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Multi-scale structural inheritance of fracture systems pattern in coal-bearing measures of the Lorraine-Saar coal Basin

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The Lorraine-Saar Basin (LSB) is one of the major Paleozoic coalfields of Western Europe that has been shapedover two centuries as a heartland of underground coal mining and associated industrial activities in the transborderarea of France and Germany. The Basin still has considerable coal reserves accumulated in numerous laterally continuous coal seams that were affected by processes of thermogenic production of gaseous hydrocarbons during post-Carboniferous burial and related coalification. The LSB stands out by its up to 6 km sedimentary column and its inversion resulting in Paleozoic erosion in the range of 750 m (French part of the Basin) and pre-Mesozoic (Permian) erosion between 1800 and 3000 m (German part of the Basin). Historically, coal production in the Lorraine and the Saar portions of the entire Basin was associated with numerous mining hazards because of the high methane content in coal seams. The LSB has the potential to host an enormous unconventional resource base including coalbed methane (CBM). Coal mines here are no longer operated to produce coal; however, methane generated in deep compartments is venting here via fracture swarms to the Earth's surface. Cutting natural methane emissions throughout CBM production within coal-bearing terrains is a crucial opportunity for slowing global warming rates. Nearly all CBM plays worldwide are affected in some way by natural multiscale fracture sets ranging from large fault zones to closely spaced joints, micro-shears, or cleat sets in coal seams. The LSB is not excluded indeed from this trend because of the long-term experience of geological exploration during extensive coal mining in the past. Characterization of structural patterns of fracture networks at different scales is a pragmatic process boosting the reliable perception of the performance of coalbed methane gas reservoirs. The focus of this contribution is to get an insight into the style and kinematic description of the multi-scale fault and cleat patterns in the LSB based on results of subsurface and underground geological mapping, and X-ray computer tomography. It will benefit the right mindset to ensure proper technical decisions for efficient exploration and exploitation of CBM reservoirs in the Basin.

Key words: Lorraine-Saar coal Basin, coalbed methane, environmental challenges, mitigating methane emissions, geologic structure, fracture networks, multi-scale analysis, X-ray computer tomography, cleat systems.

Introduction. The Lorraine-Saar basin (LSB) is one of the largest geologically and commercially important Carboniferous-Permian infill sedimentary basins in Western Europe. The coal-bearing measures here host numerous coal layers varying in thickness from a few centimeters to 4—5 m, unusually 15 m, or even more for the thickest seams that distributed through the Pennsylvanian sequences, which are beneath the Mesozoic sedimentary cover in France, and mostly outcropping in the German part of the basin. The industrial revolution launched large-scale commercial exploitation of the coalfield in Germany and France in the nineteenth century.

Historically, coal production in the Lorraine and Saar portions of the entire basin was associated with multiple mining hazards and a dramatic chain of fatal incidents because of the high gas content (more than 96 % CH_4) in coal seams. Thermal maturation of essentially vegetable organics in sedimentary clastic rocks and coal seams here has led to the formation of coalbed methane (CBM) resources stored within the porous coal matrix and fracture systems. The petroleum systems of the LSB are ultimately associated with the Carboniferous source rocks. Historic parametric deep wells have shown methane showings throughout the Pennsylvanian Westphalian and Stephanian sequences in the interval 1.0—5.7 km with progressive increasing diagenetic and catagenetic alterations with depth from sub-bituminous coals to meta-anthracites.

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 of its abnormal ability to trap heat in the atmosphere (more than 25 times potent comparing with CO_2) [Nisbet et al., 2019].

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 a result, on the French side, coal mining ceased in 2004, and coal extraction in Saarland ended in 2012. Coal mines in the LSB are no longer operated to produce coal; however, even these abandoned mining «naturally gassy» sites can still produce significant GHG venting into the atmosphere through diffuse shafts and boreholes and natural fracture systems corridors. The migration of methane towards the surface takes place for many years following the closure of a mine [Alsaab et al., 2008; Krause, Pokryszka, 2013; Pryvalov et al., 2020]. This hazardous phenomenon of methane release on the surface is associated with active mining and, more specifically, with the post-mining period.

The dense network of tectonic fractures together with post-mining subsidence effects, including fault reactivations, may also increase the permeability of a coal-bearing massive and provide sites for local discharging ground or even mine waters accompanied with a breathing of deadly explosive and environmentally hazardous mine gases. From 2006, mine workings got progressively flooded, creating huge mine water reservoirs [Corbel et al., 2017]. In the conditions of flooding closed methane mines, the uprising of the water table facilitates the methane migration to the surface within post-mining areas.

The CBM reservoirs are quite different from conventional gas reservoirs. However, extracted methane from coal beds is virtually identical to the gas produced from conventional sandstone reservoirs. Commercially successful production of CBM from coal-bearing formations is still restricted to the North American and Australian terrains. However, the interest for targeting CBM resource plays is progressively sweeping towards Europe. Several EU member states are attempting to cover gaps between steadily growing energy demand and supply possibilities and considering the ultimate aim to ease their dependence on imported fossil fuel with the help of CBM developments.

The latest estimate of CBM within just local site «Bleue Lorraine» (168 km^2) is 1,783 million cubic meters of proven reserves and up to 32 billion cubic meters of contingent resources. The latest state-in-art engineering geological models and advanced techniques based on them are of crucial importance in the utilization of this unconventional resource. Some of these developments include adaptations of existing technologies used in conventional oil and gas deposit harnessing, while others include new applications designed specifically to address the unique properties of coal, which serves both as source rock and a storage reservoir for gas. 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. Moreover, CBM is a very captive source of energy and is also a clue for success in ecological transition. An independent study performed in February 2016 by the IFEU (Institute for Energy and Environmental Research de Heidelberg, Germany) highlighted that the production of CBM locally in Lorraine coalfield must be considered as an environmentally friendly asset providing the reduction a carbon footprint in 10 times comparing with the utilization of imported gas.

