between open cleats, mineral filled cleats and mineralized layers (bedding). The data has been processed in a spread-sheet in the same way as the cutting data, however, without using the geometrical filter. As an additional approach all cleat lengths with the

same orientation were cumulated and the accumulated lengths plotted against the cleat angles. This method is described in EPHRAIM et al., 2002.

5. Examples of the methodology

An example of the procedure described above was performed using a French coal sample from the Lorraine basin (Sample 495). The following illustration is extracted from work performed in the ICBM European project. The same is used in the RECOPOL European Project (pilot project of a CO2/ECBM operation in the Silesian basin), thus allowing a field application of this new approach.

Fig. 2 shows an example of the scanned images available along with the hand interpretation of the lineaments (open and closed macro-cleats) and fractal number interpretation (Fig. 3). As stated above only the Darcy scale was our concern in this work.

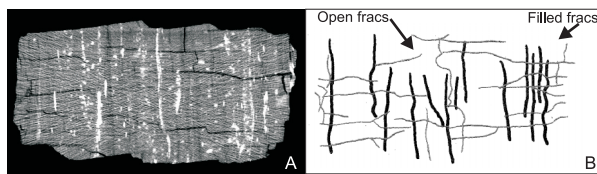


Figure 2. CT slice (A) and cleat interpretation (B).

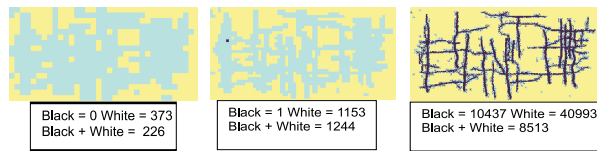


Figure 3. Fractal number determination for each slice.

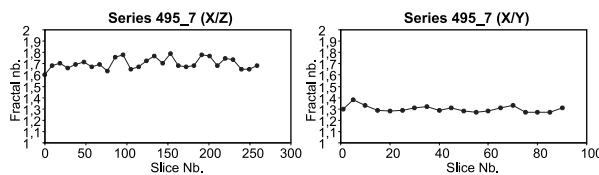


Figure 4. Fractal number variation in two directions.

From the above cleat interpretation (obviously ambiguous since done by eye inspection, thus “pessimistic” or “optimistic” depending on the interpreter but cancelling out to an “average” since many slices are considered) one can determine the fractal number corresponding to the entire fracture system. The first step is to fill the entire picture with boxes; completely black if within the fracture, completely white outside the fracture and part black and part white at the border between those two domains, using three mesh resolutions: 50, 10 and 2.

The determination of the fractal number is that of the black and white box -counting. Thus one can write :

$$N_{BW}(r) = D_{BW} \left(\frac{1}{r} \right) + K_{BW}$$

In this equation r is the resolution and D is the slope when plotting on log-log paper N boxes found (black and white). Results of the fractal dimension for selected slices, in two directions: A - the X/Y plane going in the Z direction and B – the X/Z plane going in the Y direction.

Results show a variation of the fractal number. For A the average fractal number is 1.4 whereas for B it is 1.7. Along with the fractal numbers several statistics of the cleat were also collected. These are density, frequency, length distribution, aperture distribution and average distance between fractures (Fig. 5, 6, 7, 8, 9). The figures below show results for the A case.

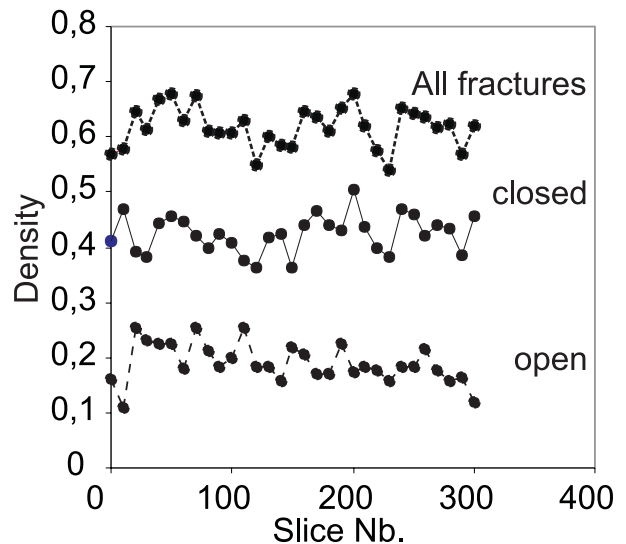


Figure 5. Density = cumulative length / area.

