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Natural fracture systems in CBM reservoirs of the Lorraine-Saar coal Basin from stand-point of X-ray computer tomography

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Abstract: The Lorraine-Saar Basin is one of the largest geologically and commercially important Paleozoic coal-bearing basins in Western Europe, which has considerable coal reserves in numerous coal beds. The Basin stands out by its up to 6 km sedimentary column and its inversion resulting in Paleozoic low-amplitude erosion in the range of 750 m (French part of the Basin) and pre-Mesozoic (Permian) erosion between 1800 and 3000 m (the Saar coalfield or German part of the Basin). Thermal maturation of organic matter in sedimentary clastic rocks and coal seams has led to the formation of prolific coalbed methane (CBM) plays in many domains throughout the Carboniferous Westphalian and Stephanian sequences. Coal mines here are no longer operated to produce coal; however, methane generated in "dry gas window" compartments at a depth exceeding 3.5 km has escaped here via several major faults and fracture corridors forming "sweet spots " sites. Faults, a dense network of tectonic fractures together with post-mining subsidence effects also increased the permeability of a coal-bearing massive and provided pathways for the breathing of environmentally hazardous mine gases. Nearly all CBM plays can be classified as naturally fractured reservoirs. The Lorraine-Saar Basin is not excluded indeed because of the experience of geological surveys during extensive coal-mining in the past. The knowledge of geometrical features of fracture patterns is a crucial parameter for determining the absolute permeability of a resource play, its kinematics environment, and further reservoir simulation. The main focus of this contribution is to get an insight into the style and structural trends of natural cleat patterns in the Basin based on the results of X-ray computer tomography (CT) to ensure technical decisions for efficient exploration of CBM reservoirs. To explore the architecture of solid coal samples we used X-ray CT of coal specimen collected from the Westphalian D coal from exploratory well Tritteling 1. The studied coal specimen and its subvolumes were inspected in 3 series of experiments. At different levels of CT resolutions, we identified two quasi-orthogonal cleat systems including a smooth-sided face cleat of tensile origin and a curvilinear shearing butt cleat. The inferred cleat patterns possess features of self-similarity and align with directional stresses. Results of the treatment of obtained cleat patterns in terms of their connectivity relationship allowed distinguishing the presence within studied samples interconnected cleat arrays potentially facilitating success in CBM extraction projects.

Keywords: Lorraine coal Basin, coal-bed methane, X-ray computed tomography, cleat systems, kinematic fracture type, tectonic stress field

1. Introduction

The Lorraine-Saar Basin is one of the major coalfields of Central Europe which has been shaped for two centuries as a heartland of underground coal mining and associated industrial activities in the transfrontier area of France and Germany. The Basin has considerable coal reserves accumulated in numerous laterally continuous coal seams with a variable thickness (from a few centimeters to four or five meters, unusually fifteen meters, or more for the thickest) affected by processes of thermogenic production of gaseous hydrocarbons during post-Carboniferous burial and related coalification.

Historically, coal production in the Lorraine and Saar portions of the entire Basin was associated with numerous mining hazards because of the high methane content in coal seams. During coalification, large quantities of methane-rich gas were generated and stored within the porous coal matrix and fracture systems. The Basin hosts significant quantities of unconventional gas plays including coalbed methane (CBM). Recent expertise concluded that CBM resources in the Lorraine Basin (Moselle East permit) can be estimated to 371 billion tons which are corresponding to 8 years of French national gas consumption.

CBM has the potential to emerge as a significant clean energy resource because it is over 90% methane, and it is suitable for direct introduction into commercial pipelines with little treatment.

Nuclear power as the largest source of electricity in France and global environmental challenges had replaced most of the heavily polluting production of energy from coal-fired power plants. As result, coal mines here are no longer operated for coal extraction since 2004, however, the migration of methane towards the surface takes place for many years following the closure of a mine. Methane is the second most important greenhouse gas after carbon dioxide, and it is responsible for more than a third of total anthropogenic climate forcing because of its abnormal ability to trap heat in the atmosphere.

Faults, a dense network of tectonic fractures together with post-mining subsidence effects may also increase the permeability of a coal-bearing massive and provide sites for local discharging ground waters accompanied with the seeping of environmentally hazardous methane. From 2006, mine workings got progressively flooded. In the conditions of flooding, the uprising of the water table facilitates the methane migration to the surface within post-mining areas.

