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CLEAT SYSTEMS IDENTIFICATION IN COALBED METHANE RESERVOIRS OF THE LORRAINE BASIN WITH THE HELP OF X-RAY COMPUTER TOMOGRAPHY

Purpose. *The Lorraine Basin is one of the largest geologically and commercially important coalfields in the Europe. It has the potential to host significant quantities of unconventional plays including coalbed methane (CBM). Nearly all CBM plays are affected in some way by natural fractures sets or cleat, which is just a miner's term for closely spaced fractures or joints in coal. The main focus of this contribution is to get an insight into 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.*

Methods. *To explore the architecture of solid coal samples we used X-ray computed tomography of coal specimen collected from the Westphalian D coal seam 10 of exploratory well Tritteling 1. The studied coal specimen (principle sample) and its 2 local subvolumes were inspected in 3 series of experiments (with resolutions with 30, 10 and 2 µm).*

Results. *Detailed analysis using X-ray CT reveal the spatial distributions of interconnected network of cleat systems that provide the most of the macroporosity in coal seams. 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 are often sealed by mineralization possessing drastic density contrast on the background of coal matter. These microfissures may reactivate during CBM reservoir exploitation contributing to bulk permeability. The inferred discrete fractures and tectonically induced cleat patterns clearly possess features of self-similarity and align with directional stresses.*

Scientific novelty. *This paper presents results from an analysis of structural trends of natural fracture and cleat patterns in the Lorraine Basin.*

Practical significance. *Fracture characterisation is crucial for ensuring CBM reservoir performance. The study of cleat and fracture systems is an important first step in evaluating possible transfer of methane from coal reservoirs and following CBM production.*

Key words: *Lorraine coal Basin, coal-bed methane, X-ray computed tomography, , cleat systems, kinematic fracturetype, tectonic stress field.*

Introduction.

The Lorraine Basin is one of the major and the mature coalfields in the Western Europe, which contains a number of conventional hydrocarbon accumulations and has the potential to host significant quantities of unconventional plays including coalbed methane (CBM) gas [1,2].

The Basin has considerable coal reserves and numerous coal beds with variable thickness (from a few centimetres to 4-5 m, unusually 15 m, or even more) are distributed through a thick stratigraphic section.

A recent expertise concluded that CBM resources in the Lorraine Basin (Moselle East permit) can be estimated to 371 billion tons which is corresponding to 8 years of French national gas consumption [3]. CBM has the potential to emerge as a significant clean energy resource, because in fact it is exceptionally pure compared even to conventional natural gas, containing only very small portions of heavier gaseous hydrocarbons and minor quantities of other gases (e.g., hydrogen sulphide and carbon dioxide). Methane is the second most important greenhouse gas (GHG) after carbon dioxide (CO_2), and it is responsible for more than a third of total anthropogenic climate forcing, because its abnormal ability (21 times greater comparing with CO_2) to trap heat in the atmosphere.

Coal mines in the Lorraine Basin are no longer operated to produce coal; however, even these abandoned mining "naturally gassy" sites can still produce significant GHG venting into the atmosphere throughout diffuse shafts/boreholes and natural fracture systems' corridors.

The migration of methane towards the surface takes place for many years following the closure of a mine [4]. This hazardous phenomenon of methane release on the surface is associated both with active mining and, more specifically in our case, with the post-mining period.

Faults, 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 or even mine waters accompanied with breathing of deadly explosive and environmentally hazardous mine gases. From 2006, mine workings got progressively flooded, creating mine water reservoirs [5]. In the conditions of flooding closed methane mines, the uprising of water table facilitates to the methane migration to the surface within post-mining areas.

Therefore, CBM extraction in the Lorraine Basin must be considered as low-cost option targeted to mitigation GHG emissions in the region and overall stabilization of anthropogenic climate change.

CBM is virtually identical to the gas produced from conventional sandstone reservoirs, but coalbed gas is over 90% methane, and it is suitable for direct introduction into commercial pipelines with little or even without treatment. The latest state-in-art engineering geological models and advanced techniques based on them are of crucial importance in development of this unconventional resource.

Some of these developments including adaptations of existing technologies used in conventional oil and gas deposits harnessing, while others include new applications designed specifically to address unique properties of coal, which is in fact serves both as a source rock and a storage reservoir for gas.

The efficient development of CBM is critically dependant from the type of well construction. Specific well types mainly include vertical wells, directional wells (cluster wells), single-lateral horizontal wells, multiple-lateral horizontal wells, U-shaped wells, etc. Among them, directional multiple-lateral subhorizontal wells are the most common well-types used in practical development activities for CBM extraction.

