

Article

Risk Assessment of Sudden Coal and Gas Outbursts Based on 3D Modeling of Coal Seams and Integration of Gas-Dynamic and Tectonic Parameters

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Abstract: Sudden coal and gas outbursts pose a significant hazard in deep-seated coal seam extraction, necessitating reliable risk assessment methods. Traditionally, assessments focus on gas-dynamic parameters, but experience shows they must be supplemented with tectonic factors such as fault-related disturbances, weak interlayers, and increased fracturing. Even minor faults in the Karaganda Basin can weaken the coal massif and trigger outbursts. The integration of 3D modeling enhances risk evaluation by incorporating both dynamic (gas-related) and static (tectonic) parameters. Based on exploratory drilling and geophysical studies, these models map coal seam geometry, fault positioning, and high-risk structural zones. In weakened coal areas, stress distribution changes can lead to avalanche-like gas releases, even under normal gas-dynamic conditions. An expert scoring system was used to convert geological and gas-dynamic data into a comprehensive risk index guiding preventive measures. An analysis of Karaganda Basin incidents (1959–2021) shows all outbursts occurred in geological disturbance zones, with 43% linked to fault proximity, 30% to minor tectonic shifts, and 21% to sudden coal seam changes. Advancing 3D modeling, geomechanical analysis, and microseismic monitoring will improve predictive accuracy, ensuring safer coal mining operations.

Keywords: coal and gas outbursts; risk assessment; tectonic disturbances; 3D modeling; gas-dynamic parameters



Academic Editor: Ali Cemal Benim

Received: 26 March 2025

Revised: 4 June 2025

Accepted: 4 June 2025

Published: 17 June 2025

Citation: Portnov, V.; Mindubayev, A.; Golik, A.; Suleimenov, N.; Zakharov, A.; Madisheva, R.; Kolikov, K.; Imanbaeva, S. Risk Assessment of Sudden Coal and Gas Outbursts Based on 3D Modeling of Coal Seams and Integration of Gas-Dynamic and Tectonic Parameters. *Fire* **2025**, *8*, 234. <https://doi.org/10.3390/fire8060234>

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1. Introduction

Sudden coal and gas outbursts (GDP) are among the most hazardous emergency situations in the development of deep-seated coal seams. These events can result in significant economic losses, injuries, and fatalities, further emphasizing the urgent need for the development of reliable risk assessment methods. In the past, the assessment of outburst hazards was primarily based on the study of gas-dynamic parameters such as gas release rate, pressure, gas content, coal strength, and moisture [1–3]. However, experience from deep mine operations has shown that dynamic indicators alone are often insufficient to account for the influence of the structural and geological features of the coal massif. This limitation arises due to the absence of factors such as fault-related disturbances,

characteristics of adjacent fragmentation zones, the presence of weak interlayers within the coal seam, and areas of increased fracturing [4–7].

Recent studies indicate that a comprehensive assessment of GDP risks should include both dynamic and static parameters that define the mining and geological conditions of the coal seam. In this regard, the application of 3D geological modeling, based on exploratory drilling data and the interpretation of geological and geophysical information along exploration lines, enables a detailed characterization of the geometric structure and qualitative properties of coal seams, considering them as influencing factors in GDP. The resulting model allows for a quantitative assessment of the tectonic variability of the coal massif and helps identify critical zones where structural disturbances may contribute to the avalanche-like outburst of fine coal and gas release.

Changes in the structure and properties of a coal seam significantly affect the stress distribution within the rock mass and can act as triggering mechanisms for coal and gas outbursts, even under relatively “normal” values of dynamic parameters [6–9].

The geological characteristics of coal seams may have a decisive influence on the rock mass’s susceptibility to sudden outbursts by reducing the mechanical stability of the seam [3,9].

In recent years, research on the integration of static (geological) and dynamic (gas dynamic) parameters has been actively developing to create more objective models for assessing the risk of GDP. The application of 3D geological modeling enables a detailed reconstruction of the geometric structure of coal seams and the identification of critical zones characterized by local disturbances [10,11]. Integrating data on geological faults with measurements of gas-dynamic parameters improves the accuracy of predicting hazardous situations and helps identify safe areas for tunneling operations [10].

The development of 3D modeling is also progressing within the framework of numerical methods such as FLAC3D, UDEC, and others, which make it possible to model the stress–strain state of the rock mass by taking into account the influence of tectonic conditions [12–15]. Despite their high accuracy, these models require significant computational resources and extensive data on the physical properties of the coal-rock massif, making their application challenging for real-time monitoring during mine development.

Due to these limitations, researchers are increasingly turning to expert scoring systems, where geological exploration data and gas-dynamic measurements are converted into dimensionless indices, which are then summed to assess overall risk [16,17]. Although this approach is less detailed than numerical models, it allows for the rapid processing of heterogeneous data and the adaptation of the expert assessment methodology to the specific conditions of mines and coal seams.

The analysis of materials presented in the work by Fominykh E.I., Karev N.A., and Khodzhaev R.R., “Catalog of Sudden Coal and Gas Outbursts” [18], which covers incidents that occurred in the Karaganda Basin mines from 1959 to 2021, indicates that all coal and gas outbursts took place in zones of geological disturbances. Of these, 23 out of 53 cases occurred when mine works approached fault zones, primarily thrust faults, 19 occurred in areas with minor tectonic disturbances, and 11 outbursts were recorded in zones of seam thickness variation, where intense coal deformation or abrupt changes in seam elevation were observed. These facts provide grounds for using 3D models of the coal seams in the basin and analyzing the identified tectonic disturbances when assessing the risk of gas-dynamic events.

References [19,20] established a correlation between changes in coal strength, initial gas desorption rate, moisture content, and gas pressure in the coal seam with the comprehensive outburst hazard index, depending on the depth of seam D6 in the Tentek section of the basin. The hazardous value of this index was determined to be 10.5 ± 1.17 , which occurs at

a depth of 480 m, provided there is no influence of complicating geological factors such as geological faults or zones of increased methane concentration. It was also found that a coal seam is considered disturbed when the M.M. Protodyakonov strength coefficient is less than 0.8, which is characteristic of geological disturbance zones associated with increased rock pressure, transition areas from the edges of pillars or abandoned stopes, changes in the tectonic structure of coal seams, variations in seam thickness, mining operations conducted along or across geological faults, and exposure and retreat from outburst-prone seams such as K10, K12, and D6 from the floors of areas near moderate-amplitude geological disturbances. The classification of tectonic structures adopted in the basin includes five classes: very large fault disturbances (more than 1000 m), large faults (100–1000 m), medium faults (15–100 m), small faults (3–15 m), and very small faults (1–3 m).

Special attention is given to the integration of 3D geological models into the outburst risk assessment system for GDP. Combining geological data obtained through modern modeling methods with real-time measurements during development work allows not only for an overall hazard assessment but also for identifying local zones where the risk of an accident is particularly high [21]. This comprehensive approach enables an accurate separation of information sources: the geological model is used to calculate the tectonic index I_T , which reflects the static structure of the rock mass, while gas-dynamic parameters measured directly at the face are used to determine the gas-dynamic index I_{GD} [10,19,21].