CBM extraction in the Lorraine-Saar basin must be considered a low-cost option targeted to mitigate methane emissions in the region and overall stabilization of anthropogenic climate change.

Geologic setting and structural framework of the Lorraine-Saar Coal basin. In gross structural terms, the LSB was settled and developed since Namurian-Westphalian time upon the southern-western portion of the Saxo-Thuringian zone due to the late evolution of the Variscan Belt Europe. During the Late Palaeozoic Variscan orogeny, multiple coal-bearing environments were formed in sedimentary basins across Western Europe, where the formation of coal seams took place in the coastal plain (paralic) environments linked with the open sea (for instance, the Ruhr basin in Germany, the Wallonian and the Kempen basins in Belgium, the Nord et Pas de Calais basin in Northern France). Unlike most coal basins, the intramontane Lorraine-Saar coal basin had no hydrological connection with the sea at the time of peat deposition.

As it was mentioned by Korsch and Schäfer [1995], exclusively non-marine sediments in the basin were deposited in a narrow, structurally controlled pull-apart basin, which sedimentary infill has been built for two stages of sedimentation: the Late Paleozoic one, when the Lorraine was simply a limnic coal-bearing basin within the framework of units of the Variscan chain [Izart et al., 2005], and the Early Mesozoic one, when the Lorraine-Saar basin become a part of the newly-born Paris basin [Guillocheau et al., 2000].

Dextral strike-slip deformation component is widely recognized across Middle-Late Paleozoic Europe along NW-SE and W-E striking sub-concentric wrench faults, e.g., Wight-Bray-Vittel, North Artois faults [Badham, Halls, 1975; Arthaud, Matte, 1977; Privalov et al., 2019].

The LSB forms a narrow half-graben structure in structurally SW-NE trending a 300-km-long, 70-km-wide megablock of parallelogram shape (Fig. 1) that lies on the basal detachment of the Metz-South Hunsrück (MSH). The eastern limit of the megablock is bounded by subsurface damage zone and related scarp of the MSH Fault, which was formed during oblique extension (>35 %) along with an inverted Variscan thruste [Korsch, Schäfer, 1995]. Careful examination of the seismic data [Henk, 1993; Korsch, Schäfer, 1995]depicted that the MSH Fault is not subvertical 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 ~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 western limit of the megablock may be drawn roughly at the subhorizontal décollement level wherein the surface of basal detachment flattens and dies.

Geologically, the LSB 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) [Izart et al., 2016] and pre-Mesozoic (Permian) erosion between 1800 and 3000 m (the Saar coalfield or German part of the basin) [Hertle, Littke, 2000]. A key moment for successful interpretation of all data available is the unique information source obtained from isopach maps constructed for the Carboniferous units [Korsch, Schäfer, 1995]. 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 (see Fig. 1).

The classical interpretation of the geologic history of the basin by Donsimoni [1981]

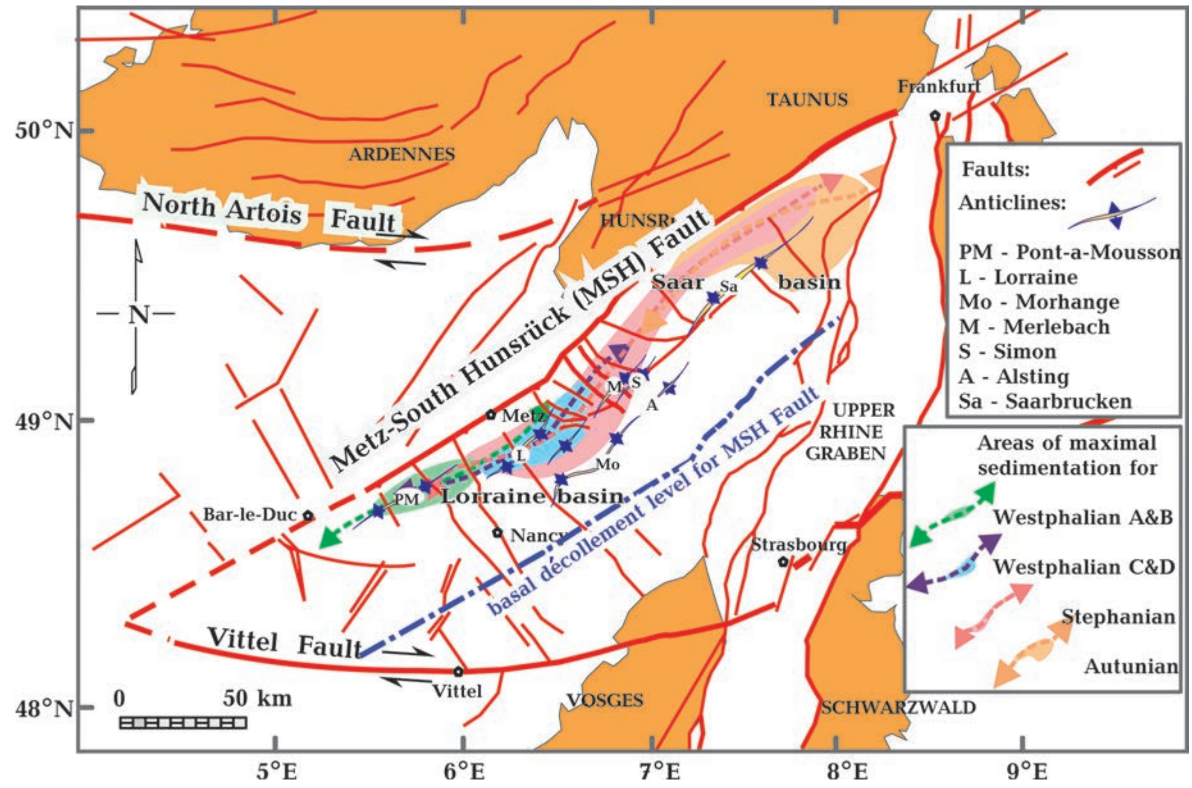


Fig. 1. The structural setting, tectonic elements, and depocentres of maximal sedimentation of the Lorraine-Saar basin.