Geological characteristics of the Lorraine Basin.

During the Late Palaeozoic Variscan orogeny multiple coal-bearing basins were formed in the Western Europe. The most of them, or so-named paralic sedimentary basins located in Germany, Belgium and Northern France.

These basins (Fig. 1, yellow ellipse and arrow) triggered coal formation that originated in a body of water once linked with the open sea [6]. The coal-bearing deposits here contain marine intercalations or horizons with marine fauna, which index fossils provide excellent basis for age determination of coal-bearing strata.

The intramontane Lorraine coal Basin (Fig. 1, red ellipse and arrow) does not seem to have had any connection with the open sea. In fact, it is a structurally controlled coal basin, wherein entirely non-marine Late Carboniferous to Early Permian clastic continental sediments of alluvial fans, braided and meandering rivers, deltaic and lacustrine facies were deposited without any presence of marine interbeds [7].

Fig. 1. Location map of the principal coal-bearing basins in the Western Europe.

In gross structural terms, the Lorraine Basin is a result of the late evolution of the Variscan Belt of the Europe, which had been formed during the convergence of the Laurussia with the Gondwana continents by a closure of different oceans and produced several suture zones including the Rheno-Hercynian and the Saxo-Thuringian zones. The Lorraine Basin was settled and developed since Namurian-Westphalian time upon southern-western portion of the Saxo-Thuringian zone bounded on the south by Bray-Vittel transcrustal fault and bordered with Rheno-Hercynian foldbelt zone along scarp line of continuous deep-seated listric Metz – South Hunsrück fault (Fig. 2).

Geologically, the Lorraine Basin stands out by its up to 5 km sedimentary column and its inversion resulting in Paleozoic low-amplitude erosion in range of 750 m (French part of the basin) [2] and pre-Mesozoic (Permian) erosion between 1.8 and 3.0 km (the Saar coal field or German part of the basin) [9].

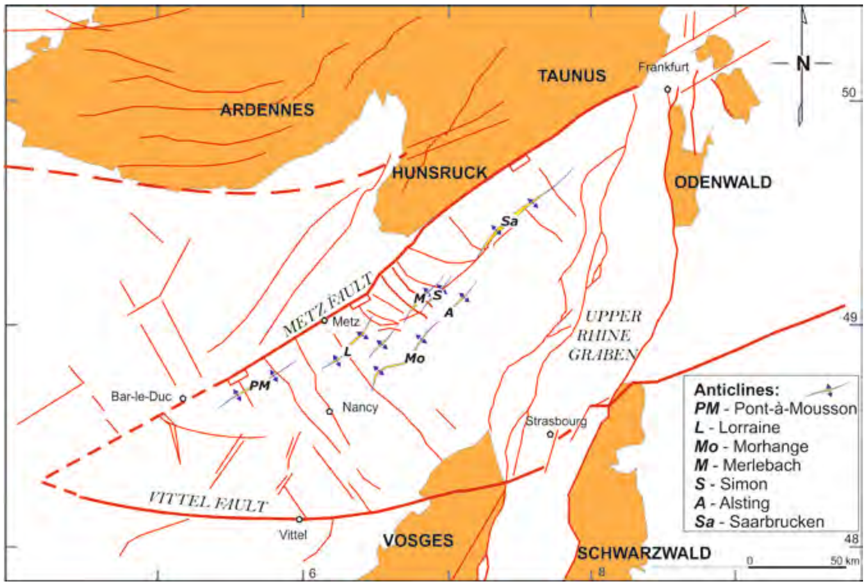

Fig. 2. Structural setting and tectonic elements of the Lorraine Basin.

The petroleum systems of the Lorraine Basin's sedimentary carapace and the superimposed Paris Basin in the Lorraine province are mostly associated with the Carboniferous source rocks and historic parametric deep wells have shown hydrocarbon showings throughout the Carboniferous Westphalian and Stephanian sequences in interval 1.0 - 5.0 km. 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 formation of an enormous unconventional gas resource in many localities throughout the Lorraine Basin.

The Gironville borehole intersects, at depths between 1 and 5.7 km mainly, Carboniferous coal-bearing formations with progressive increasing diagenetic and catagenetic alterations with depth from subbituminous coals to meta-anthracites.