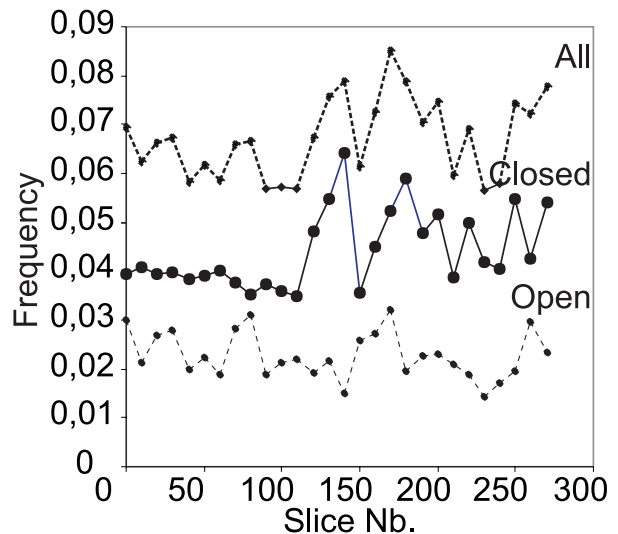


Figure 6. Frequency = Number of fractures / area.

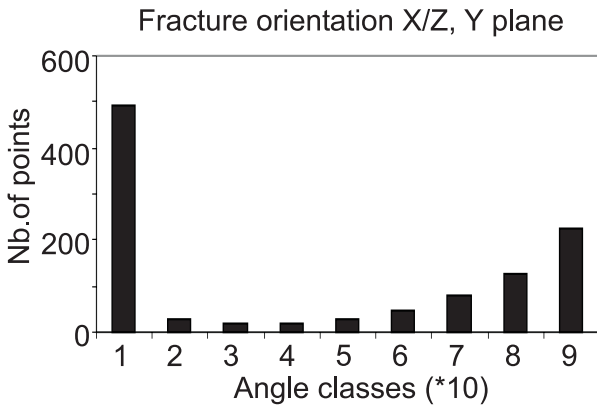


Figure 7. Cleat orientations (arranged according to tenths of degrees classes).

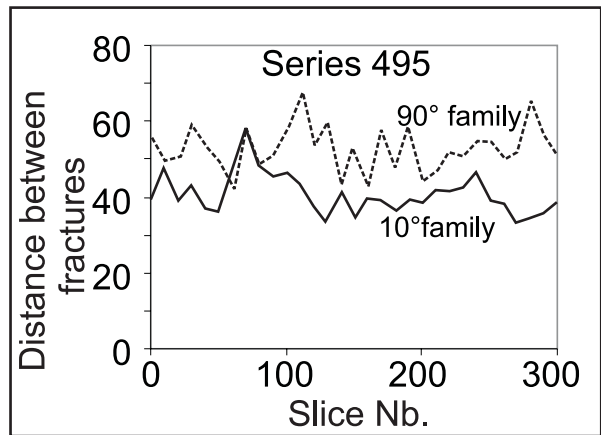


Figure 10. Average distance between fractures (in mm).