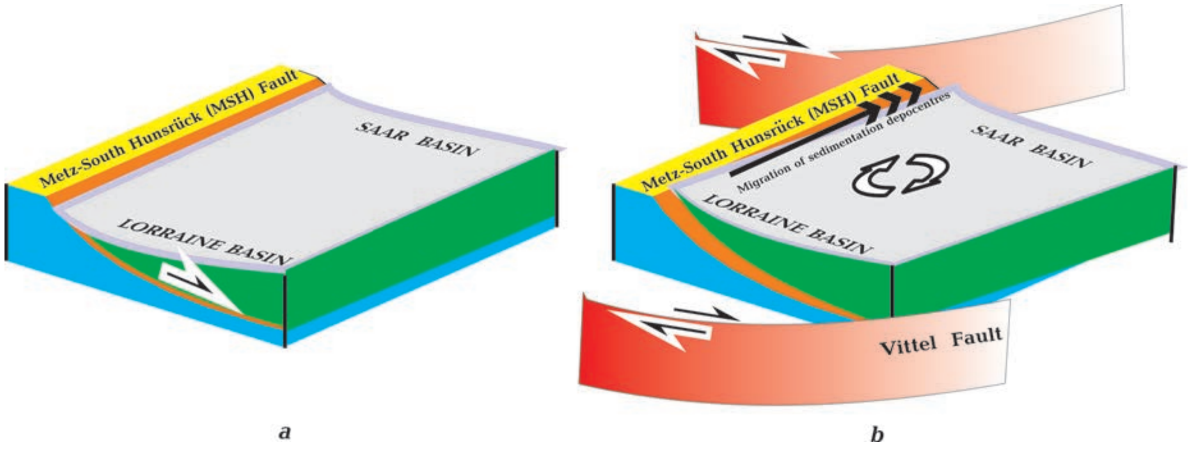


Fig. 2. Model of structural evolution of the LSB: *a* — the initial stage of basin formation as a half-graben structure in the hanging wall of the SE-dipping detachment of the MSH normal fault; *b* — the NE-trending migration of depositional centers during Carboniferous-Early Permian triggered by sustained clockwise rotation of basin megablock in the framework of right-lateral reactivation of master Vittel and North Artois shear faults.

considers an extensional control of the sedimentary sequences during the Carboniferous since Namurian. Meanwhile, Schäfer [2011] cited two compression episodes, the first during Viséan (340 Ma) and the second one corresponding to the folding-and-thrusting event in the Lorraine coal basin during Moscovian (Westphalian C, 310 Ma). More specifically, there is the principal contradiction in the age of the principal compressive deformation in the Lorraine and the Saar portions of the entire basin.

From Beccaletto et al. [2019], a folding associated with reverses faulting in the Merle-