Thermally generated gas from deep compartments and low-permeability levels (3.5-5.5 km – dry gas window) have escaped via several major fault and fracture zones forming structurally related gas accumulations in antiform-type (e.g. Lorraine, Merlebach and Alsting anticlines – Fig. 2, wherein strata folded upwards tend to produce internal fracturing due to stretching of the rocks) or associated fault-breached structures.

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 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).

Natural fracture systems and their importance for CBM plays.

Nearly all CBM plays can be classified as naturally fractured reservoirs. In fact these are affected in some way by natural fractures sets or cleat, which is just a miner's term for closely spaced fractures or joints in coal.

Understanding how the methane molecules are stored within the coal seam helps gas companies decide their production strategy.

The major exploration risk in most CBM reservoirs is generally 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 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 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 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.

A proper understanding of natural fracture and cleat patterns is a key factor to understanding of the performance of coalbed methane gas reservoirs. The process by which these discontinuities become critically 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.

The knowledge of geometrical features of fracture and cleat patterns is crucial parameter for determining the absolute permeability of a resource play, its kinematics environment and further reservoir simulation. Hence the study of cleat and fracture systems is an important first step in evaluating possible transfer of methane from coal reservoirs and following CBM production.

Methods of investigation.

Computer tomography (CT), that was originally developed mostly in the field of medical sciences, allows 2-D or 3-D characterization of internal characteristics of a specimen. Because of its widespread application into geological sciences, this method should be an extremely helpful for characterisation of natural cleat systems.

To explore the architecture of microcleat patterns in coals of the Lorraine Basin we used CT by the means of X-ray Nanotom Phoenix GE system of Laboratory of Georessources. The X-ray CT is a non-destructive technique of inspection of internal structure of solid specimen based on recording abnormal attenuations levels of X-rays after passing them through a specimen, which are dependent on density contrasts within 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 microfissures are often sealed by mineralization possessing drastic density contrast on the background of coal matter.

For research we chosen coal specimen collected from the Westphalian D coal seam 10 of exploratory well Tritteling 1 at depth of 1239 m. The studied coal specimen (principle sample) and its 2 local subvolumes were illuminated in 3 series of experiments (with resolutions with 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 internal structure of studied samples, was recorded as a set of radiographic images collected around the object at different viewing angles by 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 vertical axis of scan direction. For digital geometry processing and following 3D visualization, exploration and quantification analysis of cleat patterns VGStudio 2.2 and Avizo FEITM software packages were used.

Characterization of patterns of fracture and cleat systems.

Much of the literature on coalbed methane reservoirs focuses on quasi-orthogonal cleat patterns (e.g. [10-12]), which orientation depends on the main tectonic directions and strain ellipsoid.

Cleats in coal are intimately related to stress fields within the basin during and after coalification. Historically, a lot attention has been given to so-named endogenetic cleat developing by the resulting of endogenic (or devolatilisation) stresses in coal during thermal maturation. Much more attention needs to be given to exogenetic cleat [13], when tectonic stresses impose orientations of individual fractures and cleat system sets.

The face cleat surfaces, as a role, tend to strike are almost perpendicular to perpendicular to fold axes, indicating that stresses associated with folding determined their orientation. In the basin of strike-slip origin, like the Lorraine Basin, wherein strike-slip component of deformation is recognized across the entire basin [1,7], this cleat could be classified as the primary, related with tensional stresses during folding of the strata.

The optimal orientation of such cleat of clear ellipsoid shape is along the maximum principal horizontal stress and influenced by regional compressive stress direction [14,15]. However, coal is some kind of brittle rock lithotype that is sensitive to shear stresses and that is why in regions of strike-slip deformations coal seams could contain a diverse array of structures associated with wrench faulting. Results of the previous investigations in the Donets Basin (also of strike-slip origin) have shown [16] that coal seams possess a set of mentioned above fractures typical for development of strike-slip zones (Fig. 3).

At different levels of X-ray CT we identified 2 quasi-orthogonal systems of cleat (Fig. 4) including i) system of smooth-sided cleat of tensile origin, because of prominent ellipsoid geometry, or face cleat; ii) curvilinear shearing cleat system or butt cleat.

Actually, intensity of face (tensile) cleat is critically dependent from maceral composition of coal microlayers. 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 (Fig. 5).The butt cleat is along the direction of horizontal minimum compressive principal stress and it represented by curvilinear shearing compressive and strike-slip structures. A result of our observations on a range of different resolution scales have shown that this cleat is in fact is combination of compressive structures *C* and shears of type *X*.

