DOI: 10.31643/2027/6445.47
Earth and Planetary Sciences: Earth-Surface Processes

Study of Rock Mass Fracturing in the Sherubaynurinsky Site

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Received: *February 27, 2026*
Peer-reviewed: *March 14, 2026*
Accepted: *April 2, 2026*

ABSTRACT

This study investigates the fracturing of the rock mass and coal-bearing strata at the Sherubaynurinsky site of the Karaganda Coal Basin, under the complex geological and geomechanical conditions characteristic of this methane-bearing sector of the basin, in order to support coalbed methane development. Borehole image logging was carried out in exploration well Sh-9 over the depth interval of 155–905 m using a Formation MicroImager (FMI) together with standard open-hole logs. The interpretation made it possible to determine bedding dip angles, identify intra-seam layering, and detect faults, microfaults, conductive, partially conductive, and healed fractures, as well as borehole breakouts and drilling-induced fractures. Four structural zones were distinguished within the studied interval, and the predominant fracture orientation was found to be NE–SW. The obtained results improve the understanding of fracture distribution and stress-related features of the massif and can be used for geological modeling, well trajectory design, and the selection of promising methane-drainage zones.

Keywords: coal seam fracturing, coalbed methane development, azimuthal electrical microimager, borehole images, methane-enriched zones.

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Introduction

One of the main challenges in methane extraction is the identification of high-methane-bearing zones within a coal seam based on specific indicators. To address this issue, it is necessary to shift the conceptual framework toward a structural and methane-oriented characterization of the coal seam. First and foremost, the simplified empirical understanding of natural methane content and coal seam structure should be reconsidered [[1], [2], [3]].

In addition to the heterogeneity of methane distribution within the coal seam, permeability is also spatially variable. Methane in coal occurs as gas adsorbed on the coal surface or within pore surfaces. When reservoir pressure decreases, methane expands within the pore space [4]. As a result, coal fracturing and the corresponding permeability increase [[5], [6]]. For effective methane extraction from coal seams, it is essential to first identify zones with the highest methane concentration and then determine the drainage capacity of the target zone or define the permeability field [[7], [8]]. Fracturing plays a crucial role in controlling the migration of gas and water within the coal seam, underscoring the necessity of studies aimed at identifying methane-enriched zones associated with natural fracturing. Such zones can be identified through the construction of a detailed geological model of the coal deposit.

The foundation of well-based methane extraction technology lies in modifying the stress–strain state of the seam by creating local discontinuities (cavities, slots, fractures) or by utilizing natural discontinuities (cleat fractures, geological fractures, and cavities) [[9], [10]].

Gas content in coal seams exhibits zonal characteristics and is uneven both laterally across the site and vertically with depth. This variability is governed by the geological structure of the deposit. Gas content and gas recovery are also influenced by the properties and occurrence parameters of the surrounding rocks. The existing geological models of coal seam occurrence are insufficient for accurately predicting gas characteristics due to the sparse network of exploration wells. Therefore, the development of new computational tools for constructing geological models of coal deposits using modern numerical methods is required [[11], [12], [13]].

When constructing a geological model of a coal deposit, it is necessary to account for key seam characteristics such as cleat systems, principal horizontal stresses, and gas permeability. Gas permeability strongly depends on depth and the degree of fracturing. In the Karaganda Coal Basin, permeability at depths exceeding 500 m is very low and, according to various sources, ranges from 0.002 to 0.005 millidarcies [14].

Cleat fractures are generally oriented perpendicular to the principal horizontal stresses. The gas yield of degasification wells drilled perpendicular to cleat fractures is an order of magnitude higher than that of wells drilled parallel to the cleat orientation [15].

The forecast hydrocarbon gas resources within the Sherubaynurinsky site to a depth of 500 m amount to 8,540 million m³, or 8.5 billion m³, and to a depth of 1,500 m may reach up to 20 billion m³. At the Sherubaynurinsky site, coal reserves have been developed at a relatively low rate. Most of the reserves remain undisturbed. Therefore, this site is considered promising for methane production. The objective of this study is to determine the fracture characteristics of the coal seam and surrounding rock mass at the Sherubaynurinsky site to support geological modeling and evaluate the site's potential for methane extraction.