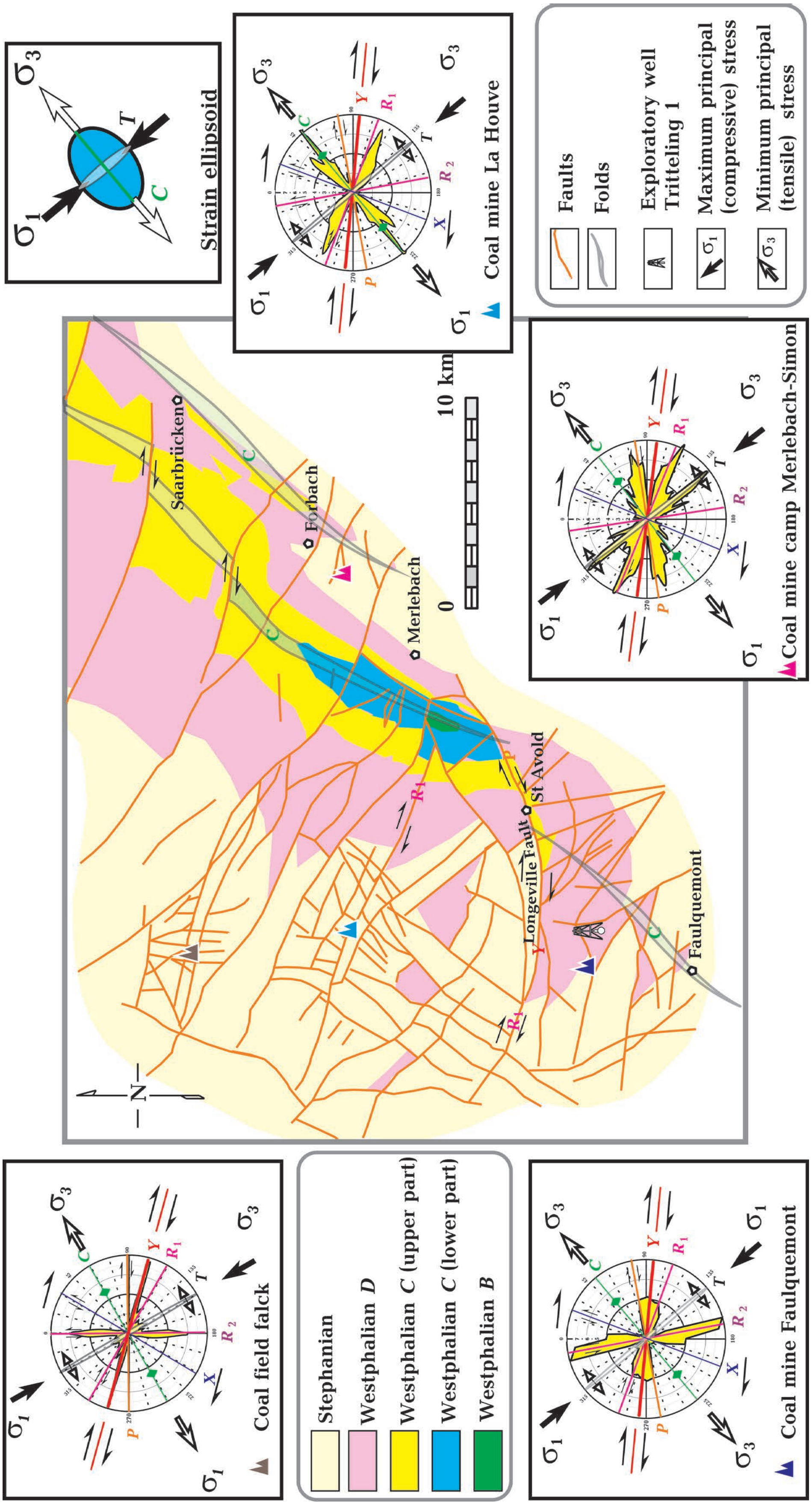


Fig. 3. Structural map of the Lorraine basin supplemented by interpretation fracture patterns in coal mine scales.

bach and the Morhange anticline occurred during the deposition of the Westphalian D and can be related to the Asturian tectonic phase; meanwhile, normal faults in distension occurred during the sedimentation of Stephanian and Autunian between the anticlines.

According to Korsch and Schäfer [1995], the most significant deformation patterns are concentrated in the strip between the MSH Fault and the pervasive structure of the Saarbrücken Anticline. Past studies [Hertle, Littke, 2000] have shown that the Saarbrücken anticline and superimposed overthrust complex with displacement in the range of 3.6 km were formed during the Saalian tectonic phase, which took place from the Stephanian to the Permian. However, from sections presented by Donsimoni [1981] deducted from shallow industry seismic reflection data, it is evident that this tectonic phase has not so dramatically expressed in the Lorraine subbasin, and it appears to be recorded only in the northernmost part of the French territory of the basin.

From these findings and records of contrasting depositional and deformational histories alone in the Lorraine and Saar parts of the basin, it seems clear that the internal structure of this largest Permo-Carboniferous basin cannot be explained simply as a result of half-graben structure evolution.

Stollhofen [1998] brought multiple sedimentary and tectonic proofs of the presence of strike-slip faults across the basin. Moreover, small-scale strike-slip faults are deducted during underground geological surveys in mining galleries from a sense of shear movement on documented slickensides [Bles, Lozes, 1980].

During Carboniferous-Permian syn-rift development, the basin underwent an intrabasinal segmentation generated by the offsets of NW-SE oriented normal faults, which were propagated perpendicular to the SW-NE basin elongation. Additionally, the entire structural pattern of the basin was breached by zones of sublatitudinally trending dextral (oblique) strike-slip faults arranged at an acute angle 45±15° anticlockwise to traces of normal faults and at the same angle clockwise to axes of anticlines.

In our interpretation, the Lorraine-Saar basin is a thin-skinned pull-apart basin that developed in the localized crustal extension domain of the hanging wall of the listric Metz-South Hunsrück (MSH) within a dextral shear zone. Its southern margin coincides with the Vittel master Fault as a fragment of the Wight-Bray-Vittel megazone [Badham, Halls, 1975; Arthaud, Matte, 1977], a basement dextral shear extending over 700 km from Bristol Channel to Eastern France and partly concealed beneath Mesozoic sediments of the Paris basin. The northern limit of the basin is along the eastern prolongation of the North Artois shear zone [García-Moreno et al., 2015], with dextral strike-slip displacement represented by a bundle of parallel faults recorded from the Weald basin across the English Channel and southern Belgium to northern France boundary. This zone roughly follows the Hercynian front and extends across the Paris basin southerly from the Southern Ardennes fault zone.

Following ideas [Christie-Blick, Biddle, 1985; Cunningham, Mann, 2007], we imply that discrepancy in subsidence and deformation patterns in the French and German portions of the entire LSB may be caused by feedbacks to motion on active strike-slip master faults, block rotation effects, and related spatial distribution of restraining and releasing bends. The particular NE-trending moving of depositional centers here during Carboniferous-Early Permian (see Fig. 1) along the SE-dipping MSH Fault preserves a record of the clockwise rotation of the LSB megablock within the frame of the dextrally reactivated shear zone bounded by Vittel and North Artois master faults. Such sustained clockwise rotation of the basin megablock (Fig. 2) has resulted in gradual narrowing and uplift of the area sedimentation in the Lorraine portion of the basin and traveling sedimentation depocentres into the German Saar part [Pryvalov et al., 2016].

The mentioned above misfit in dating of folding events in the Lorraine subbasin (Asturian tectonic phase) and the Saar subbasin (Saalian tectonic phase) also may be explained by variations in local compression environments localization as a reaction to the sign-variable rotation of the LSB, which was combined with non-rigid deformational responses (torsion, dilatation, distortion) of the megablock during alternative right- and left-lateral strike-slip reactivations of master shear faults.

Kinematic interpretation of regional and local scale tectonic fractures in the Lorraine portion of the LSB. The Lorraine-Saar coalfield is a well-documented example of a sufficiently explored coal basin wherein geological and structural maps were improved after results of underground coal mining [Bles, Lozes, 1980; Donsimoni, 1981; Villemin, 1987]. The region appears highly faulted and fractured, as indicated by the set of maps identified from the drilling and mining surveying data.

In the present study, we will concentrate on the kinematic interpretation of structural trends of multi-scale tectonic elements (fractures and folds) within the Lorraine portion of the LSB.

Our interpretation of the structural map of the Lorraine subbasin (Fig. 3) is supplemented by results of the underground documentation of kinematic indicators within small-displacement faults and mining panel-scale geologic mapping in coal mines Faulquemont [Bles, Lozes, 1980]and La Houve, coal mine camp Merlebach-Simon, coalfield Falck [Villemin, 1987].