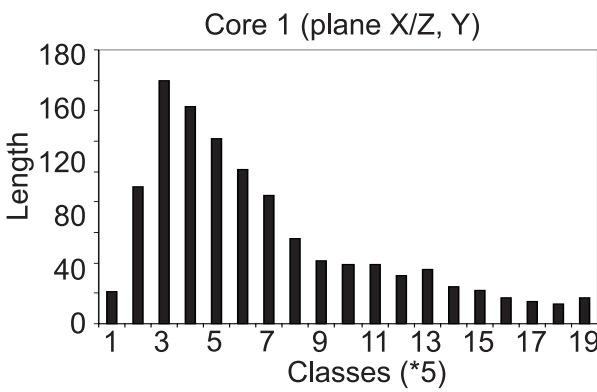


Figure 8. Length orientation (arranged by classes of 5 fractures).

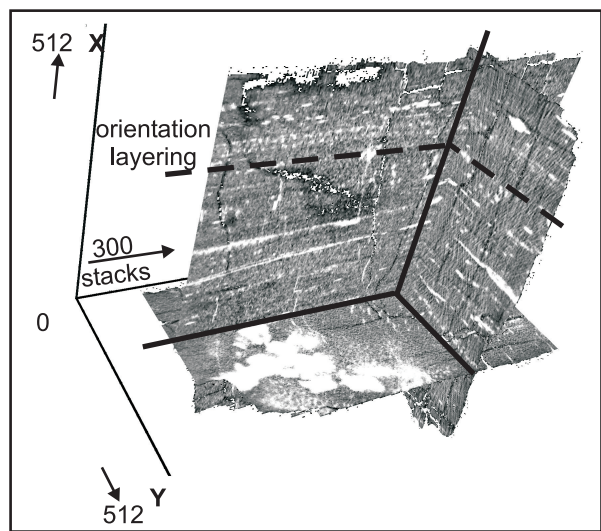


Figure 11. Image reconstruction.

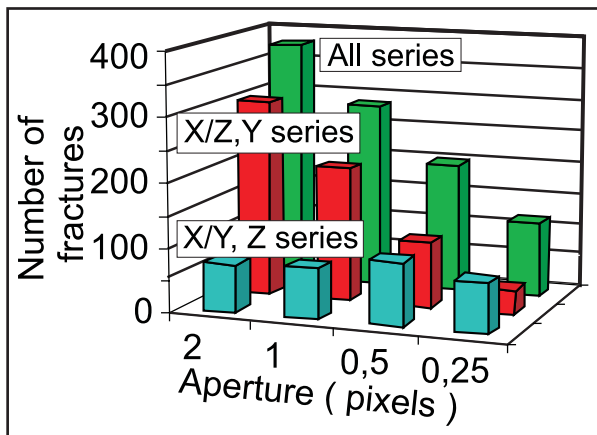


Figure 9. Aperture distributions.

The main question to be asked is the one concerning the sampling. Have we sampled entirely the objects so as to be able to accomplish a full restitution of the statistical picture? An element toward the answering of this question is provided by the reconstruction of the sample from interpreted CT images. (Fig. 11). Delft university provided an angle distribution issued from the CT reconstruction as well as a “cutting” analysis (Fig. 12, 13).

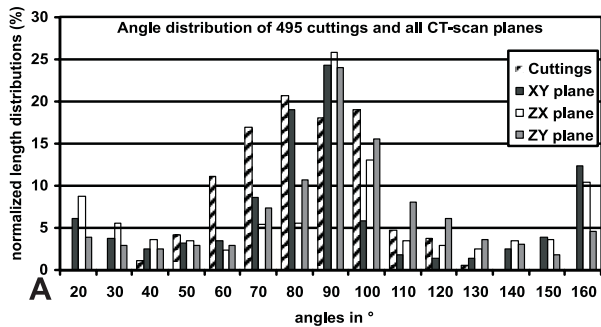


Figure 12. Angle vs. normalized cleat length distribution.