CBM extraction in the Lorraine Basin must be considered as a low-cost option targeted to mitigation methane emissions in the region and overall stabilization of anthropogenic climate change. Several characteristics of coals need to be ascertained during exploration for the understanding of the performance of coalbed methane gas reservoirs. Among them, the knowledge of geometrical features of fracture sets is a crucial parameter for determining the absolute permeability of a resource play, its kinematics environment, and further reservoir simulation. The main focus of this contribution is to get an insight into the style and structural trends of natural fracture and cleat patterns in the basin based on results of X-ray computer tomography (CT) to ensure proper technical decisions for efficient exploration and exploitation of coalbed methane reservoirs.

2. Geologic framework and tectonic interpretation of the Lorraine-Saar Basin

The Lorraine-Saar Basin encompasses a narrow structurally SW- NE trending thin-skinned pull-apart basin [1] with a lateral extent of c. 300 km x 70 km, that developed on the basal detachment of the Metz-South Hunsrück (MSH) Fault between two overlapping transcrustal latitudinal megashear zones of Wight-Bray-Vittel fault [2] and the North Artois fault [3] (Figure 1). Geologically, the Lorraine-Saar Basin stands out by its up to 6 km sedimentary column of siliciclastic rocks and its inversion resulting in Paleozoic low-amplitude erosion in the range of 750 m (French part of the basin) [4] and pre-Mesozoic (Permian) erosion between 1800 and 3000 m (the Saar coalfield or German part of the basin) [5]. A key moment for successful interpretation of all data available is the unique source of information that could be obtained from isopach maps constructed for the Carboniferous units [6].

These isopach maps delineate NE-ward orientated traveling of depocentres of sedimentation along a narrow stripe always located parallel and adjacent to the MSH Fault (Figure 1).

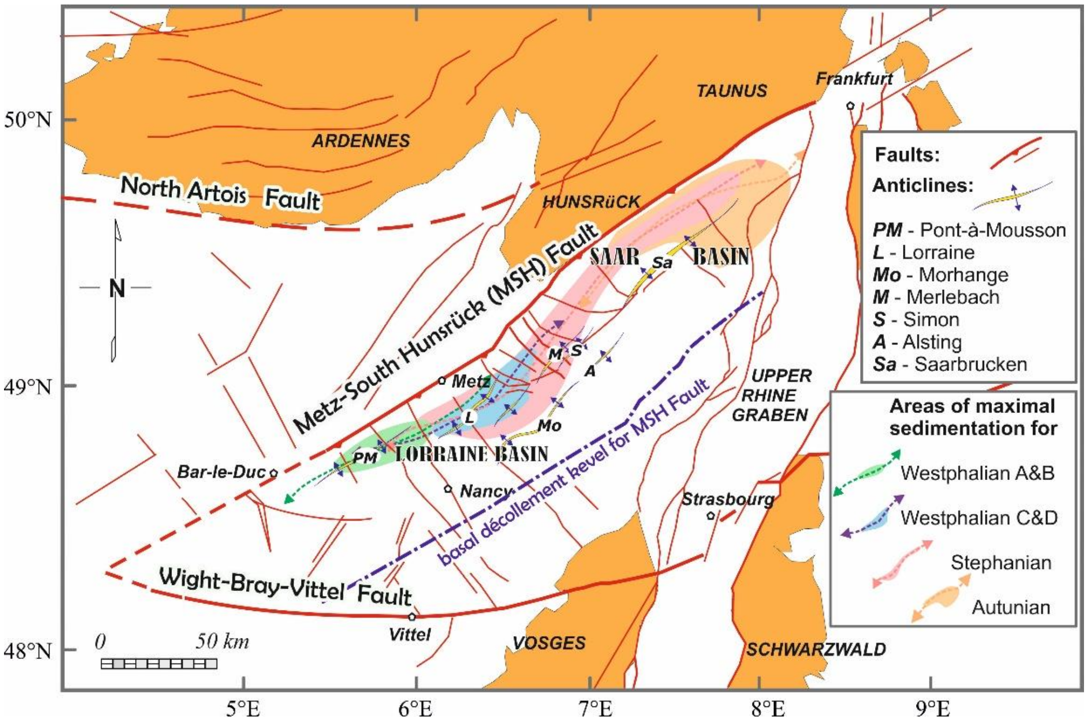

Figure 1. The structural setting, tectonic elements, and depocentres of maximal sedimentation of the Lorraine-Saar Basin.