An equally important area of research is the application of digital technologies and machine learning methods to automate the processing of large volumes of geological exploration data and improve the predictive capabilities of models [20,22]. For example, the use of cluster analysis algorithms and artificial neural networks allows for a more accurate identification of correlations between geological structure parameters and the dynamic behavior of the rock mass, which in turn enhances the quality of the integrated risk assessment [23].

This approach allows for taking into account the influence of local structural features on the outburst hazard of the rock mass, promptly identifying safe areas for tunneling operations, and implementing well-founded measures to prevent outbursts.

The improvement of the methodology for assessing CGO (coal and gas outburst) risks is possible through the integration of geomechanical calculations (stress–strain state of the rock mass), petrographic studies of coal, and microseismic monitoring of the coal-bearing rock mass, which makes it possible to improve the forecasting accuracy to ensure the safety of mining operations under conditions of deep coal seam occurrence [21].

The scientific novelty of the present study lies in the following key points: a detailed three-dimensional model of the Karaganda Basin is developed and implemented, which is updated as new underground drilling data become available and provides continuous refinement of the geometry, ash content, and thickness of coal seams and the amplitudes and dip angles of geological faults; a principle for calculating the integrated risk indicator is proposed, in which geological characteristics are extracted from the 3D model, and gas-dynamic parameters (gas emission rate, reservoir pressure, coal strength, etc.) are obtained from real-time face measurements; an algorithm is developed for calculating the tectonic index I_T and the gas-dynamic index I_{GD} which are aggregated into the integrated indicator I_{Total} . This approach allows for the consideration of the influence of local structural features on the outburst hazard of the rock mass, enables prompt identification of safe areas for mine drivage, and supports the implementation of justified measures to prevent outbursts.

2. Materials and Methods

Construction of a 3D Model of Coal Seams

For constructing the 3D model, the software ‘Vulcan’ (ver. 2024.1) was used, which provided data input on the geological description of the core from 414 exploration wells—results of coal sample analyses, which were collected by seam-bottom samplers and used to determine the thickness, structure, and composition of coal seams, as well as to assess ash content, volatile matter yield, and maceral composition; borehole coordinates; lithological characteristics of the geological section; and boundaries and thickness of coal seams results of geophysical well logging using various methods: apparent resistivity method, lateral current logging for correlation and structural analysis of coal seams, gamma–gamma logging for determining ash content, structure, and composition of coal seams, borehole polarization method to assess coal oxidation levels and sulfide mineralization, natural gamma activity method for identifying clayey interlayers and correlating borehole sections, cavernometry to detect borehole cavities associated with increased diameters in deformed or weakened intervals caused by tectonic disturbances, and inclinometry to determine the true thickness of coal seams and the spatial position of boreholes. All these data were utilized to build a 3D model to assess the variability and thickness of the mineable coal seams.

The modeling of coal seams and geological faults was carried out using Maptek Vulcan 2024 software. The geological grid was generated using the Integrated Stratigraphic Modeling (ISM) module, based on triangulation interpolation [10]. The block model was constructed using the HARP module with a block size of $25 \times 25 \times 0.25$ m [20].

Table 1 presents Coal seam thickness at “Kostenko” mine with minimum, maximum, mean, median, standard deviation and coefficient of variation. The analysis of data from seams K1, K2, and K3 shows that the minimum thickness of seam K3 is 1.2 m, while the maximum thickness of seam K1 is 6.97 m, with average values ranging from 3.41 m (K3) to 4.85 m (K2), indicating various geological conditions of occurrence. The median values are generally close to the mean, suggesting a fairly symmetrical distribution of seam thickness. The coefficients of variation indicate relative stability, ranging from 0.388 to 0.43. The standard deviation also confirms the heterogeneity of the seams. For example, seams K1 and K2 have the highest standard deviations of 1.91 and 1.68, respectively, characterizing significant thickness variations, whereas seam K3 has a slightly lower standard deviation of 1.45 m, indicating its relative uniformity. Table 2 presents the qualitative characteristics of coal, including ash content, volatile matter, and moisture content, which help assess the variability of coal properties in different sections of the seam. These indicators are also considered when planning coal extraction using longwalls, positioned along identified tectonic faults (Figure 1).

Table 1. Coal seam thickness (m) at “Kostenko” mine (minimum, maximum, mean, median, standard deviation and coefficient of variation).

Seam	Min.	Max.	Mean	Median	Std. Deviation	Coeff. of Variation
K1	2.20	6.97	4.59	4.65	1.91	0.42
K2	1.60	5.90	4.48	4.85	1.68	0.38
K3	1.20	4.50	3.41	3.60	1.45	0.43

Table 2. Quality characteristics of coal seams.

Seam	Ash Content, %	Moisture, %	Volatile Matter, %	Plasticity Index, mm	Relative Density, g/cc
K3	28.94	0.89	27.71	19.04	1.52
K2	30.69	1.12	27.80	8.85	1.54
K1	31.46	1.21	26.87	8.01	1.56