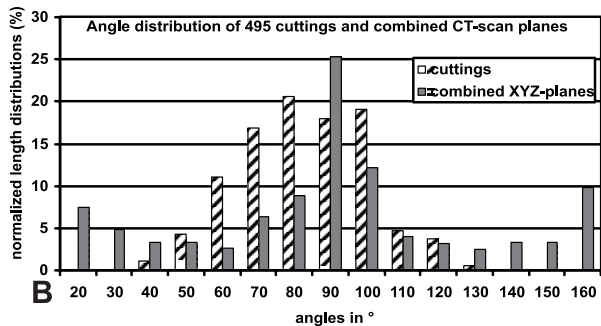


Figure 13. Angles vs. summed cleat length.

As seen in these figures the angle distribution issued from the CT image reconstruction and the “cuttings” are not equivalent. The “cuttings” method indicates a larger number of angles which implies that we have not sampled all cleats, but only part of them. This issue is even more apparent when inspecting the length distribution (Fig.14).

Region I and III show under-sampling effects, in region I due to resolution problems (some small length cleats at the macro or meso scale are underestimated by the CT) and by the sampling of the coal in region III (the vertical truncation of lengthy cleats due to the coring.). The cuttings method, complementary to the tracing method could improve length distribution estimation, which is an important parameter for simulation purposes (FRACA simulation), since it helps in deciding if CT-scans sampling is adequate enough. In our case the answer is positive.

Once all statistics acquired, the next step was to generate a 3D block using the FRACA software. Two types of distributions were used: log-normal and fractal distributions. As we will see, application of this type of simulation is greatly influenced by the distribution used. Properties used are shown in Table 1 & 2

The approach used in FRACA implies to:

- generate a fracture distribution at a large scale using some distribution (fractal, power, or log-normal) in several directions (using a fractal dimension in a direction and another one in the other direction).
- from a frequency, to determine the total number of fractures to be generated.
- define one or several fracture families of different apertures and orientations of the different families.

Log-Normal Distribution (2 families)

-Minimum length	0.02 m
-Maximum length	0.5 m
-Standard deviation	1
-Fisher coefficient	100
-Average spacing	0.08 m
-Directions :	10 and 90 degrees

Fractal Distribution (2 fracture families)

	Family 1	Family 2
Mean length	0.3 m	0.3 m
Min. length	0.1 m	0.1 m
Max. length	1 m	1 m
Fractal Nb.	1.7	1.4
Orientation	90	10
Nb. of fractures	20000	15000
Std. Dev.	1	1
Av. Width	0.0015	0.0015

- define a probability of vertical crossing (in our case it is 1.0) and place the minimum and maximum fracture length. The vertical crossing (or Z crossing) probability is that probability a fracture has to have to cross two layers in the Z direction.

The result of the statistics (log-normal and fractal) are shown here-below, for a block of 10m*10m*10m (Fig. 15 and 16).

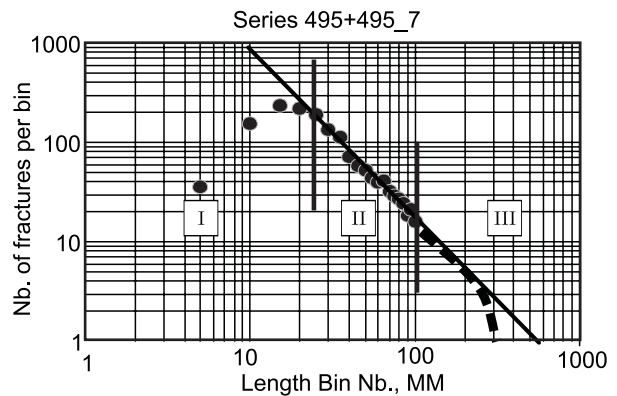


Figure 14. Length distribution.