In some cases, we observed the linkage of *C* and *X* assemblages with *P* shears and even crosscutting patterns of this by R_2 shears (Fig. 6). The angle between *P* and *X* shears after topographic research is in range of 122° and this value is in good correspondence with suggested strike-slip model of deformation of coal seams [1].

There is an essential difference in rheological properties of an entire coal seam, and specifically, its microlayers, because of different maceral composition, and more competent hosting beds. Within contacts of coal beds and layers of other lithologies and even between contacts of coal microlayers this phenomenon caused an abundant appearance of sliding planes as well as formation of specific compression duplexes or small-scale thrusts that connect bedding-parallel detachments. These steeply dipping with sigmoidally curved imbricated surfaces fractures of mostly compressive origin often occurred in association with the localised thickening of seams and can be explained by «progressive easy slip thrusting» mechanism [14,15]. There is a strong connection between overpressure in coal seams and formation of these fractures. In local environment of coal seam during formation of compression duplexes compression axis lies subhorizontally and extension axis occupies subvertical position. But immediately after their formation because of release of compressive stress only vertical extensional forces are active, and this stress state creates subhorizontal microcracks, which are eventually represent natural example of microscale hydraulic fracturing.

We found such system of thin-plated subhorizontal cleat also in samples from the Lorraine Basin. In horizontal projection they are clearly orthogonal to compression structures C within butt cleat (Fig 6). 3-D relationship between thin-plated subhorizontal cleat orthogonal to compression duplexes and tensile cleat of ellipsoid shape is presented on Fig. 7. Actually this cleat system is developing in a close vicinity to shearing microthrusts duplexes and, because of its younger age in a comparison with others, these could be served as structural pockets for favourable methane preservation.

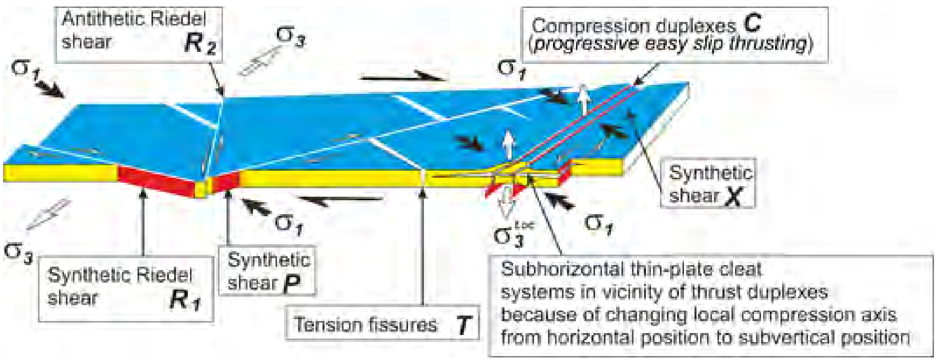

Fig. 3. Different type of subsidiary fractures developing in a dextrally wrenched coal seam including: (1) Conjugated dextral synthetic *R_1* and sinistral antithetic *R_2* Riedel shears; (2) Conjugated dextral synthetic *P* and sinistral antithetic *X* shears; (3) Reversed faults, thrusts, compression folds *C*, which formed parallel to the strain ellipse long axis *T*; (4) Tension fractures, normal faults *T*, which formed parallel to the strain ellipse small axis *C*; (5) Subhorizontal thin-plate cleat systems in the vicinity of thrust duplexes because of changing local compression axis from horizontal position to subvertical position.