Observations on the nature and appearance of fractures suggest that the kinematic behavior of the fracture pattern may be explained by the scheme of development of subsidiary structures within a strike-slip zone, wherein the maximum and minimum principal stresses σ_1 and σ_3 lay in the horizontal plane and the intermediate principal stress σ_2 is vertical.

The total set of the fault-and-fold population is consistent with the NW-SE compressive stress σ_1, and SW-NW tensile stress σ_3 within the dextral shear zone of the principal direction Y (azimuth 275—285°) includes:

- Conjugated dextral synthetic R_1 (azimuth 290—300°) and sinistral antithetic R_2 (azimuth 350—0°) Riedel shears;
- Conjugated dextral synthetic P (azimuth 80—90°) and sinistral antithetic X (azimuth 20—30°) shears;
- Reversed faults, thrusts, compression folds C, which formed parallel to the strain ellipse long axis (azimuth 50—60°);
- Tension fractures, normal faults T (azimuth 320—330°), which formed perpendicular to the strain ellipse long axis.

Synthetic Riedel shears R_1 are normally the first subsidiary fractures to occur at an acute angle ~15° clockwise to a dextral principal displacement zone Y. Generally R_1 individually, or in assemblage with master Y shears and synthetic P shears, build the most prominent set within the roses-diagrams.

For instance, the Longeville Fault of concentric geometry consists of segments of R_1, Y, and P dextral shears, and its Y — trending fragment could be considered a mainstream trend of the principal displacement (shear) zone of the study area. In like manner, antithetic R_2 shears (i.e., with a sense of displacement opposite to the bulk movement within Y shear) are recorded (Fig. 3, coalfield Falck and mine Faulquemont). In the eastern and north-eastern parts of the basin, the transpression has generated highly shortened anticlines complicated by over thrusts C.

Similarly, considering differences in rheological properties of «mechanically weak» coal layers and more competent hosting lithologies (sandstones, siltstones, etc.), we can highlight the presence at mine underground levels specific micro-thrusts dissecting coalbed integrity into overlapping slices. These detachments of centimeters-decimetres scale parallel to strain ellipse long axis C (Fig. 3, mine La Houve) are exclusively developed in coal seam bodies and can be explained in the framework of the «progressive easyslipthrusting»concept Frodsham, Gayer [1999].

Large dip-slip normal faults providing NW-SE segmentation of the basinal structure into subdomains and minute scale tension fractures are also widely documented during underground mine surveying. These normal faults and extensional diaclases of different scales are parallel to the strain ellipse small axis T (Fig. 3, coal mine camp Merlebach-Simon).

Natural fracture systems and their importance for the comprehension of the potential of CBM plays. 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 activated coalcharacteristics, which 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.

Perceiving 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 a typical lack of natural bulk permeability. Absolute permeability in coal is highly dependent upon the presence of natural fracture sets or cleats, which is just a miner's term for closely spaced fractures or joints in coal.