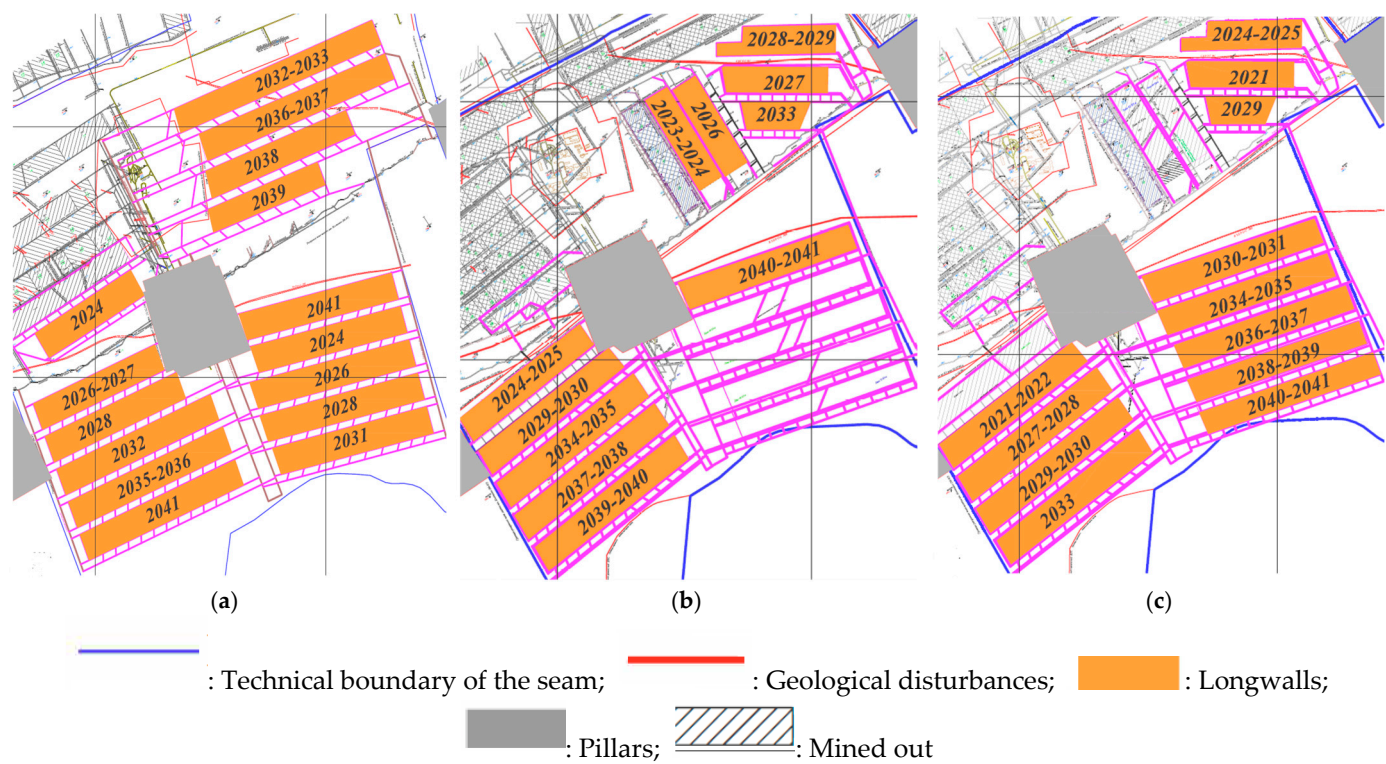


Figure 1. Planned longwall mining schedule by seams ((a) Seam K1; (b) Seam K2; (c) Seam K3).

Table 3 presents the results of the measurements of the mechanical properties of rocks and coal seams at the Kostenko mine, which are used to assess the size of the weakened zones near geological faults.

Table 3. Mechanical properties of rocks and coal seams at the Kostenko mine.

Strength	Units	Sandstone	Siltstone	Argillite	Coal	Marl
Elastic modulus	MPa	30,500	27,000	11,200–13,600	2500–4500	35,100
Poisson’s ratio	-	0.22	0.2	0.21	0.26	0.21
Uniaxial compressive strength (UCS)	MPa	50–76	33–56	20–36	10–17	52–53
Tensile strength	MPa	5.4–14.4	3.5–7.6	1.9–2.7	0.7–1.3	5.1–9.1
Bulk density	MN/m ³	2.6	2.4	2.2	1.3–1.5	2.7
Cohesion	MPa	14.2	10.2	8.7	1.2–3.6	9–14
Internal friction angle	(°)	25	25	25	18–39	23–27

Table 3 shows that sandstone and marl have the highest strength and stability, whereas coal remains the weakest and most pliable rock. This is crucial for mine planning and assessing changes under pressure and the influence of tectonic disturbances.

3. Results and Discussion

3.1. The Construction of a 3D Model of Coal Seams

For data alignment and cross-section interpretation, the spatial coordinates of boreholes are imported into specialized software, where they are converted into a unified coordinate system. This process utilizes pre-established geological survey lines and drilling profiles containing information on borehole locations, coal seam boundaries, and geological fault lines derived from core studies and geophysical borehole investigations. Files with borehole coordinates, lithology data, and qualitative characteristics are uploaded into the system, enabling the visualization of their spatial distribution.

Based on the results displayed along the geological survey lines, a detailed profile analysis is conducted, identifying zones with significant displacements, fragmentation areas, and regions of increased fracturing (Figure 2).

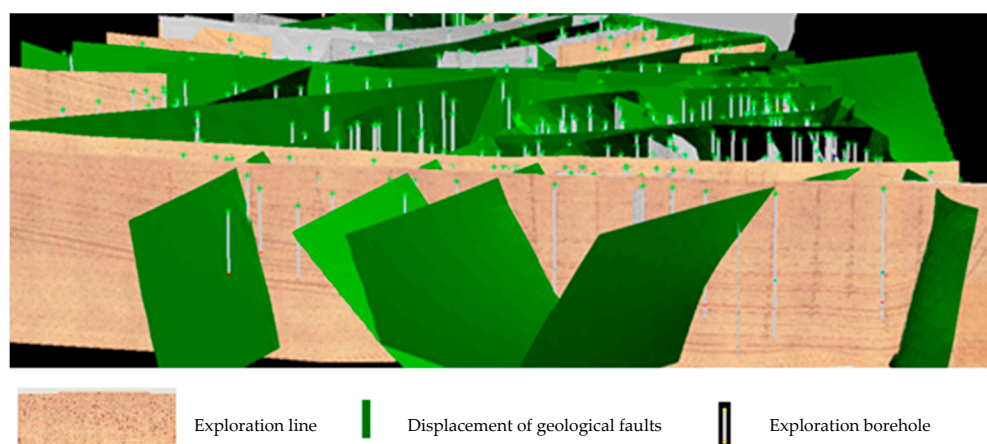


Figure 2. Correlation and interpretation of geological disturbances (green) along exploration lines at the Kostenko mine.

To identify and construct fault planes based on interpreted cross-sections, geological fault planes that interconnect to form distinct structural blocks are created.

The estimation of coal seam thickness and raw coal quality parameters was performed using the inverse distance weighting method (IDW²) and kriging with semivariogram parameters specified in Table 4. For modeling geological faults within each block, the roof and floor surfaces of coal seams are constructed based on the interpolation of data from exploration lines and interpreted cross-sections. This approach enables tracking displacements and deformations caused by faulting.

Table 4. Dimensions of the block model of Kostenko mine.

Direction	Initial Coordinate, m	Length, m	Main Block Size, m	Sub-Block Size, m
East (X)	88,925	9675	25	25
North (Y)	46,775	9875	25	25
Elevation (Z)	−1000	1600	0.25	1600

To improve the model's accuracy in representing the complex geometry of the deposit, the triangulated surface construction method was applied. This method converts a set of points obtained from cross-section interpretations into continuous surfaces that define the contours of coal seam roofs and floors, as well as the boundaries of geological faults.

Key aspects of this 3D modeling stage include accurately reproducing geometry through triangulation, which ensures high detail, especially in zones with significant

deformation, and is critical for determining fault parameters; reducing the impact of data discontinuities for a more precise assessment of fault positions and characteristics relative to exploration boreholes (Figure 3); and minimizing errors in constructing continuous coal seam surfaces (Figure 4);