According [6] the mentioned above isopach pattern is typical for an internal pull-apart basin at the border between the Rheno-Hercynian and Saxo-Thuringian Zones of the Variscides. It has been brought many sedimentary and tectonic proofs [7] of the presence of strike-slip faults in the Basin. Field evidence indicates the characteristic morphology of positive flower structure for the most prominent Saarbrücken anticline as a typical marker for the transpressional strike-slip regime.

Our interpretation of the structural map of the Lorraine Basin supplemented by results of the underground documentation of kinematic indicators within small-displacement faults and mining panel-scale geologic mapping in coal mine Faulquemont [8] suggest (Figure 2) that kinematic development of the fracture pattern may be explained by the classical scheme of development of subsidiary structures within the dextral strike-slip zone [9]. It includes master shears Y, conjugate set of Riedel shears (R_1, R_2), conjugate set of P and X shears, thrusts-compression folds C, tension fractures - normal faults T. For instance, the Longeville Fault of semiconcentric geometry consists of segments of R_1, Y, and P dextral shears, and its Y – trending fragment could be considered as a bound of the main shear zone. In the eastern and north-eastern part of the study area, the transpression has generated highly shortened folds parallel to the strain ellipse long axis C.

Careful examination of the seismic data [10] showed that the MSH Fault is not subvertical indeed as it was documented at shallow levels. At ~2 km depth its angle dip is about 65°. The MSH Fault flattens rapidly and finally soles out at the subhorizontal position of basal décollement constrained at a level of ~4-6 km depth. The MSH Fault is a well-lubricated listric detachment, which can provide a basis for sedimentation occurring between its foot and hanging wall blocks when the hanging wall block of a listric fault is pulled away from the footwall block under extensional forces.

The petroleum systems of the Lorraine-Saar Basin's sedimentary carapace and the superimposed Paris Basin in the Lorraine province are mostly associated with the Carboniferous source rocks. Historic parametric deep wells have shown methane showings throughout the Carboniferous Westphalian and Stephanian sequences in the interval 1.0-5.7 km with progressive increasing diagenetic and catagenetic alterations with depth from subbituminous coals to meta-anthracites. Thermal maturation of wide spectra of organic-rich-matter ranging from dispersed organic matter in sedimentary clastic rocks to concentrated organic matter in coal seams has led to the formation of an enormous unconventional gas resource in many localities throughout the Lorraine-Saar Basin.

Thermally generated gas from deep compartments and low-permeability levels (3.5-5.5 km – dry gas window) have escaped via several major fault-breached corridors forming structurally related gas accumulations in antiform-type structures (e.g. Lorraine, Merlebach and Alsting anticlines, wherein strata folded upwards lead to enhanced permeability and additional fracturing).