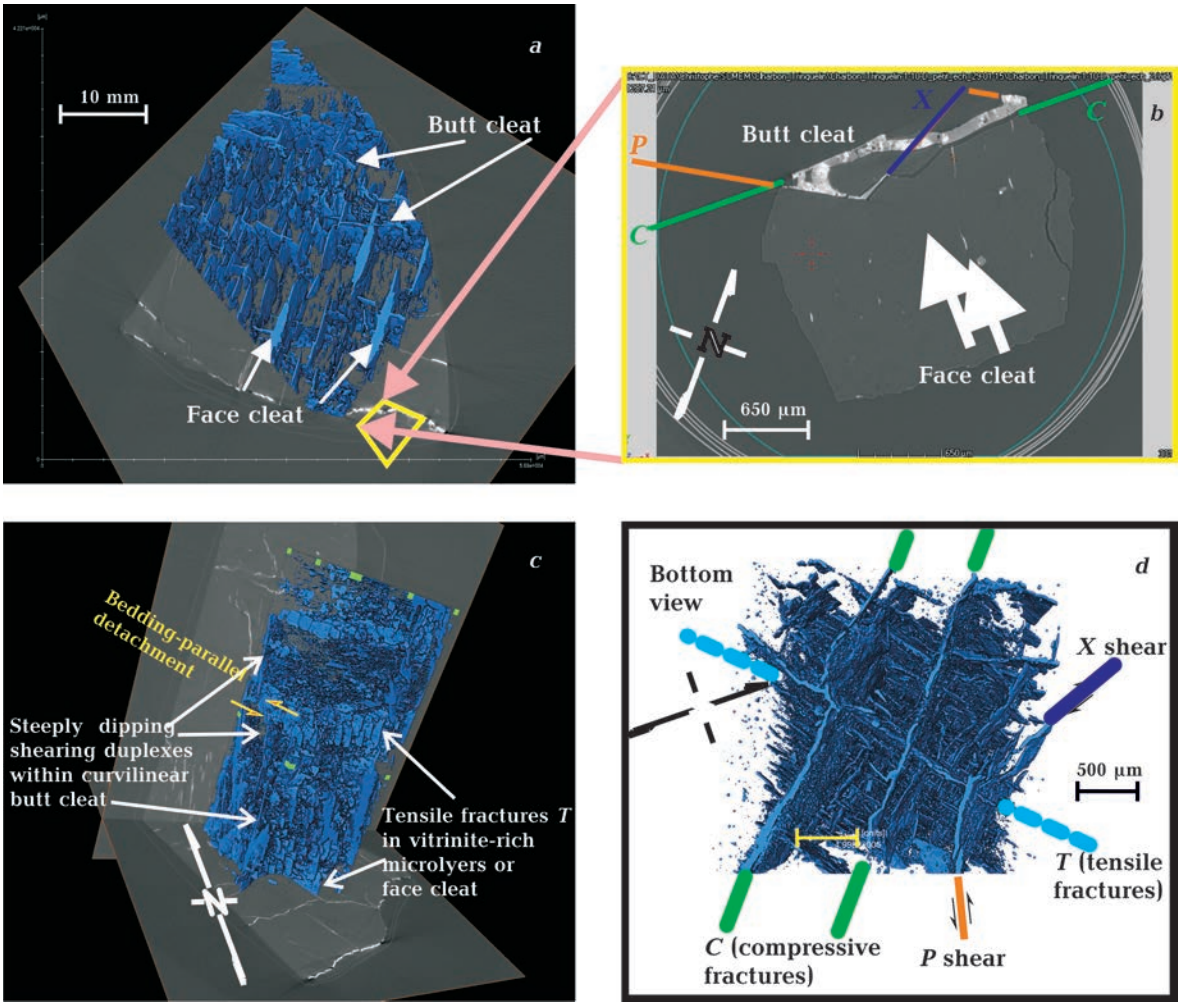


Fig. 4. Representations of the most prominent quasi-orthogonal systems of micro- and nano-fractures in the studied sample after X-ray CT experiments: *a* — the visual imagery of 3-D relationship between ellipsoidal face cleat and shearing butt cleat (resolution of X-ray CT 30 µm); *b* — the detalization of revealed patterns of the smooth-sided cleat of tensile origin (T) and the butt cleat as an assemblage of compressive (C) and strike-slip X, P shears (resolution of X-ray CT 2 µm); *c* — the 3-D view of the studied sample (resolution of X-ray CT 30 µm) that depicting the intrastratified control of tensile cleat intensity, details of shearing micro-thrust duplexes structure, and layer-parallel shear sliding; *d* — Kinematic description of curvilinear butt cleat as a combination of compressive (C) and strike-slip (X, P) fractures from the bottom view of the studied sample (resolution X-ray CT 30 µm).

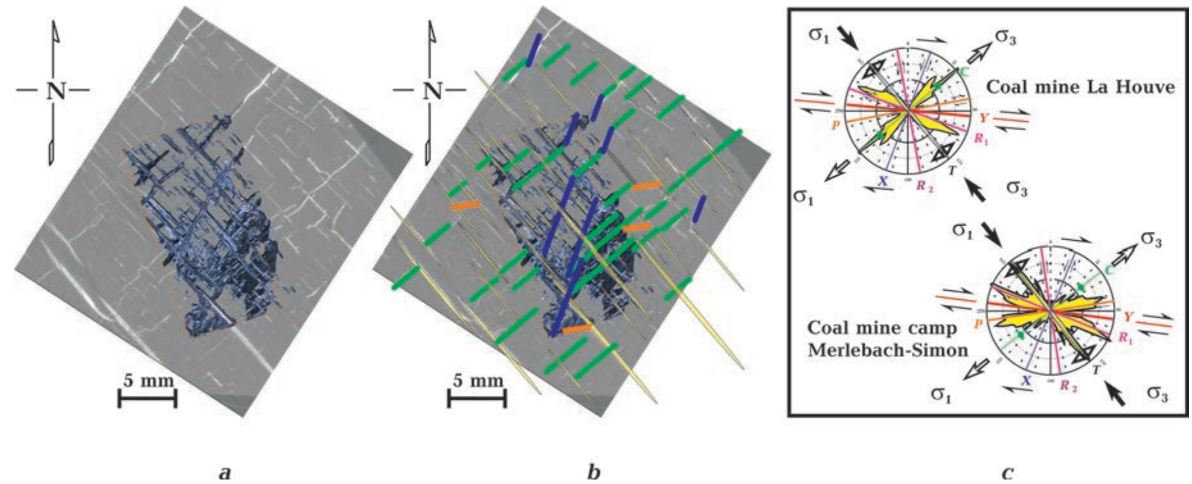


Fig. 5. Fracture systems in the studied sample (resolution X-ray CT 30 μm): *a* — the horizontal slice image from CT scan with volume rendering of stuck cleat arrays within a 5 mm-thick layer; *b* — the interpretation of cleat orientation as tensile joints T (face cleat) and curvilinear butt cleat, which is combined compressive microthrusts C and strike-slip fractures of X and P types; *c* — kinematic context of small-scale faults documented during underground coal mining.

A proper understanding of cleat patterns is a key factor in delineating the forecast of the performance of coalbed methane gas reservoirs. Opening-mode tensile cracks and their assemblages may directly serve as natural channels for CBM migration to the production well. Other cleat joints (e.g., micro-shears, micro-thrusts) can reactivate during CBM exploitation providing additional pathways for gas transport. The knowledge of geometrical features of fracture and cleat patterns is a crucial parameter for determining the real permeability of a resource play, its kinematics environment, and further reservoir simulation [Pryvalov et al., 2013].

Thermally generated gas from deep compartments and low-permeability levels (a depth exceeding 3.5 km — dry gas window) have escaped via several major fault-breached corridors forming structurally related gas accumulations in coal-bearing lithologies within antiform-type structures (e.g., Lorraine, Merlebach, and Alsting anticlines), wherein strata folded upwards lead to enhanced permeability and additional fracturing. The real fluid conductivity of coal seams is 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.

Methodology of tomography experiments for investigating multi-scale cleat patterns in coal samples. To explore the architecture of micro- and nano-cleat patterns in the coal of the Lorraine basin, we used computer tomography (CT) using 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 have chosen the coal specimen collected from the Westphalian D coal seam 10 of exploratory well Tritteling 1 at a depth of 1239 m. The studied coal specimen and its twolocal 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 an 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.