Experimental part

The study was conducted using the Formation MicroImager (FMI) azimuthal electrical microimager in an exploration well over the depth interval of 155–905 m to record borehole images and standard open-hole logging curves.

Within the Sherubaynurinsky site of the Karaganda Coal Basin, well Sh-9 was drilled to a total depth of 905 m. The FMI survey was performed in the interval 155–905 m in order to identify geological elements of the section, refine their structural characteristics, and conduct a detailed fracture analysis. The well is vertical, with a maximum deviation from vertical of 3°, and a bit size of 8.5 inches. FMI-HD images and standard logging curves were recorded in an open hole using a water-based drilling mud. FMI processing included speed correction, depth alignment of the tool electrodes, and compensation for missing data from individual electrodes within the study interval.

To accurately calculate bedding dip angles, irregular tool movement during logging had to be corrected. Speed corrections based on accelerometer data were performed in two stages. Accelerometer measurements recorded simultaneously with microresistivity data were used to compute tool velocity corrections. The corrected velocity curves were then applied to recalculate depth and eliminate abrupt tool movement variations that could result in information loss. Tool sticking or stopping during recording was diagnosed when the tool acceleration did not exceed 0.01 m/s².

Image-based speed correction utilized the electrode array configuration, individual electrode velocity calculation, and correlation between adjacent electrodes. These methods were applied together with a tool-sticking removal option to achieve optimal results.

Image equalization was performed within a 4.572 m window to compensate for minor variations in resistivity measurements among individual electrodes and to obtain an absolute resistivity level. Static and dynamic normalization were applied throughout the entire interval (155–905 m) using 256-color histogram equalization. A fixed window was used for static imaging, whereas a moving window was applied for dynamic imaging to highlight subtle resistivity variations in formations with minimal resistivity contrast. Variations in resistivity are displayed as different shades on the image: the higher the formation resistivity, the lighter the image.

The FMI recording is presented as two images: static and dynamic. The static image reflects large-scale changes related to lithological and stratigraphic variations, whereas the dynamic image enables visualization and differentiation of very small-scale amplitude changes associated with rock structure and texture.

Bedding dip angles throughout the 155–905 m interval was manually interpreted. The following structural elements were identified: bed boundaries, coal seams, carbonatized layers, intra-seam bedding, faults, microfaults, conductive and partially conductive fractures, non-conductive fractures, drilling-induced fractures, and borehole breakouts. These elements are displayed as sinusoids and vector symbols (“tadpoles”) in Figures 1–2 of the interpretation results.

Beds represent sedimentary deposits arranged in layers with varying characteristics and thicknesses [16]. On FMI images, bed boundaries appear as continuous sinusoidal lines of small amplitude in vertical wells and large amplitude in horizontal wells. Structural analysis of bed boundaries assists in determining structural dip. On the images, bed boundaries are shown in green.

Intra-seam bedding is subdivided into cross-bedding and subhorizontal bedding. Analysis of intra-seam structural elements helps determine depositional environments, providing insight into the geometry and reservoir properties of coal horizons for subsequent well placement. Cross-bedding consists of moderately inclined planar surfaces formed during sand deposition and indicates high-energy depositional conditions. Subhorizontal bedding consists of planar surfaces in sandstones deposited under low-energy conditions.

Conductive fractures are typically the result of natural tectonic forces [[17], [18], [19]]. On FMI images, they appear as dark sinusoidal features whose open spaces are likely filled with water-based drilling mud or other conductive materials such as clay. Non-conductive fractures are also of tectonic origin and appear as light sinusoidal features. These fractures are filled or cemented with non-conductive minerals such as calcite or carbonate salts, making them impermeable and preventing fluid flow.

Faults and microfaults are likewise formed by tectonic forces. On FMI images, faults appear as persistent, typically high-amplitude sinusoids, characterized by abrupt lithological changes above and below the fault plane and often accompanied by drag zones.

Drilling-induced fractures are generated by maximum horizontal stresses during drilling and form on the borehole wall parallel to the direction of maximum horizontal stress [[20], [21]]. These fractures are always open and filled with drilling mud, appearing as dark vertical or near-vertical lines on opposite sides of the tool pads.