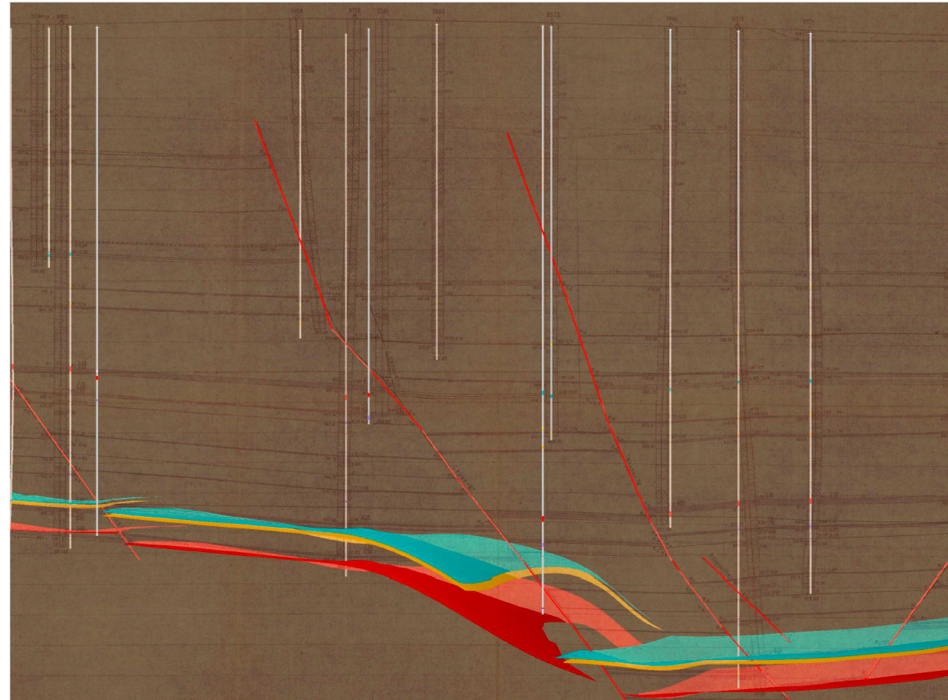


Figure 3. Roof surfaces of coal seams: K1 (red), K2 (orange), K3 (blue), and geological fault lines (red) at Kostenko Mine.



Figure 4. Cross-section of the floor surfaces of coal seams at Kostenko Mine along line A–A.

Construction of the block model of Kostenko mine

After constructing the triangulated surfaces, the formation of the block model was carried out, integrating all structural data into a unified 3D model that considered not only geometric parameters but also the qualitative characteristics of coal seams. The main stages of block model (Figure 5) formation included data integration, where all obtained structural units (from cross-section interpretation and triangulated surfaces) were combined with precise spatial referencing and visualization of qualitative characteristics, aimed at

displaying a unified model of parameter distribution, such as ash content, thickness, volatile matter content, and moisture. This approach allows for the identification of areas where geological disturbances affect coal properties. Table 4 presents the characteristics of the block model.

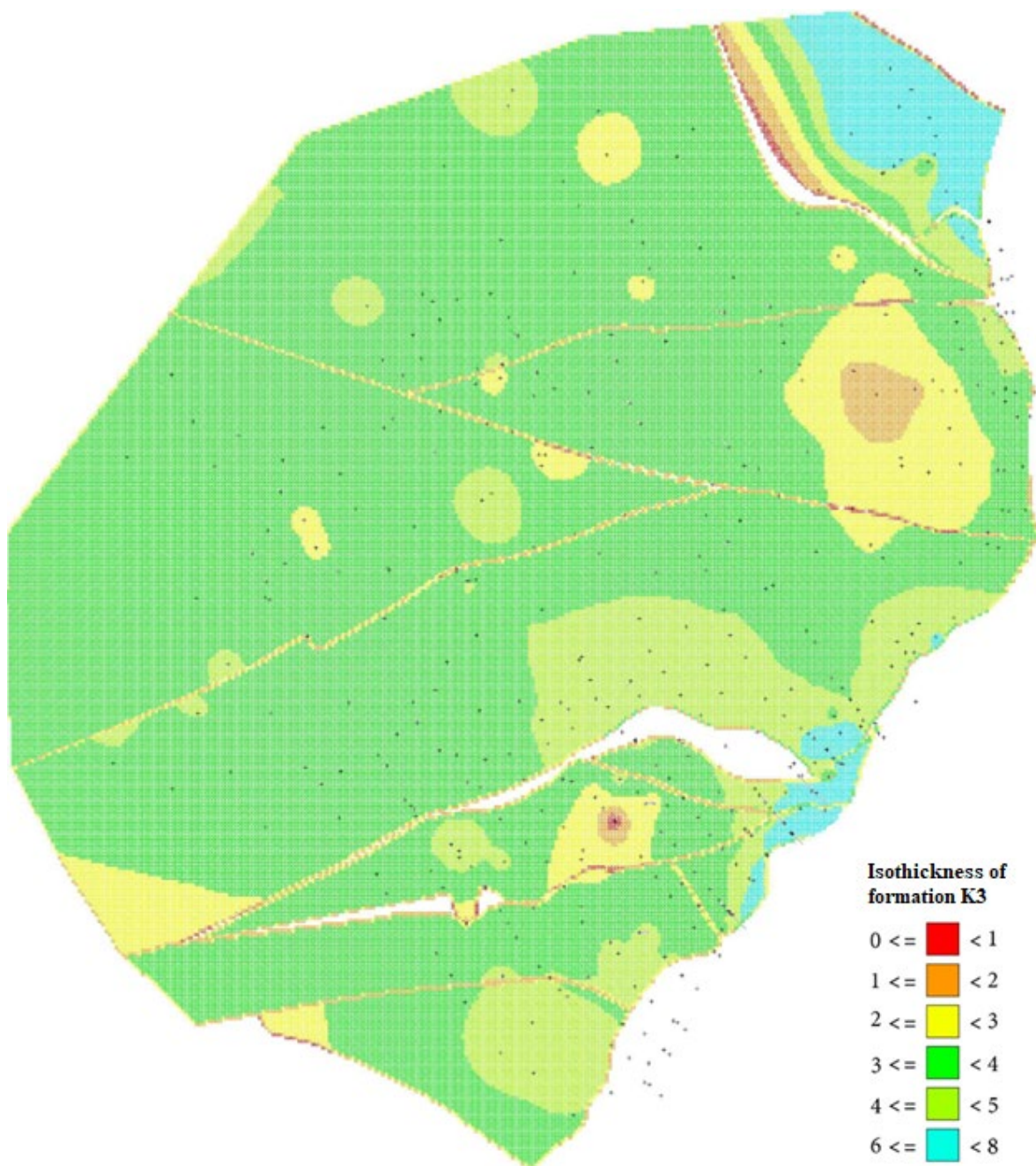


Figure 5. Block model of seam K3 thickness.

The analysis of the gas-dynamic events (GDEs) that occurred in the Karaganda coal basin, as well as the materials presented in works [1–12], show that the main fundamental factors influencing the mechanism of sudden coal and gas outbursts are the distribution of stresses in the rock mass, properties of the coal seam: gas content, porosity, strength, gas pressure, fracturing, moisture content of the coal, gas release rate, and gas content. All of these are linked to areas of tectonic disturbances.

The key results of constructing the geological 3D model include a comprehensive representation of the geological structure of the deposit based on its geometric configu-

ration, variability in qualitative characteristics that allow identifying zones with a high level of tectonic disturbances, and the ability to distinguish areas that pose a risk of sudden outbursts of GDP from those with minimal tectonic variability, which are the safest for tunneling operations. The model also provides the foundation for an integral risk assessment when determining the parameters of the tectonic index. Gas-dynamic parameters measured directly in the development face (except for stable indicators such as gas content, strength, and moisture) are taken into account when calculating the gas-dynamic index.