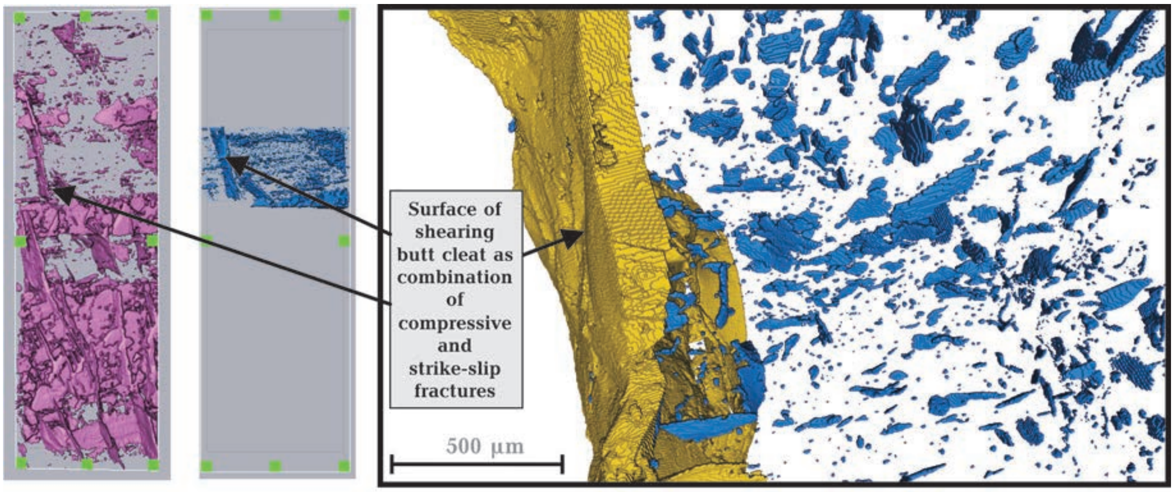
For digital geometry processing and following 3D visualization, exploration, and quantification analysis of cleat patterns, VG-Studio 2.2, Avizo FEITM, and GoCAD software packages were used.

Results and Discussion. ***The spatial patterns of cleat networks and their kinematic interpretation from X-ray CT scans and related 3-D imagery.*** At different levels of resolution in X-ray CT experiments, we identified two quasi-orthogonal systems of the cleat (Fig. 4), including the smooth-sided medallion-shape tensile fractures or face cleat and curvilinear shearing cleat system or butt cleat.

Much of the literature on coalbed methane reservoirs focuses on these quasi-orthogonal cleat patterns [Laubach et al., 1998], which orientation depends on the main tectonic directions and strain ellipsoid. Cleats in coal are intimately related to stress fields within basin infill during and after coalification. Historically, much attention has been given to the so-named endogenetic cleat developing by the discharge of devolatilization stresses in coal during the thermal maturation of organic matter. Much more attention needs to be given to exogenetic cleat when tectonic stresses impose orientations of individual fractures and cleat system sets [Pashin et al., 1999; Pitman et al., 2003].

After X-Ray CT internal inspection of samples, we delineated elliptically convexed face cleat fractures (Fig. 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 deducted from the interpretation of the distribution of small-scale faults and fractures in coal mines (Fig. 5). Their opening takes place perpendicular to the direction of the minimum (tensile) principal stress σ_3.

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-Saar basin, wherein the strike-slip component of deformation is recognized across the entire basin, this cleat could be



Cleat networks after *X*-ray CT (resolution – 30 µm)

Cleat networks after *X*-ray CT (resolution – 10 µm)

3-D block-diagram cleat networks after *X*-ray CT (resolution – 2 µm)

Fig. 6. Cleat networks after X-ray CT inspection of the principal specimen and its subvolumes with different resolutions.

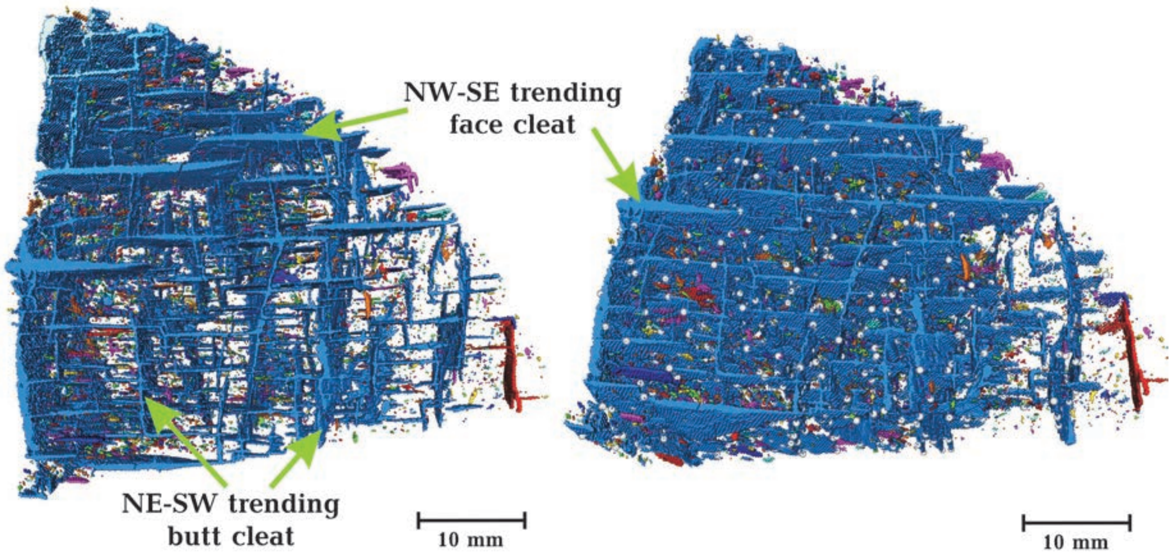


Fig. 7. Connectivity pattern of cleat networks after X-ray CT inspection of the sample (resolution 30 μm). The biggest connected cleat cluster in the sample (resolution of X-ray CT- 30 μm) is shown in blue, other connected cleat volumes are shown in different colors.

classified as related to tensional stresses during folding of the strata.

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 (see Fig. 4, *c*). 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.

There is an essential difference in the mechanical properties of an entire coal seam, and more specifically, its microlayers, because of different maceral compositions. Between contacts of coal microlayers, this phenomenon caused an abundant appearance of sliding planes and the formation of specific shearing duplexes or small-scale steeply dipping structures that connect bedding-parallel detachments.