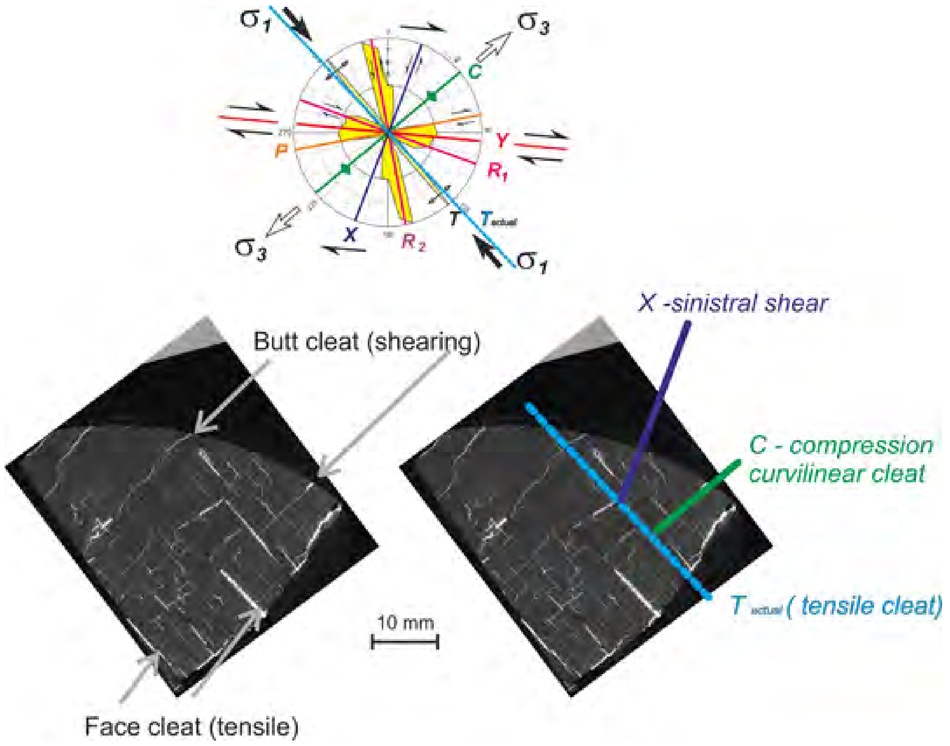

Fig.4. Results of interpretation of cleat systems in studied sample (resolution X-ray CT 30 µm) as tensile fractures *T_{actual}* (face cleat) and shearing or butt curvilinear cleat, which a combination of compressive microthrusts *C* and sinistral *X* shears. The direction of diaclases, small displacement faults in the coal seams 6, 8 and 9 documented during underground mining in coal mine Faulquemont is represented in yellow petals of rose-diagram.