The validation of the constructed geological model was carried out based on an extensive set of factual data, including information from 414 geological exploration wells at the Kostenko mine.

The validation process included two main stages: visual and statistical checks. The visual check was performed by overlaying the created 3D models onto real geological sections and the exploration well data. Figure 6 presents an example of these comparisons. These illustrations confirm the high degree of coincidence between the model surfaces and the real geological structure.

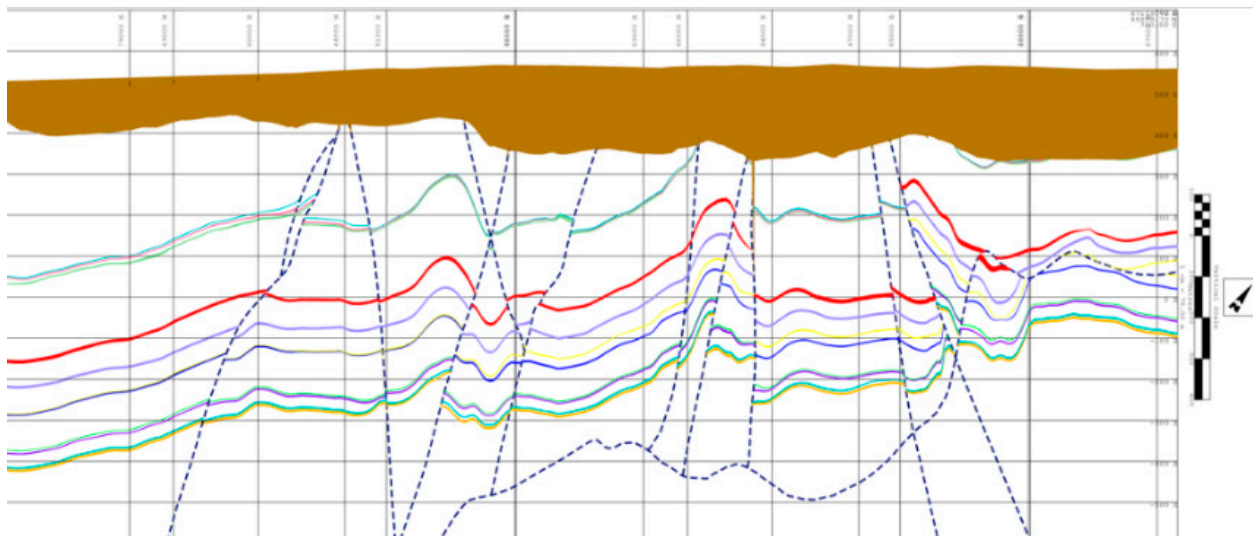


Figure 6. Cross-section of coal seams at the Kostenko mine, demonstrating the match between the model and actual data.

The statistical validation was carried out through the analysis of databases on the thicknesses of coal seams and the quality parameters of raw coal (Table 5). During the analysis, univariate statistics, histograms, box plots, and variograms were calculated.

Table 5. The statistics of the coal seam thicknesses at the Kostenko mine, showing low values of standard deviations and coefficients of variation, which indicates the reliability of the original data.

Seam	Count	Min	Max	Average	Median	Variance	Standard Deviation	Coefficient of Variation
K1	121	0.20	14.97	4.59	4.65	3.65	1.91	0.42
K2	137	0.20	13.90	4.48	4.85	2.82	1.68	0.38
K3	133	0.20	9.50	3.41	3.60	2.10	1.45	0.43
K4	137	0.25	8.75	2.16	1.91	1.58	1.26	0.58
K6	167	0.20	8.40	2.08	1.55	2.03	1.42	0.68
K7	38	1.45	5.50	2.83	2.68	0.95	0.97	0.34
K9	138	0.05	3.15	0.99	0.80	0.37	0.61	0.61

Table 5. Cont.

Seam	Count	Min	Max	Average	Median	Variance	Standard Deviation	Coefficient of Variation
K10	294	0.10	11.88	2.86	2.21	2.75	1.66	0.58
K12	280	0.15	27.99	8.84	8.40	18.81	4.34	0.49
K13	175	0.25	13.00	3.14	3.30	3.12	1.77	0.56
K14	159	0.10	8.85	2.53	2.50	1.56	1.25	0.49
K18	35	0.30	19.50	2.95	2.05	11.57	3.40	1.15

Additionally, a variographic analysis was conducted to quantitatively assess the spatial continuity and anisotropy of the parameters. Figure 7 presents the results of the variographic analysis, confirming the stability of the spatial structure of the data and the reliability of the model.

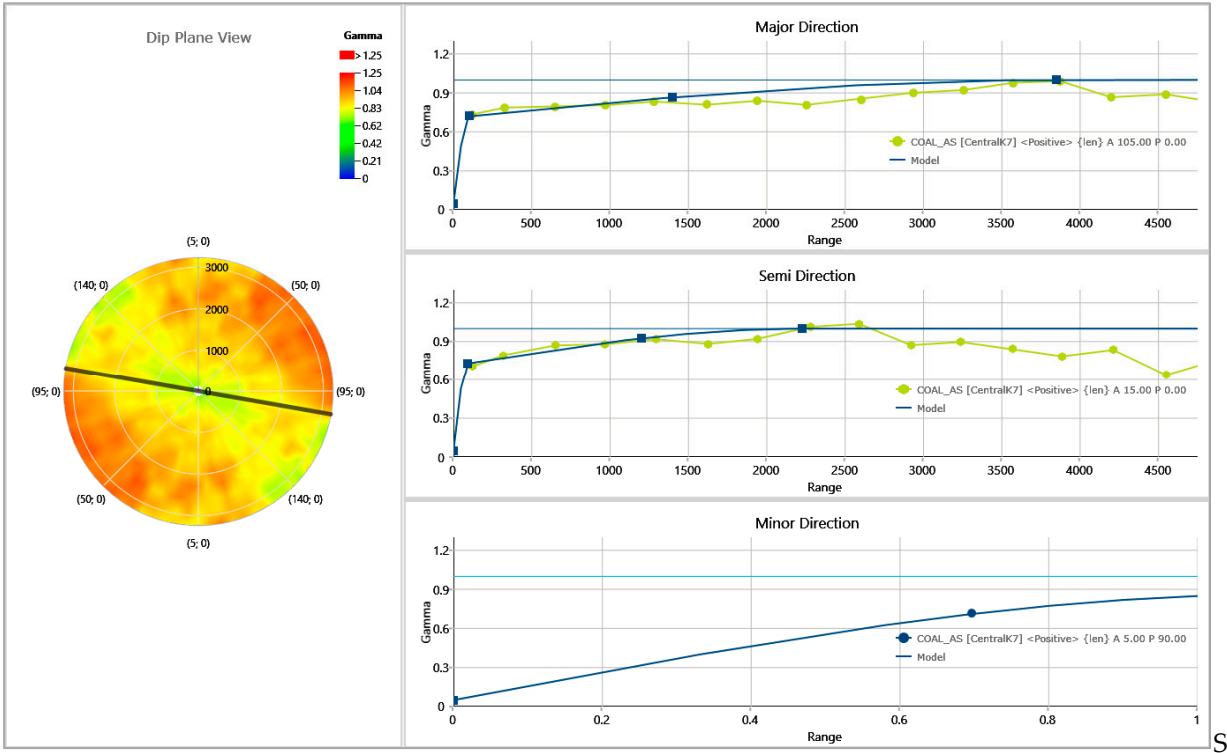


Figure 7. Variographic analysis demonstrating the spatial continuity and anisotropy of the coal seam quality and thickness parameters (The blue horizontal line between 0.9 and 1.2 on the Gamma axis shows the sill—the maximum value the variogram reaches.).