Borehole breakouts form during drilling due to the action of minimum horizontal stress, resulting in borehole enlargement (difference between caliper measurements C1 and C2) in the direction of minimum horizontal stress, provided the well is vertical or near-vertical.

The orientation of horizontal stresses serves as input data for geomechanical analysis and hydraulic fracturing (HF). Artificial fractures generated during HF propagate in the direction of maximum horizontal stress.

Legend for the FMI interpretation overview diagram (Figures 1–2): Column 1 – measured depth (MD), borehole deviation, caliper logs C1 and C2, nominal bit size (BS), FMI data quality flag (red); Column 2 – 3D borehole shape; Column 3 – borehole profile; Column 4 – static FMI image, orientation of the first FMI pad relative to true north; Column 5 – dipmeter interpretation of geological elements, bedding dip azimuth; Column 6 – structural zones; Column 7 – paleocurrent analysis (dip of cross and horizontal bedding corrected for structural dip, azimuth of cross-bedding); Column 8 – orientation of drilling-induced fractures and breakouts; Column 9 – orientation of natural fractures and faults; Column 10 – zones of common fracture strike direction; Column 11 – fracture density, fracture length, standard gamma ray log (HSGR, green), computed gamma ray excluding uranium (HCGR, red); Column 12 – standard neutron log (TNPH), density log (RHOZ), photoelectric factor log (PEF); Column 13 – coal intervals; Column 14 – double-packer intervals (OPK).

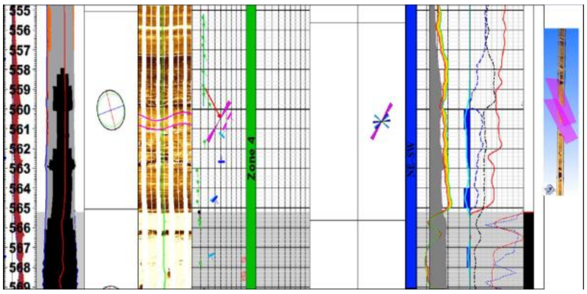

Figure 1 - FMI image showing microfaults identified at depths of 560.5 m and 561.0 m, striking NE–SW

A high fracture density and minor drag (indicated by the red arrow) are observed near the fault zone.

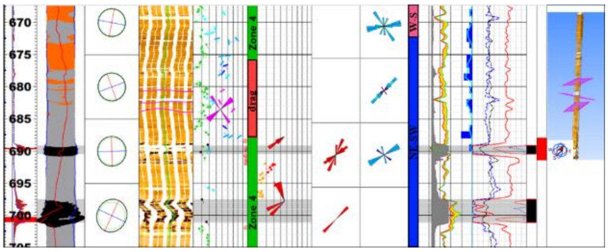

Figure 2 - FMI image showing microfaults identified at depths of 680.7 m and 683.7 m, striking NE–SW, and at a depth of 682.4 m, striking NW–SE

A high fracture density and a zone of fault drag are observed near the fault.

Structural dip analysis includes the identification of the main structural features of the deposits, such as bed boundaries and faults, as well as their statistical analysis, the distribution of dip angles, and the orientation of structural elements.

As a result of the interpretation, bedding dip angles were determined within the studied interval of 155–905 m. The dip angles range from 1° to 60°. The average bedding dip is 9.7°, with a predominant dip toward the southeast and a secondary direction toward the northeast.

Within the 155–905 m interval, four structural zones were identified:

1) zone 1: 155–183 m, 48° toward the NW;
2) zone 2: 183–371 m, 4.6° toward the NNW;
3) zone 3: 371–549 m, 6.6° toward the SE;
4) zone 4: 549–905 m, 13.7° toward the SE.

For coal seam mapping and the planning of subsequent wells, it is recommended to conduct a facies analysis based on borehole images (Figure 3). The borehole image represents a significant complement to core-based facies analysis and enables three-dimensional reservoir modeling.