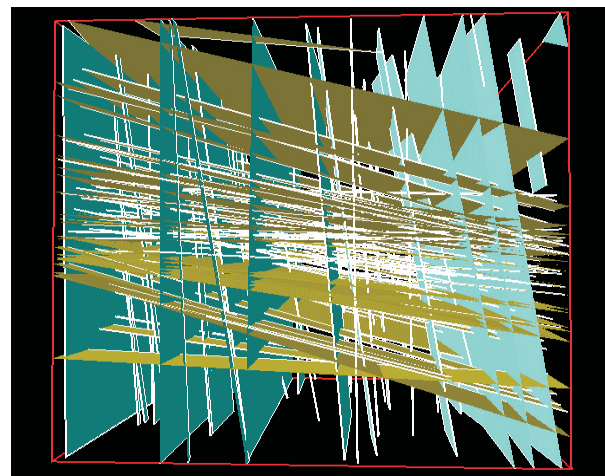


Figure 15. Log-normal fracture distribution.

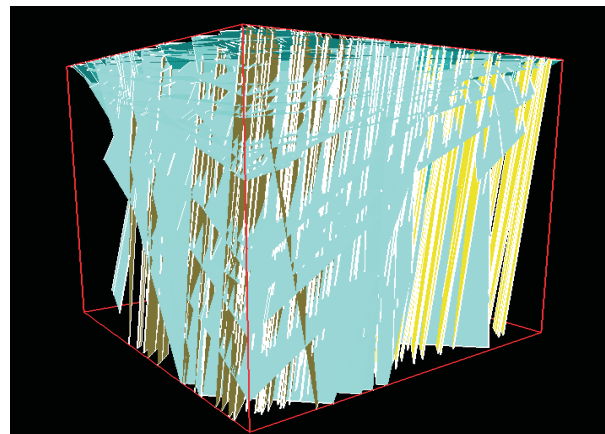


Figure 16. Fractal distribution.

Fractal simulation starts from a “generator picture” and then, given the frequency (number of fractures per unit area) places around this geometrical figure a number of fractures corresponding to the frequency multiplied by the area investigated. The geometrical figure (the generator) from which the number of fractures is generated is that of two fractures, of maximum length, as estimated from the length distribution plot (Fig. 14) and oriented in the major directions as given by orientation analysis. This explains why the orientation analysis done from CT and cuttings is important. The placement of the fractures is done in such a way as to verify a given fractal number measured by the box-counting method. During this box-counting procedure, at each placement step of a new fracture (of equal or lesser length) a fractal number. is re-calculated, and then compared to the original one imposed. The algorithm proceeds in the following manner :

- The fractal number, calculated from the box-counting method is calculated with a certain tolerance. The original fractal number given was 1.7 and 1.4 (as measured).
- The total number of fractures are placed in such a way as to verify the above condition.
- Permeability is then calculated by solving Darcy’s equation over a sub-volume chosen by the user. Given the original block size of 10 m by 10m by 10m thickness, we generated 30 values of K (K_x , K_y and $(K_x * K_y)^{0.5}$), using blocks of 1m*1m*1m.

The method of calculation of the equivalent permeability is:

- The network is discretized as nodes.
- Mass-balance equations are written for all nodes.
- In each direction, boundary conditions are set, and the resulting linear system is solved.
- The flow rates across block faces are computed and the equivalent permeability is calculated.

Boundary conditions used are the no-flow lateral conditions (horizontal or vertical). Flow rates across block faces are computed according to:

$$Q = \sum_{i=1}^N \frac{T_{iBi}}{\mu} (P_i - P_{bi})$$

and

$$K_{xx} = \frac{Q_{x1} + Q_{x2}}{2 * (P1 - P2)} \left(\frac{\mu}{L_y} \frac{L_x}{L_z} \right)$$

where Q= Flow-rate across a face F

N = number of nodes directly connected to face F

Pi = pressure at node I

Pbi = pressure at the contact point B to face F

TiBi = transmissivity between node I and the associated contact point

μ = viscosity of the fluid (1cp; this being an hypothesis)