The presented variogram illustrates the spatial continuity of ash content in the K7 coal seam in three orthogonal directions (Major, Semi, and Minor). On the left, a rose plot is shown, where the color scale represents semivariogram values (γ) depending on the direction of the lag intervals. On the right, experimental and modeled semivariogram curves are provided for the principal directions: the top graph corresponds to the Major direction (azimuth $\approx 95^\circ$), the middle to the Semi direction ($\approx 15^\circ$), and the bottom to the Minor direction ($\approx 105^\circ$). In each graph, empirical data points (based on borehole data) are marked in yellow, while the fitted spherical model, normalized to a sill of 1.0, is shown as a blue line. It is evident that along the Major and Semi directions, the semivariograms reach the sill at approximately 1500–2250 m, whereas along the Minor direction, the correlation

decays more rapidly—at around 1000 m. This anisotropic correlation structure was subsequently incorporated into the kriging procedure for more accurate ash content prediction in the 3D model.

Additionally, a check was performed using box plots (Figure 8), which show a high degree of correspondence between the statistical characteristics of the modeled and actual coal quality data.

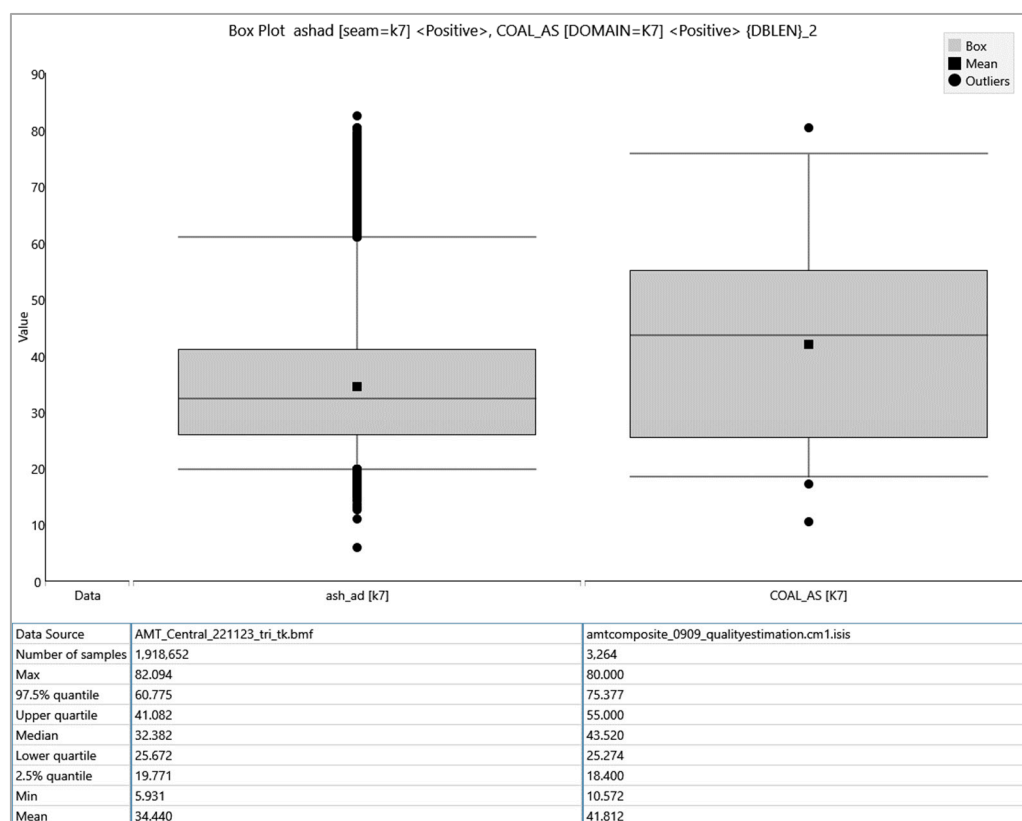


Figure 8. Comparison of box plots for the distribution of ash content (% adb) for seam K7 between the Vulcan™ HARP model.

The validation performed, based on the comprehensive use of visual and statistical analysis methods, confirms the accuracy and reliability of the developed 3D model. This model can be used further for assessing geodynamic hazards and planning mining operations.

3.2. Assessment of the Risk of Coal and Gas Outbursts Based on an Integral Indicator

From references [19,21], it can be concluded that the use of “expert scoring schemes”, where geological and gas-dynamic indicators are assessed using summary scales and then summed into a general “risk index”, is possible. This approach allows for the rapid consideration of local information on fracturing and weak interlayers, comparing it with characteristic gas emission data. In some cases, authors focus primarily on the tectonic factor (introducing only threshold values of ΔP) or conduct an in-depth gas-dynamic analysis without examining the coal seam structure.

In reference [10], the influence of the spatial orientation of faults on gas distribution and its migration to the working face is highlighted and examined using 3D models to identify zones with increased methane concentration in the near-face area. This provides a basis for incorporating fault characteristics into the tectonic index for the Karaganda coal basin, where all gas-dynamic events (GDEs) occur in close proximity to tectonic

disturbances. Therefore, identifying these disturbances in 3D models plays a crucial role in forecasting the risk of a GDE.

In recent years, the mining industry has shown a trend toward developing integrated models that simultaneously account for both dynamic (gas-dynamic) and static (tectonic) parameters of the rock mass [20,22,23]. This involves comparing the results of 3D geological mapping with methane monitoring data and coal strength properties to refine the boundaries of hazardous zones. Particular attention is given to the fact that even a small crushing zone (5–10 m) near a fault offset can be a critical factor for a sudden outburst if the coal strength is close to the critical threshold [18]. Experience from several mines in China indicates that such combinations of tectonic and gas dynamics lead to a sharp increase in outburst hazard, with discrepancies between actual and predicted risk levels reaching several tens of a percent.

The analysis of the research results indicates that a “multi-parameter” assessment of GDP is becoming increasingly important in deep coal seam mining and complex fault tectonics. At the same time, there remains a demand for formal but practical methodologies that allow for the systematic organization of diverse data (fault displacement amplitude, gas emission rate, weak interlayers, etc.) into a unified quantitative format and the rapid identification of high-risk zones.

In this regard, the approach of combining the tectonic index I_T (which includes amplitude, dip angle of the fault, fragmentation zone, weak interlayers, and fracturing) with the gas-dynamic index I_{GD} (gas emission rate— ΔP), coal strength F , coal seam gas content X , gas pressure in the seam P , and coal moisture W) into a single integral indicator I_{total} is a logical and practically oriented solution.