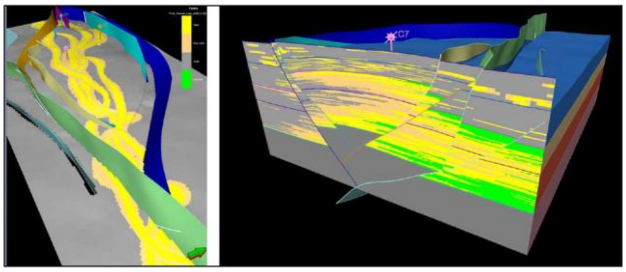

Figure 3 - Three-dimensional model of the deposit constructed from facies analysis results

The input data for such an analysis include sandstone layers identified within the studied interval that exhibit cross-bedding and subhorizontal bedding. The orientation of these structures indicates the direction of paleowater flow during sedimentation and, consequently, the direction of sand body development. Knowing the spatial distribution of sand bodies makes it possible to predict the location of potential flooding zones where coal formation may occur.

To determine the paleoflow direction and assess the depositional environment, a correction for the structural dip angle was applied. Before correction, the dip angle of intra-seam bedding ranged from 1° to 35°, with a predominant dip azimuth toward the southeast and a secondary direction toward the northwest (Figure 4).

After applying the structural dip correction, intra-seam bedding can be subdivided into cross-bedding and subhorizontal bedding. The paleoflow direction is determined by cross-bedding, which shows multidirectional orientations, indicating frequent changes in depositional conditions within the studied interval.

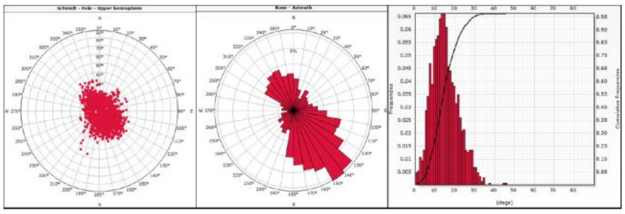

Figure 4 - Distribution, orientation, histogram, and strike directions of intra-seam bedding before structural dip correction

The dip angle of intra-seam bedding varies from 1 to 35 degrees, with a predominant dip azimuth toward the southeast and a secondary direction toward the northwest.

Fractures identified on FMI images are represented by high-amplitude sinusoids in vertically drilled wells and low-amplitude sinusoids in horizontal wells. In the presence of fractures in the section, unlike faults, the correlation of geological horizons is not disrupted. Within the studied interval, conductive, partially conductive, and non-conductive (healed) fractures were identified. Partially conductive fractures are visible only on 2–3 tool pads. Conductive fractures are likely filled with water-based drilling mud. This type of fracture may also be healed by any electrically conductive mineral, for example, clay. Healed fractures exhibit high resistivity on FMI images due to infilling with high-resistivity minerals (primarily calcite)

The strike of conductive fractures predominantly trends NE–SW and N–S. The strike of partially conductive fractures is NW–SE and NE–SW. The predominant strike of non-conductive (healed) fractures is NE–SW.

Fracture strike varies by interval (Figure 5): NE–SW zone: 155–195 m, 840–905 m; multidirectional strike zone: 195–265 m; NNW–SSE zone: 265–315 m, 465–525 m; NW–SE zone: 575–673 m; NE–SW and NW–SE zone: 315–465 m, 755–840 m.

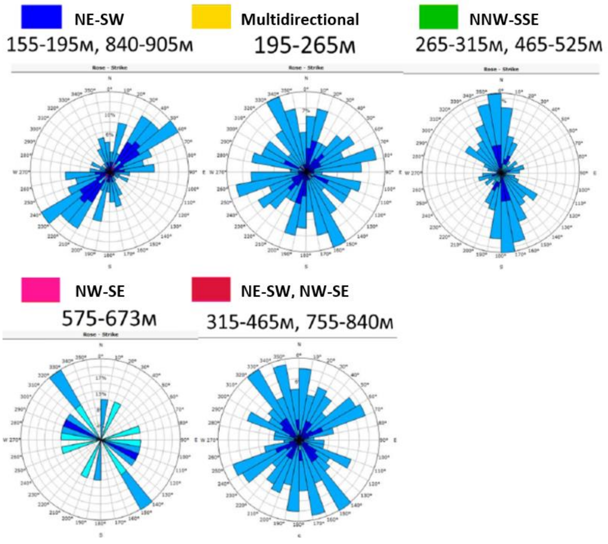

Figure 5 - Distribution of fracture strike directions by structural zones

Results and Discussion

As a result of the interpretation, the dip angles of the layers in the research interval of 155-905 m were determined. The dip angles vary from 1 to 60 degrees. The average dip angle of the layers is 9.7 degrees, with a predominant dip to the southeast and a secondary dip to the northeast.