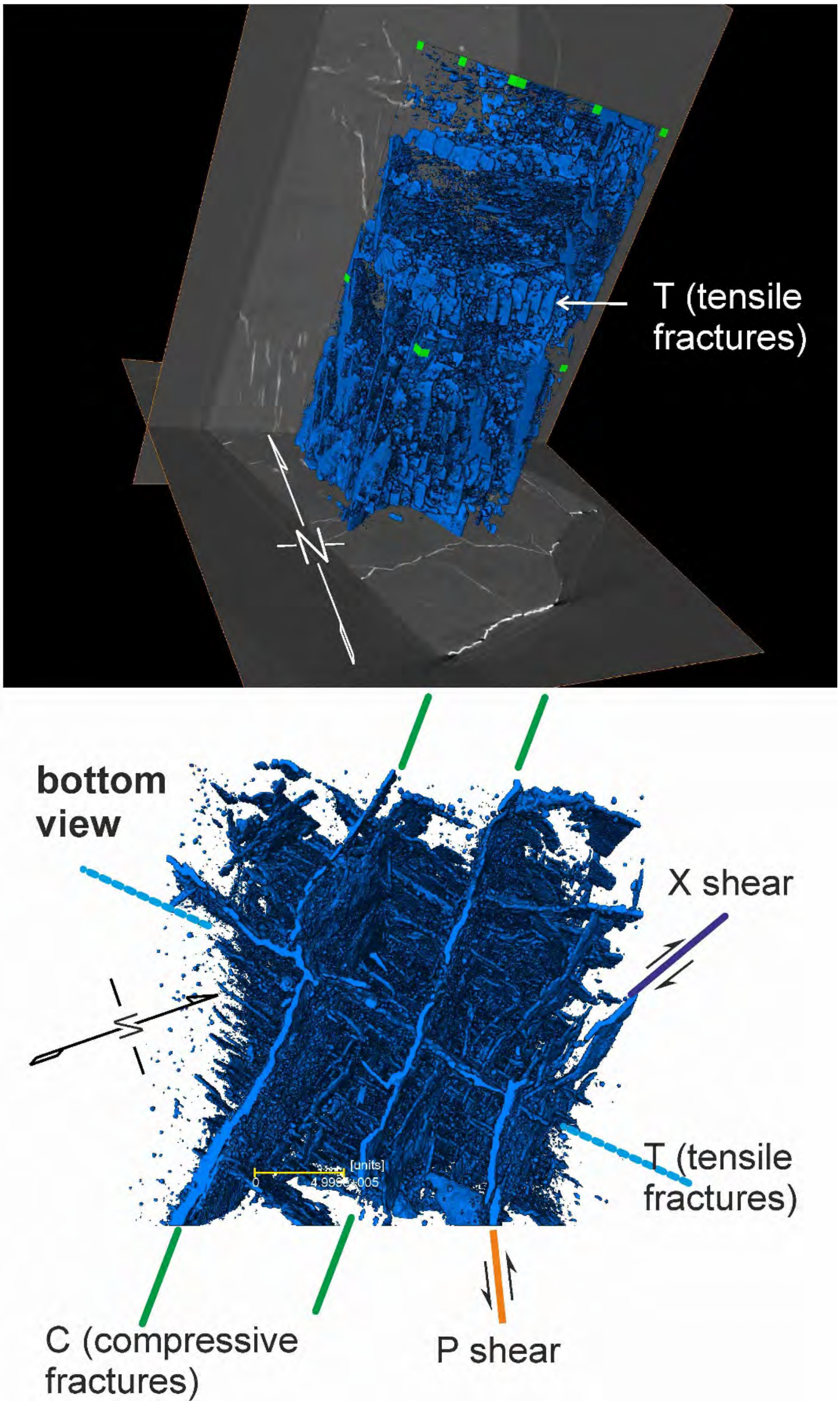

Fig. 5. 3-D patterns of principal cleat systems within the studied coal sample (resolution 30 µm). Note low inset shows the bottom view of sample.