Let us consider the mechanism of such integration using the D6 and K10 seams of the Karaganda Basin as an example to assess the risk of gas-dynamic phenomena (GDP) and provide recommendations for further expansion and adaptation of the methodology. For this purpose, the results of the investigation of the causes of GDP in the Karaganda Basin mines were used. The formal algorithm for calculating the integral indicator I_{total} , intended to estimate the probability of sudden coal and gas outbursts (GDP), includes two indices (Figure 9)—the tectonic index I_T and the gas-dynamic index I_{GD} , each of which combines similar factors into a numerical value ranging from 0 to 1, with their sum determining the final indicator I_{total} :

$$I_{total} = \alpha I_T + \beta I_{GD}, \quad (1)$$

where α and β are weighting coefficients determined based on expert assessments and mining experience at each site or specific seam (in our case, both are set to 0.5). If necessary, for coal seams with high gas saturation or complex tectonics ($\alpha > 0.5$ or $\beta > 0.5$) can be selected.

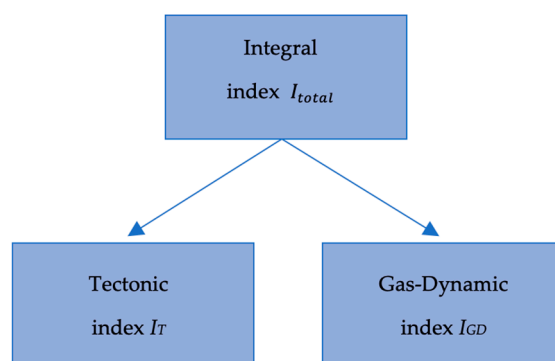


Figure 9. Integral index I_{total} .

The accepted expert assessment I_{total} characterizes the zones of the coal seam near tectonic faults, dividing them into the following:

$I_{total} < 0.3$ —non-hazardous zone for GDP occurrence;

$0.3 \leq I_{total} < 0.6$ —moderately hazardous (requires enhanced monitoring of all factors contributing to GDP occurrence);

$I_{total} \geq 0.6$ —highly hazardous (immediate anti-outburst measures must be taken).

The tectonic index represents a cumulative characteristic of the structural and geological features of a coal seam that can significantly increase the risk of sudden coal and gas outbursts. It takes into account several key parameters, each responsible for a specific aspect of disturbance in the coal mass. One of these parameters is the amplitude of geological fault displacement, which determines the scale of the rupture—the greater the amplitude, the higher the likelihood that a fractured zone with reduced strength and increased gas permeability has formed near the fault. The dip angle of the fault plane is also crucial, as steeper faults tend to accumulate localized stresses and form fractured areas that facilitate the sudden release of gas when the coal face is exposed. If a fractured zone is present in the coal mass, its width indicates the extent and intensity of rock deformation—the greater the fragmentation, the more likely a sharp increase in gas emission during mining operations. The presence of weak interlayers within the coal seam and its fracturing also influence its tectonic stability. A weak layer composed of clayey or carbonaceous rocks significantly reduces the stability of the coal mass, and under the influence of gas pressure and shear deformations, it can trigger a sudden outburst. Fracturing, whether of genetic origin or caused by local tectonic processes, increases the likelihood of a critical situation by forming a network of cracks, enhancing methane permeability, and creating zones of crushed coal with accumulated gas. For each of these parameters, the model assigns scales that allow the conversion of raw values (amplitude, dip angle, fractured zone width, weak interlayer thickness, and fracturing level) into dimensionless indices. These partial assessments are then summed with specific weighting coefficients reflecting the relative importance of each variable. As a result, the tectonic index ranges from zero to one, where a higher value indicates a greater level of structural disturbance in the seam and, consequently, a more critical state in terms of the potential for sudden outbursts.

The tectonic index consists of five normalized indicators (Figure 10): fault displacement amplitude (A), fault dip angle (i), fracture zone width (W_d), presence of a weak interlayer (f_{soft}), and fracturing (f_{frac}). These indicators are then summed with corresponding weighting coefficients.

$$I_T = w_A f_A(A) + w_i f_i(i) + w_{Wd} f_{Wd}(W_d) + w_{soft} f_{soft} + w_{frac} f_{frac} \quad (2)$$

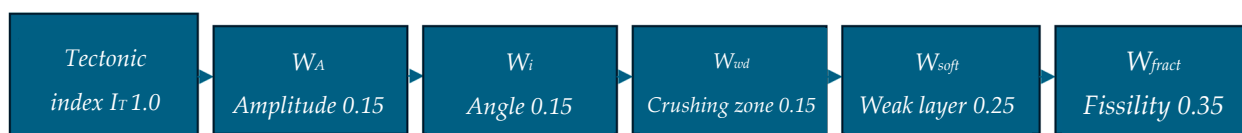


Figure 10. Weighting coefficients of the tectonic index I_T .

These parameters are included in the assessment of the structural and geological condition of the coal seam and can be adjusted if, in certain deposits, they play a more decisive role than others. For example, a large fault displacement amplitude or the presence of weak interlayers can significantly increase the hazard level, leading to higher assigned weighting coefficients compared to fracture zones or fault dip angles. The selection of weighting coefficients is typically based on empirical data and an analysis of all recorded sudden outbursts. If statistical data indicate that a particular variable is more frequently associated with critical situations, it is assigned a higher coefficient, ensuring that the total

value of all coefficients remains within the range of zero to one. Depending on the depth of the coal seam, tectonic complexity, and accident analysis at a specific mine, the coefficient system can be revised for a more accurate representation of each factor's contribution. This approach maintains the methodology's versatility, as in some conditions, a distinct fracture zone may be the key indicator, while in others, the sudden appearance of weak interlayers may be more critical. If, during operation, a specific parameter is found to have a stronger impact on outburst probability than initially assumed, its influence must be adjusted to ensure that the final tectonic index accurately reflects the actual GDP risk conditions.

For the Karaganda coal basin, expert assessments have established the following values (Figure 10):

The geological structure features of the coal seam, reflected in the tectonic index, take the following form:

The function $f_A(A)$ in Formula (2) defines the ratio of the amplitude of the tectonic disturbance of the coal seam at the studied site A to the maximum amplitude $A_{\max}$ determined based on the geological model of the site. It ranges from 0 to 1 and reflects the degree of potential hazard of the fault: the higher it is, the larger the rupture, and the more significant its contribution to the tectonic index.

$$f_A(A) = \frac{A}{A_{\max}} \quad (3)$$

The analysis of materials from the commission assessing the causes of GDP occurrences in the Karaganda Basin mines indicates that if the exact value of $A_{\max}$ is unknown, an interval or point-based scale for f_A can be used. For an amplitude of up to 2 m, $f_A(A) = 0.2$; in the range of 2–4 m—0.5; for 4–5 m—0.7; and for amplitudes above 5 m—1.0. This approach allows the methodology to be applied in cases where precise data on the maximum possible displacement magnitude is unavailable, while still considering the amplitude of tectonic disturbance as a significant factor in the formation of potential sudden outburst zones.