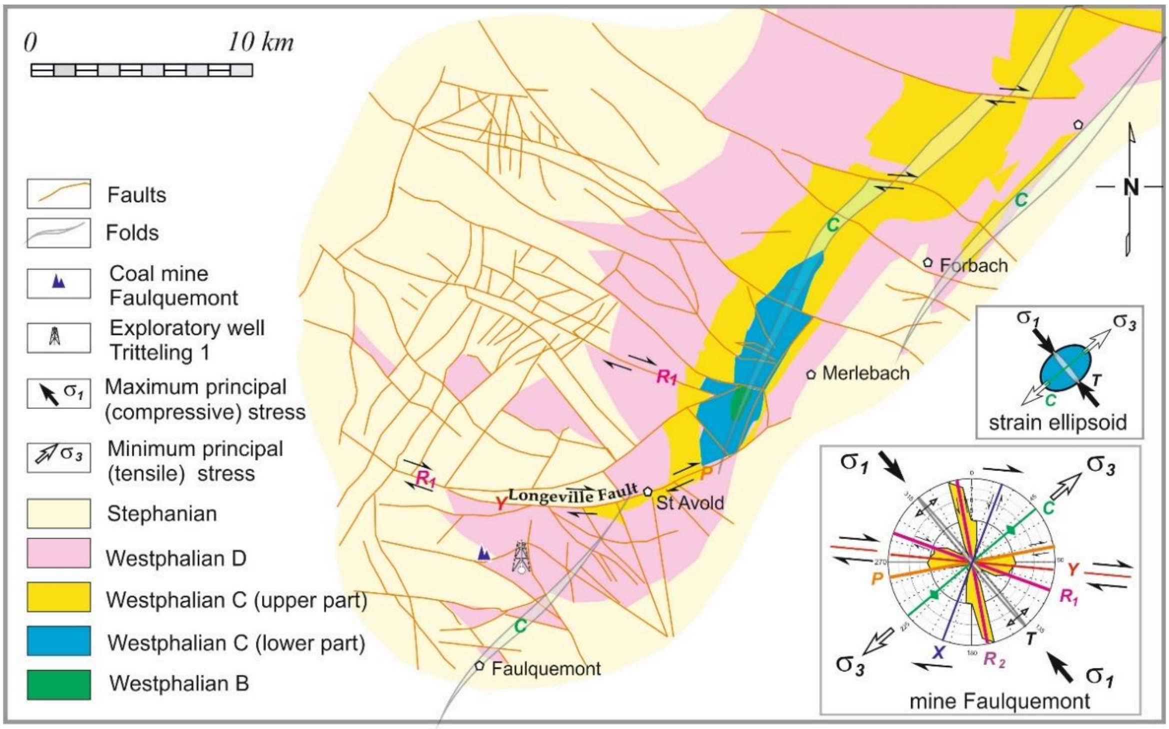

Figure 2. Structural map of the Lorraine Basin supplemented by interpretation fracture patterns in coal mine Faulquemont.

Unlike conventional hydrocarbon reservoirs, wherein gas-prone source rocks and reservoirs are separated in space, CBM may accumulate in an adsorbed state within micropores of the coal matrix (adsorption properties of low-volatile bituminous black coal can be compared with characteristics of activated coal and these are in the range of 300 - 800 m^2/g, that is why for a given reservoir pressure much more gas can be stored in a coal seam than in a comparable sandstone reservoir).

3. Natural fracture systems and their importance for CBM plays

Nearly all CBM plays can be classified as naturally fractured reservoirs. These are affected in some way by natural fracture sets or cleat, which is just a miner's term for closely spaced fractures or joints in coal. The major exploration risk in most CBM reservoirs is generally a typical lack of natural bulk permeability. Based on the results of work conducted by numerous research entities in many CBM localities throughout the world, the absolute permeability of the fragmented coal samples from coal exploration core holes appears to be low and can be measured in the order of millidarcy scale. However, the real fluid conductivity of coal seams can be influenced by tectonically induced structural variations, particularly in the vicinity of releasing bends along strike-slip tectonic zones and associated fold structures, wherein the absolute permeability increased significantly.

The ability of fluids and gases to travel through coal-bearing sequences is largely controlled by the interplay of fracture systems within coal seams, host rocks (e.g. alluvial and deltaic sandstones), and tectonic stress field. Cleat systems together with discrete networks of small-displacement faults result in the compartmentalization of coal bed structure, important for final producibility of gas trapped in coal seams is two-fold. Firstly, they may be partly in open-mode (e.g. small-scale tension fractures) without any artificial stimulation and serve as natural channels for CBM migration to the well. Secondly, these planes of structural weakness (different sets of joints including shears and even fissures sealed by mineralization) can reactivate with enhancing natural apertures during exploitation. which is the most critical component from the geotechnical and gas filtration standpoints. Reliable characterization of natural fracture networks and related cleat systems in coal seams can improve significantly the management of CBM reservoirs.

4. Coal tomography experiments

To explore the architecture of micro-cleat patterns in coals of the Lorraine Basin we used CT by the means of X-ray Nanotom Phoenix GE system of Laboratory of GeoRessources (Université de Lorraine-CNRS). The X-ray CT is a non-destructive technique of inspection of the internal structure of a solid specimen based on recording abnormal attenuation levels of X-rays after passing them through a specimen, which is dependent on density contrasts within the studied specimen. The process by which microfractures or cleat systems become critically visible for X-ray CT is two-fold. Firstly, they may be partly in open-mode and containing void space. Secondly, these joints and micro-fissures are often sealed by mineralization possessing drastic density contrast on the background of coal matter.