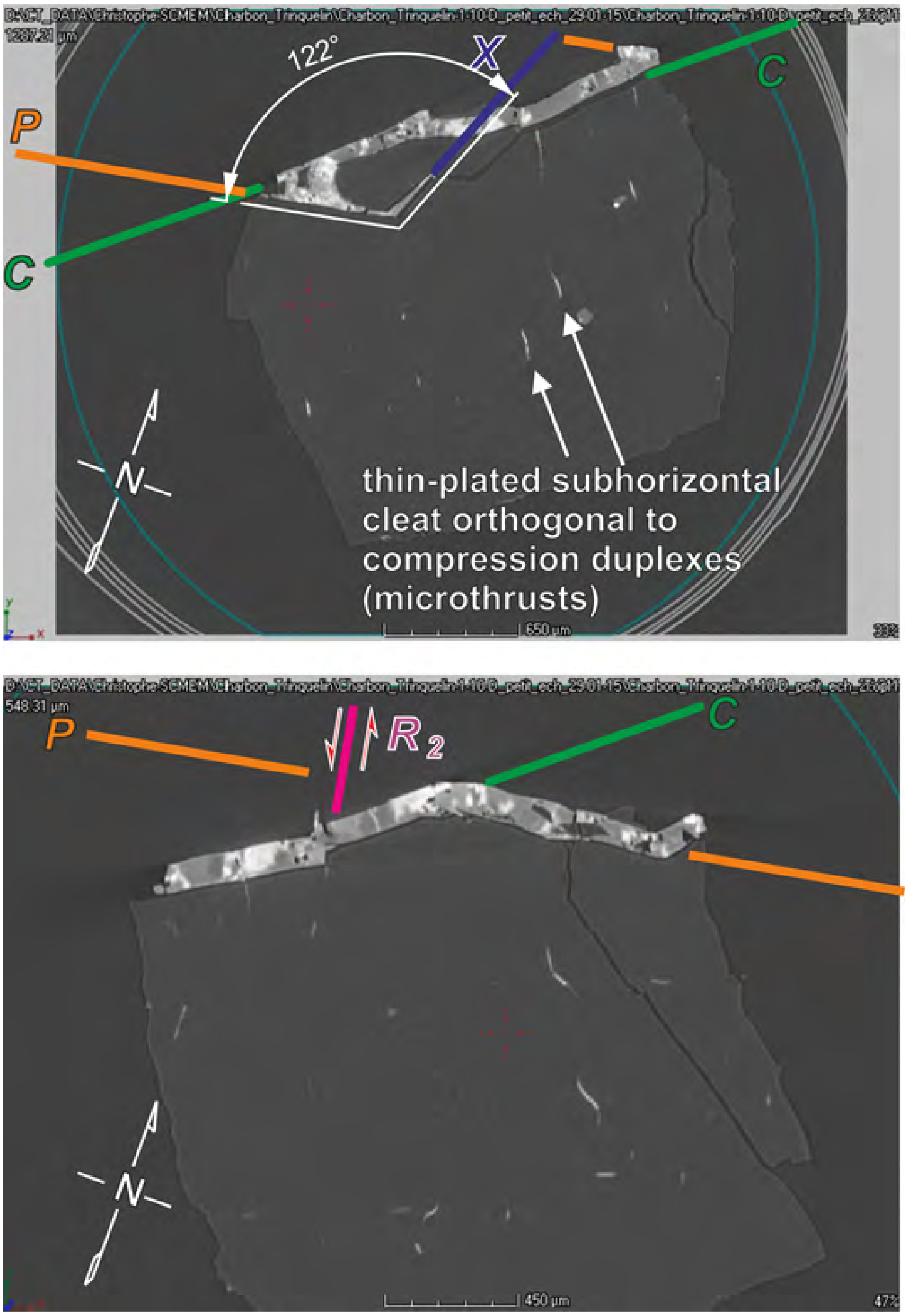

Fig.6. Results of interpretation of cleat systems in studied sample (resolution X-ray CT 2 µm) as shearing fractures or butt cleat, which a combination of compression duplexes (microthrusts) *C*, sinistral *X* shears, dextral *P* shears. Note the presence of antithetic sinistral R_2 Riedel shears and thin-plated subhorizontal cleat orthogonal to compression duplexes *C*.

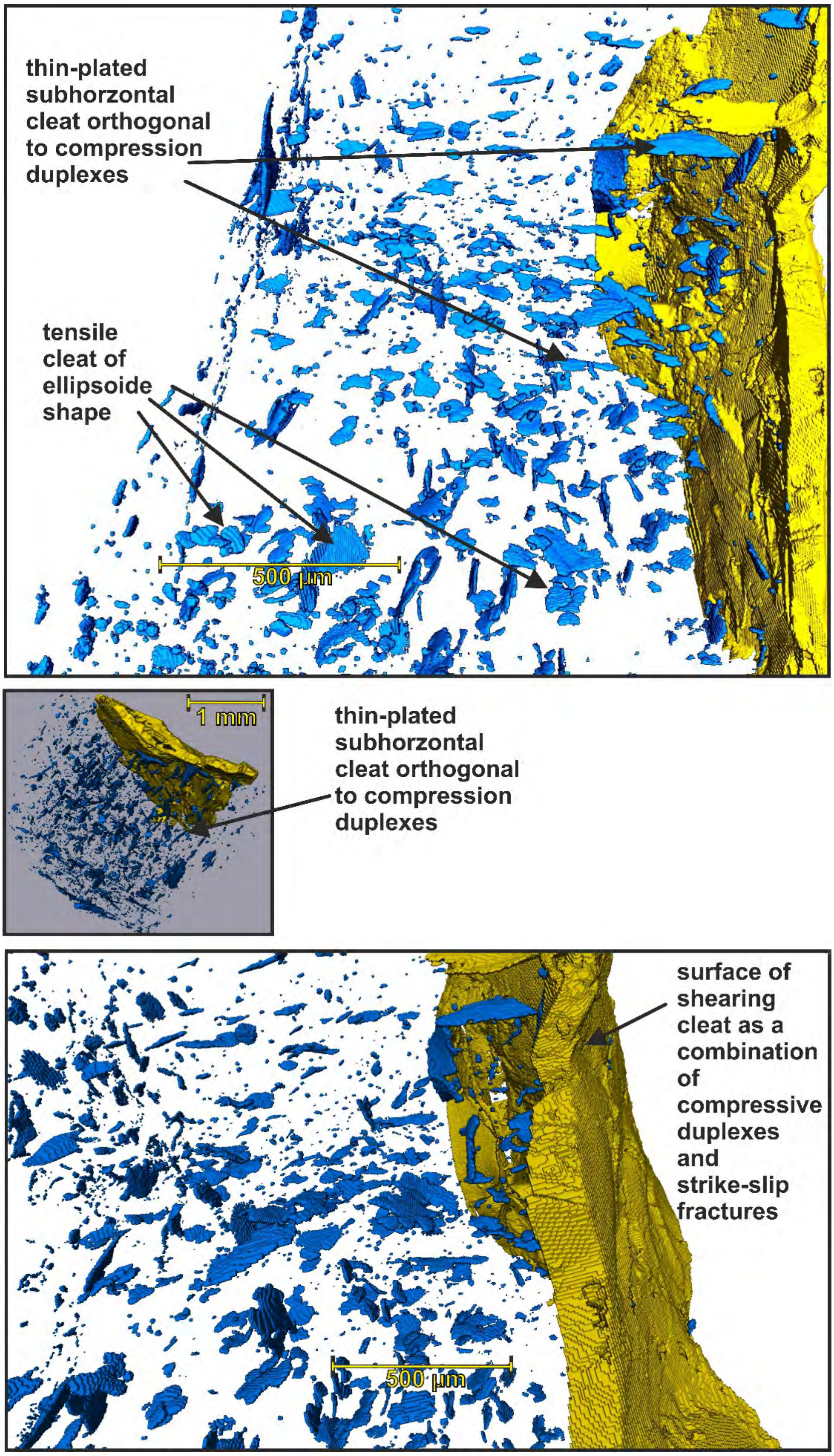

Fig. 7. 3-D relationship between thin-plated subhorizontal cleat orthogonal to compression duplexes and tensile cleat of ellipsoid shape (resolution X-ray CT 2 µm).