In the research interval of 155-905 m, four structural zones were calculated: zone 1: 155-183 m, 48 degrees to the northwest; zone 2: 183-371 m, 4.6 degrees to the west-northwest; zone 3: 371-549 m, 6.6 degrees to the southeast; zone 4: 549-905 m, 13.7 degrees to the southeast. In the studied interval, intra-layer stratification was identified. To determine the direction of paleoflow and assess the sedimentary environment, a correction for the structural angle was introduced.

In the FMI image, fault planes were highlighted at depths of 262.1 m and 307.8 m, with strike directions of northwest-southeast, at depths of 382.5 m and 383 m with strike directions of northeast-southwest and north-south, respectively. Changes in lithology or filtration reservoir properties along the fault plane, increased fracture density, and slight displacement of the layers (fault at a depth of 262.1 m) confirm the fault interpretation [[22], [23]].

In the FMI image, microfracture planes were highlighted at depths of 560.5 m, 561 m, 680.7 m, and 683.7 m with a strike of northeast-southwest, and at a depth of 682.4 m with a strike of northwest-southeast. Along the microfracture planes, slight displacement of the layers is observed, and areas of dragging are also visible near the microfracture planes.

In the studied interval, conducting, semi-conducting, and non-conducting (healed) fractures were identified on the FMI-HD images. The strike directions of the conducting fractures predominantly follow the northeast-southwest and north-south directions. The strike of the semi-conducting fractures follows the northwest-southeast and northeast-southwest directions. The predominant strike of the non-conducting (healed) fractures follows the northeast-southwest direction. The strike of the fracture changes by interval:

- zone northeast-southwest: 155-195 m, 840-905 m;
- zone of opposite strikes: 195-265 m;
- zone west-northwest-southeast: 265-315 m, 465-525 m;
- zone northwest-southeast: 575-673 m;
- zone northeast-southwest, northwest-southeast: 315-465 m, 755-840 m.

In the research interval, collapses and technogenic fractures were identified. The predominant direction of collapses (minimum horizontal stress) is northeast-southwest. The predominant direction of technogenic fractures (maximum horizontal stress) is northwest-southeast.

Conclusions

The interpretation of FMI data in the 155–905 m interval made it possible to identify the main structural features of the studied rock mass, including bedding dip, intra-seam layering, faults, microfaults, conductive, semi-conductive, and healed fractures, as well as borehole breakouts and drilling-induced fractures. The results showed that the interval is structurally heterogeneous and consists of several zones with different fracture orientations and deformation characteristics.

The study confirmed that natural fracturing plays an important role in the spatial distribution of methane-bearing zones at the Sherubaynurinsky site, since fracture systems control permeability and gas migration pathways. The obtained structural data can therefore be used to refine the geological model of the site and to support the planning of coalbed methane extraction, including well placement and the selection of intervals with higher drainage potential.

Further research should focus on integrating the identified fracture systems into a 3D geological and geomechanical model of the site and on evaluating the relationship between fracture parameters and methane productivity using additional logging, core, and production data.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

CRediT author statement: **D. Akhmatnurov:** Conceptualization, Methodology, Software; **A. Sadchikov:** Data curation, Writing draft preparation, Visualization; **N. Zamaliyev:** Investigation, Supervision; **E. Reshetnyakov:** Software, Validation, Reviewing and Editing.

Acknowledgements. This study was supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan as part of the program-targeted funding for the implementation of the scientific and scientific-technical program IRN BR28712407.