For research, we chosen the coal specimen collected from the Westphalian D coal seam 10 of exploratory well Tritteling 1 at depth of 1239 m. The studied coal specimen and its 2 local subvolumes were illuminated in 3 series of experiments (with resolutions of 30, 10, and 2 μm) by X-ray beam generated in 180 kV micro-focus X-ray tube-generator. Registration of absorbed beam, which maintained information on inhomogeneities and defects in the internal structure of studied samples, was recorded as a set of radiographic images collected around the object at different viewing angles with the help of X photon CMOS 5 Mp digital image sensor. For generating spatial models of cleat arrays in dimensional horizontal slices taken perpendicular to the vertical axis of scan direction. For digital geometry processing and following 3D visualization, exploration, and quantification analysis of cleat patterns VGStudio 2.2, Avizo FEITM, and GoCAD software packages were used.

5. Results and Discussion

At different levels of X-ray CT we identified 2 quasi-orthogonal systems of the cleat (Figure 3) including the smooth-sided medallion-shape tensile fractures or face cleat, and curvilinear shearing cleat system or butt cleat.

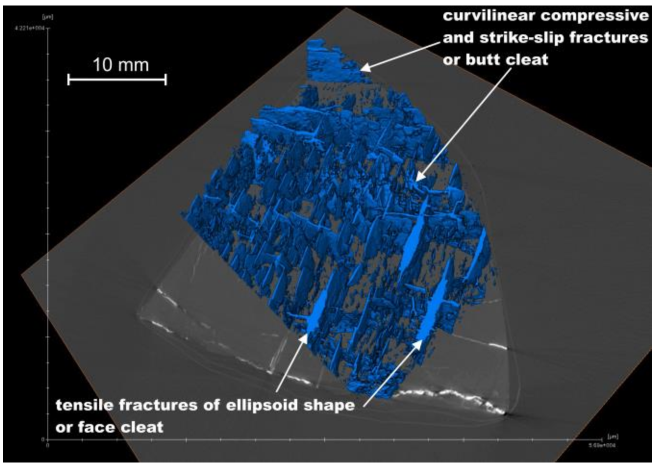

Figure 3. Two of the most prominent quasi-orthogonal systems of the cleat in the studied sample (resolution X-ray CT 30 μm).

Much of the literature on coalbed methane reservoirs focuses on these quasi-orthogonal cleat patterns [11], which orientation depends on the main tectonic directions and strain ellipsoid. Cleats in coal are intimately related to stress fields within basinal infill during and after coalification. Historically, a lot of attention has been given to so-named endogenetic cleat developing by the discharge of devolatilization stresses in coal during thermal maturation. Much more attention needs to be given to exogenetic cleat when tectonic stresses impose orientations of individual fractures and cleat system sets [12,13]. After X-Ray CT internal testing of samples, we delineated elliptically convexed face cleat fractures (Figure 4), which can be interpreted as extensional micro-fissures. These cracks are always gashed the layered coal matrix parallelly to the maximum (compressive) principal stress σ_1. Their opening takes place perpendicular to the direction of the minimum (tensile) principal stress σ_3.

We also documented a microlayer control of the constraints of the face cleat propagation. The intensity of the face (tensile) cleat is critically dependent on the maceral composition of coal microlayers (Figure 4). Bright vitrinite-rich and definitively more fragile bands of coal in studied samples are ultimately more intensively fractured by tensile cleat than inertinite-durain rich dull coal microlayers.