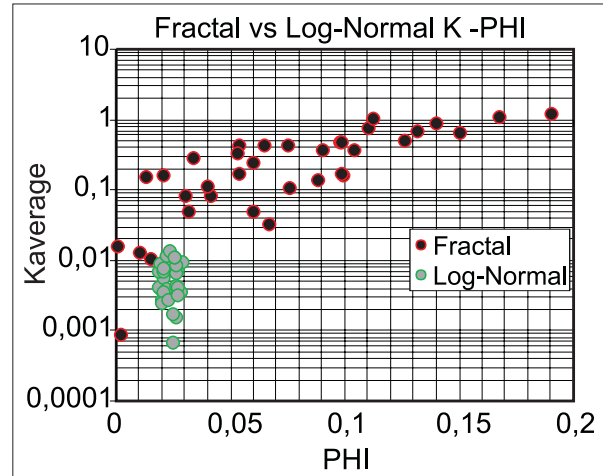


Figure 17. LnK vs. PHI.

The terms of the permeability tensor are determined from the flow rates, Q leading to values in X, given by K_{xx} . Thus the flow rate in a given direction is the mean of the two rates computed across the opposite faces in the considered direction. With the option of no flow lateral boundary conditions, the computed rates across the faces perpendicular to flow are equal ($Q_{x1}=Q_{x2}$) and the lateral rates are equal to zero ($Q_{y3}=Q_{y4}=0$). Results of these calculations performed on blocks of 1m³ are shown in Fig. 17, for the two distributions mentioned above, log-normal and fractal.

As shown from Fig.17, the log-normal approach has the tendency to cluster data around the mean for the log-normal distribution whereas the fractal distribution shows a higher variability.

6. Discussion

The end-result of the whole approach (the lnK vs. PHI calculation) implies that a fractal description of the macro cleat system leads to a realistic picture of the permeability behavior vs. porosity, thus allowing via classical logs a vertical permeability generation. By realistic we mean that the lnK vs. PHI relationship is similar to those obtained by measurements using plugs, familiar to petrophysicists and commonly found by direct measurements of permeability and porosity on plugs from cores. These types of lnK vs PHI plots are commonly found in the petroleum literature.

The fractal numbers found are in line with work performed by FRIESEN & MIKULA, who applied fractal analysis to coal. The model they used was the Merger Sponge model. For the larger pores their results indicate fractal numbers varying from 1.93 to 1.54. Similar work performed by RONG et al. on a greater number of cores found similar results, from 1.28 to 1.4 for pores of $r > 55nm$ in one sample series A, 1.4 to 1.65 for pores of $r > 150nm$ in a second sample series B, and finally 1,26 to

1.4 for pores of $r > 122\text{nm}$ in a final sample series C. All of these correspond to macro pore sizes. An interesting relationship to explore would be a possible correlation between fractal number and rank, since we expect rank to give different pore size distributions.

As seen above, the length distribution implying a power-law distribution is not contradictory with the fractal description. An important issue is raised by the question of cleat orientations, which was disclosed by the “particle or cutting” technique presented above, which implies that more than two cleat families might have to be considered, when generating the main 3D block.

The method described used two main orientations as the fractal generator – from the lower resolution calculation using CT scans – certainly can introduce an error in the permeability calculation, due to the lack of resolution induced by the CT itself. Nevertheless, this author still thinks that results as presented, are satisfactory in the sense that the error introduced by the CT resolution are minimal and certainly valid for engineering purposes. The cuttings method, more accurate, distinguishes several orientation classes, thus more accurate. Yet, this added complexity is not easy to handle in any simulation of a fractal geometric figure and the added accuracy of the permeability and porosity values would be offset anyhow by an up-scaling procedure, mandatory for any “reservoir” simulation. This up-scaling step, not treated in the present work, is without a doubt a mandatory work, given the scales investigated in coal. The present procedure, while integrating the up-scaling within the procedure itself (properties are calculated over volumes of 1m or even 10m) is not entirely “practical”, since simulation cells are commonly tens of m.