Cite this article as: Akhmatnurov DR, Sadchikov AV, Zamaliyev NM, Reshetnyakov ED. Study of Rock Mass Fracturing in the Sherubaynurinsky Site. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2027; 343(4):134-141. https://doi.org/10.31643/2027/6445.47

Шерубайнурин учаскесіндегі тау жыныстарының жарықшақтылығын зерттеу

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Мақала келді: *27 ақпан 2026*
Сараптамадан өтті: *14 наурыз 2026*
Қабылданды: *2 сәуір 2026*

ТҮЙІНДЕМЕ

Бұл зерттеу Қарағанды көмір бассейнінің Шерубай-Нұра учаскесіндегі тау жыныстары массиві мен көмірлі қабаттардың жарықшақтануын зерттеуге арналған және көмір қабаттарынан метан өндіруді ғылыми тұрғыдан негіздеуге бағытталған. Зерттеулер осы метанды аймаққа тән күрделі геологиялық құрылым және кернеулі геомеханикалық жағдайында ескеріле отырып жүргізілді. Геофизикалық зерттеулер Ш-9 барлау ұңғымасында 155–905 м тереңдік диапазонында жүргізілді, стандартты ашық ұңғымаларды каротаждау әдістерімен бірге кешенді түрде Formation MicroImager (FMI) ұңғымаларын микросканерлеу әдісін қолдану арқылы жүргізілді. Алынған материалдарды интерпретациялау қабаттардың құлау бұрыштарын анықтауға мүмкіндік берді, қабатішілік қабаттасуларды ерекшелеу, сондай-ақ жарылымдарды, микробүзылуларды, өткізгіш, жартылай өткізгіш және бітіп қалған жарықшақтарды анықтауға мүмкіндік берді. Сонымен қатар, ұңғыма қабырғаларының опырылу аймақтары мен бұрғылау әсерінен қалыптасқан жарықтар анықталды, бұл массивтің кернеулік жағдайын бағалауға мүмкіндік берді. Зерттелген аралықта төрт құрылымдық аймақ анықталды Жарықшақтардың басым бағыты солтүстік-шығыс - оңтүстік-батыс екені анықталды. Зерттеу нәтижелері жарықшақтанудың таралу заңдылықтарын тереңірек түсінуге мүмкіндік береді және оларды геологиялық модельдеуде, ұңғыма траекториясын жобалау мен перспективалы дегазация аймақтарын таңдауда пайдалануға болады.

Түйін сөздер: көмір қабатының жарықшақтылығы, көмір қабаттары метанын игеру, азимуттық электрлік микросканер, ұңғымалық кескіндер, метанға байытылған аймақтар.

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Поступила: *27 февраля 2026*
Рецензирование: *14 марта 2026*
Принята в печать: *2 апреля 2026*

АННОТАЦИЯ

Данное исследование посвящено изучению трещиноватости горного массива и угленосных толщ на Шерубай-Нуринском участке Карагандинского угольного бассейна с целью научного обоснования разработки метана угольных пластов. Исследования выполнены в условиях сложного геологического строения и напряжённого геомеханического состояния, характерных для данного метаноносного района. Геофизические исследования проводились в разведочной скважине Ш-9 в интервале глубин 155–905 м с применением метода микросканирования стенок скважины Formation MicroImager (FMI) в комплексе со стандартными методами каротажа в открытом стволе. Интерпретация полученных материалов позволила определить углы падения пластов, выделить внутрипластовую слоистость, а также выявить разломные нарушения, микронарушения, проводящие, частично проводящие и залеченные трещины. Кроме того, были зафиксированы зоны разрушения стенок скважины и трещины, индуцированные бурением, отражающие особенности напряжённого состояния массива. В пределах исследуемого интервала выделены четыре структурные зоны. Установлено, что преобладающее направление трещиноватости имеет северо-восточное - юго-западное простирание. Полученные результаты расширяют представления о закономерностях распределения трещиноватости и могут быть использованы при геологическом моделировании, проектировании траекторий скважин и выборе перспективных зон дегазации.

Ключевые слова: трещиноватость угольного пласта, освоение метана угольных пластов, азимутальный электрический микросканер, скважинные изображения, зоны, обогащённые метаном.

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