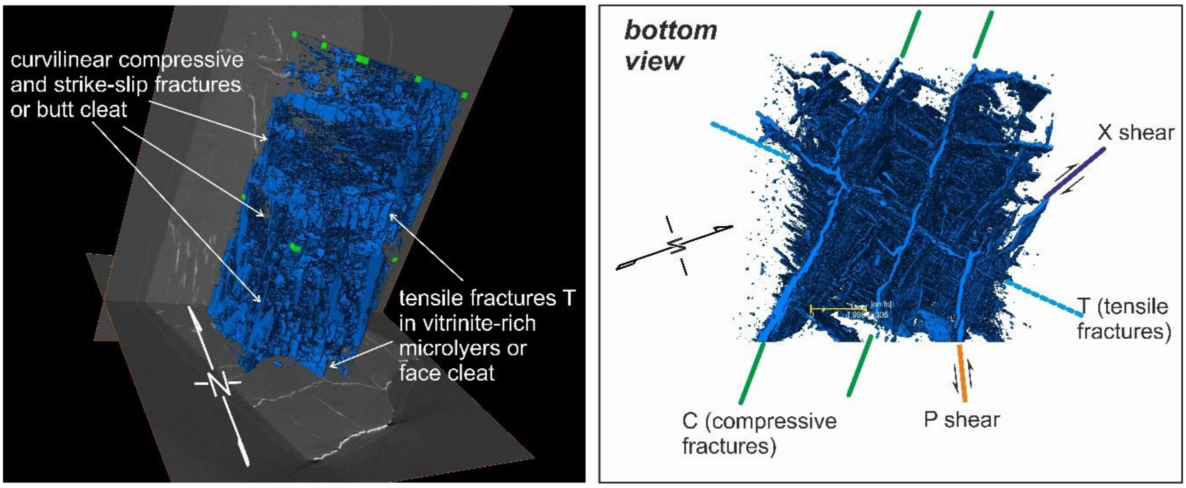

Figure 4. 3-D pattern of principal cleat systems (left) within the studied coal sample (resolution 30 μm) and the bottom view of the sample (right).

The butt cleat propagates along the direction of minimum (tensile) principal stress σ_3 and it is represented by a curvilinear shearing assemblage of fractures as a combination of compressive structures C and shears of type X and P.

The pattern of cleat array revealed within the coal seam is consistent with the strike-slip model of the structural evolution of the Lorraine-Saar Basin suggested above. The inferred cleat patterns demonstrate aligning with directional stresses, more specifically, of strike-slip-transpressional regime governed by NW-SE trending compressive axis σ_1 and NE-SW trending tensile axis σ_3.

Figure 5 exhibits the results of the X-ray CT multi-scale investigation of the principal specimen and its subvolumes performed at different resolutions. The obtained results demonstrate spatially similar behavior of different cleat systems within the entire cleat array at variable resolutions. Without the scale bar, it is mostly impossible to determine the discrepancy in structural trends of fractures for the principal coal specimen and its subvolumes. Actually, this means that interconnected cleat networks in coal can be represented as an assemblage of rescaled self-copies [14].

The fragmentation of coals into elementary self-similar subordinated blocks is of high importance to serve as the simplest model capable of simulating connectivity in coal samples. Results of treatment of obtained cleat patterns in terms of their connectivity relationship with the help of the

Avizo FEITM software (Figure 5) allowed distinguishing the presence in the sample of single domains with connected cleat arrays.

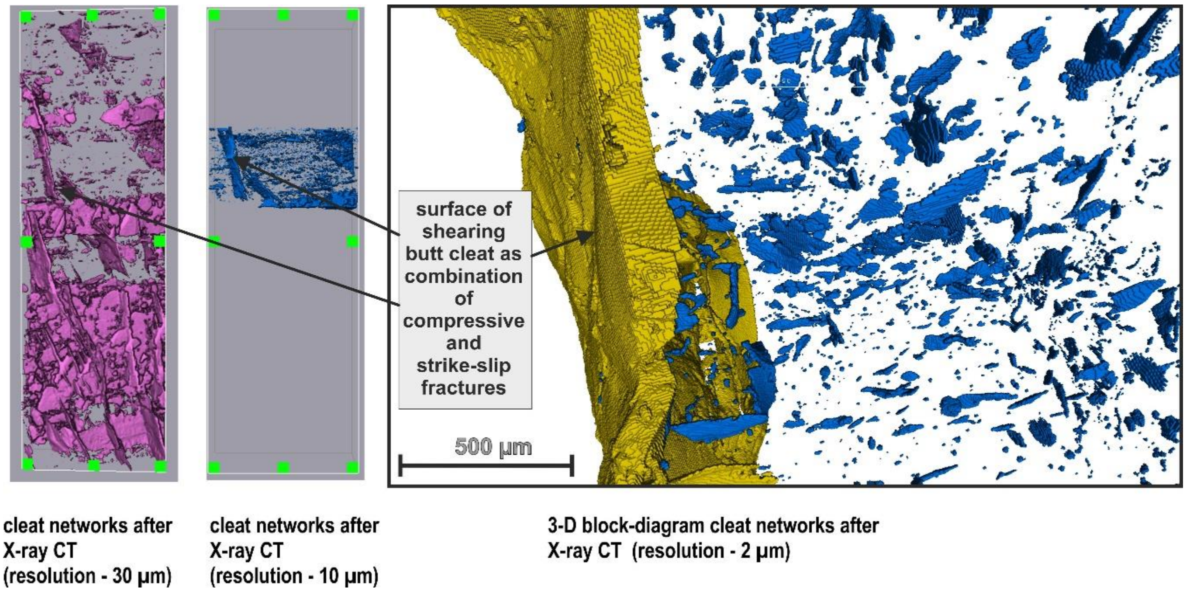

Figure 5. Cleat networks after X-ray CT inspection of the principal specimen and its subvolumes with different resolutions.