Rigorously speaking, more work is needed in order to standardize and improve the scale resolution results using this procedure of the procedure. Nevertheless, one would also have to wonder if this improvement would have any impact at the simulation stage.

The number of cleats analyzed were 976 in one direction and 617 in the other, which makes our statistics representative.

The surprisingly realistic relationship $\ln K$ vs. PHI obtained is due to the non-stationarity nature of the distribution obtained when generating cleats from fractal dimensions. By opposition, the log-normal distribution gives only a clustered $\ln K$ vs. PHI relationship (due to the stationary nature of the resulting cleat distribution). The spatial non-stationarity allows us to sample within the domain regions of varying cleat densities, which mimic the variance encountered in reality. One problem when using the K-PHI relationship is the fact that results are generated from un-stressed coal. We do not think this to be a problem if a relationship between stress, PHI and K is obtained. The use of the K-PHI relationship as determined above can still be useful if a correction is performed. This can lead to further research in terms of stress effects on cleat aperture families, in order to assess

the in-situ conditions impact on the overall $\ln K$ vs. PHI relationship.

As stated before, the methodology used above could be improved by merging several statistical measurements from different cores, improving the representative value of the **Unitary Cell** volume obtained. Similarly, we expect similar results to be obtained using network models based on percolation theory.

One added value of recording statistics above concerns the kinetics of diffusion, which is dependent on the diffusion coefficient, the cleat spacing and the gas concentration gradient. If one measures the diffusion coefficient, an estimation of the diffusion kinetics can be easily done using the ratio of the cleat spacing squared, divided by the effective diffusion coefficient (λ^2 / D^*). Of course the D^* coefficient is related to the coal micro and meso porosity, although the meso scale probably covers both the Darcy and the Fick domain. An example of such an application is given for a Polish coal ($D^* = \text{diffusion} \cdot \text{porosity} \cdot \text{tortuosity}$, λ being the half-length between fractures). The half-lengths for these samples are 3,27cm and 4.6cm, giving characteristic times of diffusion ranging from 2.44days to 24.50 days considering a D^* of either $5E-09$ or $1E-09\text{m}^2/\text{s}$.

Along with potential application to log analysis (the sonic log being sensitive to the macro-cleat density) the half-length values between fractures can provide insight on either CBM or ECBM operations such as CO_2 injection.

The procedure used above, developed in the ICBM and RECOPOP project still needs to be improved. Standardized procedures should be developed so as to be able to feed integrating simulators such as network models or FRACA type models with pertinent data. At the same time coupling stress relationships along with K-PHI relationships should be developed.

7. Conclusions

The work performed leads us to the following conclusions:

- Statistics collected from CT image analysis allows at the same time to estimate: the degree of continuity of the permeability in the coal, the degree of mineral content present in the coal and thus its impact on permeability estimation.
- Quantification of the permeability along with the development of a $\ln K$ -PHI relationship improves characterization by providing petrophysical properties at the log scale, thus making possible the generation of a K profile in a well if porosity is known.
- The fractal formalism used seems adequate and representative of coal cleat characteristics, in line with other studies. The non-stationarity implied by the fractal distribution is an important feature of the entire procedure, which allows the generation of a $\ln K$ vs.

PHI representative of such relationships observed in hydrocarbon reservoir studies.

- The CT scan resolution, although not being able to capture the entire “picture” concerning the macro and meso scale, appears to be satisfying towards the purpose of this work, namely the generation of a realistic $\ln K$ vs. PHI relationship.
- The procedure described allows an intermediate up-scaling (calculations being done at the 1m and 10m scale) between the very fine scale inherent to coal and the numerical scale (10’s of m) used for simulation purposes.
- Information concerning the kinetics of diffusion is also available from image analysis, which is an important information for ECBM operations.
- The challenge for the future is to find a standardized sequence of image analysis procedures in order to render the above an easier procedure which could be used in the industry. Tools and procedures are currently under development, which could lead to a software especially dedicated to CBM characterization.

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