These steeply dipping with sigmoidally curved imbricated surface fractures of mostly compressive origin often occurred in association with the localized thickening of seams. There is a strong connection between overpressure in coal seams and the formation of these fractures [Frodsham, Gayer, 1999].

The butt cleat propagates along the direction of minimum (tensile) principal stress σ_3, and it a curvilinear shearing assemblage of fractures represents it as a combination of compressive structures C and shears of type X and P (see Fig. 4, Fig. 5).

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. 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.

Fig. 6 exhibits cleat networks depicted from results of the X-ray CT multi-scale investigation of the principal specimen and its subvolumes performed at different resolutions. The obtained 3D imagery demonstrates 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. This means that interconnected cleat networks in coal can be represented as an assemblage of rescaled selfcopies [Jing et al., 2017]. The fragmentation of coals [Pryvalov et al., 2017] into elementary self-similar subordinated blocks is of high importance to serve as the model capable of simulating connectivity in coal samples.

The connectivity pattern of cleat networks from the acquisition of X-ray CT data. Coal transport properties during CBM recovery are highly dependent on the estimates of the fracture networks' integration into swarming arrays. Linked sets of fractures have to act as major gas and water flow pathways within a coal seam during CBM recovery.

Our connectivity estimations were based on the calculation of the ratio between the total length of cleat intersection and the entire length of detected cleat [Rodrigues et al., 2014]. The results allow distinguishing the presence in the studied sample's of a highly connected fracture cluster (Fig. 7), which contains almost 92.2 % of the total volume of the cleat.

To summarize, almost all fractures here are connected into a merging assemblage of NW-SE trending face and NE-SW trending butt cleats.

The existence of well-connected natural fracture arrays at the X-Ray CT scans is the promising signal for presence in coal beds of the Lorraine-Saar basin naturally fractured high-permeability spots, wherein interconnected microfractures will provide success in the commercial development of CBM.

Conclusions. Multi-scale fracture system characterization is critically important for success in the implementation of CBM projects, especially in mature coal-mining districts, wherein closed mines and adjoined virgin coal-bearing sites might produce intensive venting, through fracture corridors, of environmentally hazardous methane into the atmosphere.

Located in the transfrontier area of France and Germany, the Lorraine-Saar coal basin is characterized by the presence of a high range of scale-variable natural fracture systems. These systems include large and minor faults and stress-related cleat sets, which provide most of the interconnected macroporosity in coal. Observations on the nature and appearance of fractures within regional and underground mine-panel scale structural maps suggest that their structural pattern was induced by the strike-slip regime of deformation. Kinematic characteristics of the generated fault-and-fold population are consistent with the NW-SE compressive stress σ_1 and SW-NW tensile stress σ_3 affected the LSB.

Based on the X-ray CT experiments with different resolutions, we identified orientation and kinematic characteristics for two quasi-orthogonal systems of the cleat. It is important to underline that the inferred spatial pattern of kinematically induced cleat systems possesses features of structural inheritance and 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 fault-and-fold structures set up in the basin in concert with the strike-slip tectonic model of the basinal evolution.

Documented through X-ray CT experiments, the 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.

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Мультимасштабна картина структурного успадкування систем тріщин у вугленосних товщах Лотаринзько-Саарського вугільного басейну

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Лотаринзько-Саарський басейн (ЛСБ) — один з головних палеозойських вугільних басейнів Західної Європи, котрий протягом двох століть виконував роль важливого осередку підземного видобутку вугілля та пов'язаних з ним багатопрофільних видів промислової діяльності у транскордонному районі Франції та Німеччини. Басейн має значні запаси вугілля, зосереджені в численних латерально витриманих вугільних пластах, в яких під впливом процесів вуглефікації під в процесі занурення кам'яновугільних відкладів генерувалися газоподібні вуглеводні. ЛСБ виділяється потужним осадовим чохлом до глибини 6 км, який зазнав інверсійних рухів, що призвели до палеозойської денудації близько 750 м у французькій частині басейну та домезозойської (пермської) денудації в діапазоні 1800—3000 м у німецькій частині басейну. Історично вуглевидобуток у районах Лотарингії та Саару був пов'язаний зі значними ризиками безпеки підземних робіт через високий вміст метану у вугільних пластах. ЛСБ має величезний потенціал щодо видобутку нетрадиційної вуглеводневої сировини, включаючи метан вугільних пластів. Вугільні шахти тут більше не експлуатують для видобутку вугілля; однак метан, що утворився на глибоких горизонтах унаслідок термогенних перетворень органічної речовини, мігрує по тріщинах до земної поверхні. Скорочення природних викидів метану за рахунок видобування метану вугільних пластів є винятково важливою можливістю для уповільнення темпів глобального потепління. Практично всі відомі родовища вугільного метану в світовому масштабі так чи інакше порушені системами природних різномасштабних тектонічних розривних дислокацій — від великих зон розломів до близько розташованих мікрозсувів і тріщин кліважу у вугільних пластах. З огляду на багаторічний досвід геологічних досліджень під час видобутку вугілля в минулому, ЛСБ не є винятком з цієї тенденції. Характеристика структурних закономірностей розподілу тріщинуватості у різних масштабах є прагматичним процесом, що підсилює адекватне сприйняття продуктивності покладів вугільного метану. Основна мета статті — отримати уявлення про стиль і кінематичні характеристики мультимасштабних систем тріщин у вугленосних товщах на підставі аналізу результатів геологічного довивчення площ ЛСБ, підземної геологічної документації гірничих виробок, а також рентгенівської комп'ютерної томографії зразків вугілля. Це допоможе вибрати правильну стратегію забезпечення належних технічних рішень для ефективної розвідки та видобутку метану вугільних пластів у басейні.

Ключові слова: Лотаринзько-Саарський вугільний басейн, метан вугільних пластів, екологічні проблеми, зменшення викидів метану, геологічна структура, тріщинуватість, мультимасштабний аналіз, рентгенівська комп'ютерна томографія, системи кліважу.