For estimating global connectivity frequency (GCF), which represents the calculated ratio between the total length of cleat intersection and the total length of cleat detected, we used the approach proposed by [15]. The 3-D model of coal sample based on CT scans of coal with a resolution of 30 µm (Figure 6) predicts the value of GCF = 92.2%. This attests that almost all discrete fractures in the studied coal seam are connected into one big high-permeability array which will enhance the ability of methane to travel from coal reservoirs to CBM production wells even without any kind of reservoir stimulation.

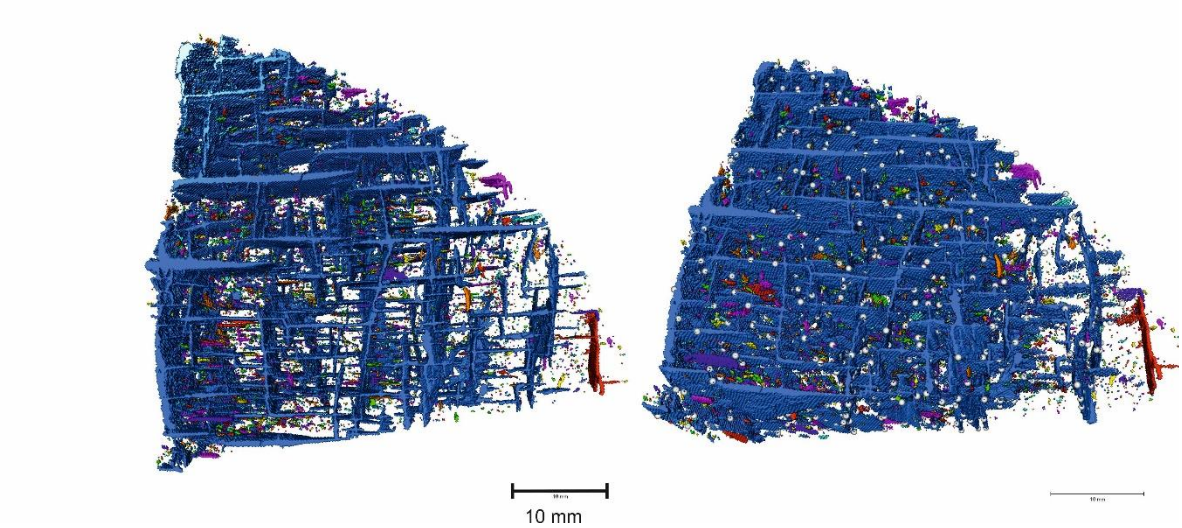

Figure 6. Connectivity pattern of cleat networks after X-ray CT inspection of the sample (resolution 30 µm). The biggest connected cleat array in the sample (resolution of X-ray CT- 30 µm) is shown in blue, other connected cleat volumes are shown in different colors

6. Conclusions

Documented by means of X-ray CT internal architecture of studied samples as coal matrix penetrated by interconnected cleat sets acting as high-permeability microfracture array can be interpreted as a promising signal arguing for the presence of magnified fluid-and-gas conductivity in CBM reservoirs. This feature advocates a brighter future of the Lorraine-Saar Basin as a target for coalbed methane resource assessment and wide-scale gas extraction activities.

It is important to underline that the inferred spatial pattern of kinematically induced cleat systems possesses features of self-similarity through different resolution levels of X-ray CT scans. The dominant trends of the tensile face cleat and curvilinear shearing butt cleat match strikes of principal regional faults and fold structures set up in the Basin in concert with the strike-slip tectonic model of the basinal evolution governed by NW-SE trending compression σ_1 and NE-SW trending extension σ_3 stresses.

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Conflicts of Interest: The authors declare no conflict of interest.

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