Conclusions.

We have to conclude that inferred presence of cleat sets opens very promising horizons for a brighter future of the Lorraine basin. It is important to note that inferred microfracture clearly possess features of self-similarity that may be used as important and proper argument for choosing optimal exploration strategy.

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ІДЕНТИФІКАЦІЯ СИСТЕМ КЛІВАЖУ У ВУГІЛЬНИХ КОЛЕКТОРАХ МЕТАНУ ЛОТАРИНЗЬКОГО БАСЕЙНУ ЗА ДОПОМОГОЮ МЕТОДІВ РЕНТГЕНІВСЬКОЇ КОМП'ЮТЕРНОЇ ТОМОГРАФІЇ

Мета. *Лотаринзький басейн - одне з найбільших геологічно і комерційно важливих кам'яновугільних родовищ Західної Європи. Басейн має незаперечний потенціал щодо видобутку вуглеводневої сировини із нетрадиційних колекторів, включаючи значні поклади метану в вугільних пластах, яким властиві природні системи кліважу. Кліваж вугільних пластів виявляється у вигляді систем відкритих або заповнених мінералізацією тріщин та чисельних поверхонь сколювання у вугіллі. Саме по тріщинах відбувається міграція метану, що міститься в вугільних пластах. Кліваж і його параметри (орієнтування тріщин, ступінь їх розкриття), а також кінематичний тип безпосередньо впливають на процеси, що відбуваються в вуглепородному масиві, бо роблять вугільні пласти проникними, служать шляхами міграції флюїдів, зокрема метану. Метою цієї публікації є дослідження є визначення на підставі результатів рентгенівської комп'ютерної томографії (КТ) просторових тенденцій розподілу екзогенного кліважу, що виникає під дією різних за кінематикою тектонічних рухів з метою забезпечення належних технічних рішень для ефективної розвідки та експлуатації вугільного метану.*

Методика. *Для дослідження тріщинуватості вугілля нами було використано рентгенографічну комп'ютерну томографію (КТ) зразка вугілля з дослідницької свердловини Tritteling 1 (пласт 10 з вестфалу D). Досліджений зразок вугілля та його два локальні об'єми були обстежені за методом КТ в трьох серіях експериментів (з роздільною здатністю 30, 10 і 2 мкм).*

Результати. *Детальний аналіз за допомогою рентгенівської КТ дозволив ідентифікувати просторовий розподіл взаємозв'язаних мереж систем мікротріщинуватості, які забезпечують максимум проникності у вугільних пластах. Розпізнавання кліважних тріщин за цим методом можливо за рахунок двох властивостей. По-перше, вони можуть бути частково відкриті та містити порожнечий простір. По-друге, ці тріщини часто ущільнюються мінералізацією, що сприяє різкому контрасту щільності на тлі вугільної речовини. Ці кліважні тріщини можуть повторно активуватися під час експлуатації колекторів метану, що має сприятиме зростанню об'ємної проникності. Досліджені на різних рівнях роздільної здатності, тобто системи тріщин вугілля різних ієрархічних щаблів, мають ознаки самоподібності та ідентичний структурний малюнок, що узгоджується з напрямками тектонічного поля напруг.*

Наукова новизна. *У цій роботі представлені результати аналізу структурних тенденцій систем кліважу у вугільних колекторах метану Лотаринзького басейну.*

Практична значимість. *Характеристика тріщинуватості вугілля має вирішальне значення для визначення ефективності видобутку метану з колектора. Тріщини кліважу мають бути достатньо добре розвинутими, щоб вугільний метан зміг мігрувати до свердловини. Вивчення та деталізація систем кліважу є важливим першим кроком в оцінці можливості промислової розробки газу.*

Ключові слова: *Лотаринзький вугільний басейн, метан вугільних пластів, рентгенографічна комп'ютерна томографія, системи кліважу, кінематичний тип тріщин, тектонічне поле напруг.*

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