$$f_A(A) = \begin{cases} 0.2, & A \leq 2 \text{ m}; \\ 0.5, & 2 < A \leq 4 \text{ m}; \\ 0.7, & 4 < A \leq 5 \text{ m}; \\ 1.0, & A > 5 \text{ m}. \end{cases} \quad (4)$$

The function defining the position of the fault displacement, $f_i(i)$, is equal to 0 (a minimally influencing factor) at low angles (up to 30°) and reaches 1 at angles of 60° and above. All other values within this angular range can be determined using linear proportion. When the fault dip angle is 30° or less, the analysis of past GDP occurrences indicates that its influence on stress concentration changes is insignificant. However, if the angle exceeds 60° , the influence of the $f_i(i)$ factor becomes “significant”, indicating a high potential risk of GDP occurrence.

$$f_i(i) = \begin{cases} 0, & i \leq 30^\circ; \\ \frac{i-30^\circ}{60^\circ-30^\circ}, & 30^\circ < i < 60^\circ; \\ 1, & i \geq 60^\circ. \end{cases} \quad (5)$$

The function $f_{Wd}(W_d)$ determines the influence of the width of the crushed zone in the area of a tectonic fault or fracture. In most cases, this zone has specific dimensions, and its impact on the risk of sudden gas and coal outbursts needs to be compared with the

so-called “maximum” width observed in the seam. If the value of $W_{d,max}$ is known, then $f_{Wd}(W_d)$ is determined as follows:

$$f_{Wd}(W_d) = \frac{W_d}{W_{d,max}} \quad (6)$$

If the value of $W_{d,max}$ is not determined based on mine geological data or general information about its dimensions from previous outburst experiences, a scoring (or interval) scale is used:

$$f_{Wd}(W_d) = \begin{cases} 0.3, & W_d \leq 5m, \\ 0.5, & 5 < W_d \leq 10m; \\ 0.7, & 10 < W_d \leq 15m; \\ 1.0, & W_d > 15m. \end{cases} \quad (7)$$

The analysis of gas and coal outbursts (GDP) at mines showed that a small-width crushing zone indicates the presence of tectonic disturbances, including small-amplitude ones, and a low probability of GDP occurrence. As a result, this leads to a lower contribution to the overall tectonic index. However, with a significant width of the fractured coal-rock mass, associated with a reduction in the mechanical strength of coal (0.22–0.60 units), the risk of sudden outbursts increases noticeably. This is related to the formation of crushing zones due to increased fracturing and the weakening of the mechanical strength of the mass, which creates conditions for the accumulation and rapid release of gas during the avalanche-like development of the mining-dynamic phenomenon.

The presence of a weak rock layer in the coal seam (f_{soft}), near a fault or as part of a deformed zone, reduces the strength and shear resistance of the seam. Under additional gas or mining pressure, this layer can easily become a sliding plane or a potential starting point for sudden rupture. To account for the influence of the weak layer, a progressive formula has been proposed to calculate this factor, depending on the thickness of the weak layer (h_{soft}):

$$f_{soft} = \begin{cases} 0, & h_{soft} = 0m, \\ 0.3, & 0 < h_{soft} \leq 0.1 m, \\ 0.6, & 0.1 < h_{soft} \leq 0.3 m, \\ 1.0, & h_{soft} > 0.3 m. \end{cases} \quad (8)$$

The degree of fracturing f_{frac} determines how extensively the coal and surrounding rocks are penetrated by a network of fractures of various origins. High fracturing significantly increases the risk of gas outbursts (GDP), as evidenced by expert evaluations of almost all gas outbursts in the coal seams of the basin, especially the high-risk ones (K10, K12, D6). This is because fractures act as “transport channels” for gas, promoting the rapid growth of destruction zones due to the overall reduction in rock strength. With low fracturing, a limited zone forms along the fault, while with strong fracturing, large areas of fragmented coal are created, which is extremely dangerous for mining operations. The degree of fracturing is calculated using linear normalization and is visually determined by the geological service during tunneling (presence of small cracks, coal cracking, etc.).

$$f_{frac} = \begin{cases} 0, & \text{mass without significant fractures;} \\ 0.3, & \text{moderate fracturing;} \\ 0.7, & \text{High fracturing;} \\ 1.0, & \text{Extreme fragmentation.} \end{cases} \quad (9)$$

The gas-dynamic index is determined as the average of five key criteria that reflect the “gas” condition of coal seam hazard. Based on the analysis of GDP, five main indicators are

identified: coal strength, gas emission rate, moisture content, gas content, and gas pressure within the coal seam.

$$I_{GD} = \frac{1}{N} \sum_{j=1}^N f_j(x_j) \quad (10)$$

where N is the number of criteria considered in the gas-dynamic index.

x_j is the actual value of the j parameter (strength f , gas emission rate ΔP , gas content, moisture content, gas pressure).

A scoring system is used to account for each gas-dynamic criterion, based on expert assessments of all GDP in the basin (Figure 11).

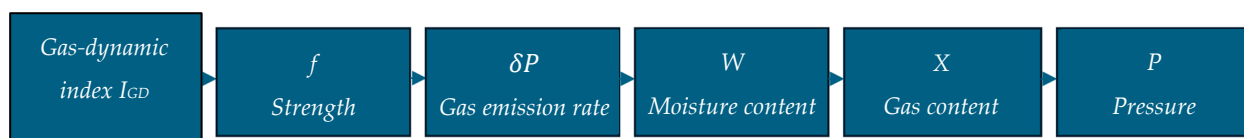


Figure 11. Criteria of the gas-dynamic index I_{GD} .

To assess the limiting value of coal strength $f < 0.8$ a conditional boundary is used, where the coal strength on the Protodyakonov scale drops below 0.8 units, indicating that the coal seam has low resistance to mechanical stresses (tearing and crushing) under the influence of geological pressure. When f is below 0.8, the coal mass is prone to brittle destruction and may quickly transition into the avalanche-like stage of an emission upon the accumulation of additional stresses and the further impact of gas.

$$f_f(x) = \begin{cases} 0, & f_f \geq 0.8, \text{ safe (stronger);} \\ 0.5, & 0.6 < f_f < 0.8, \text{ moderate risk;} \\ 0.8, & 0.4 < f_f < 0.6, \text{ close to critical;} \\ 1.0, & 0.4 > f_f, \text{ minimal strength} \end{cases} \quad (11)$$

In reference [3], critical values of gas-dynamic parameters (gas emission rate, pressure, gas content) for the case of a sudden outburst at the Xieqiao mine in China are determined. The method of scoring is also proposed for monitoring by specialists at the working face for the operational assessment of hazardous zones.

The gas emission rate ΔP serves as the primary marker of the “gas-dynamic activity” of the seam. During the drilling of control boreholes, the initial methane emission rate is measured—if it exceeds a specified threshold, i.e., $\Delta P > 10.5$ L/min·m, this indicates a high degree of the coal mass’s readiness for the sudden release of gas from the seam. An excess of this criterion indicates that the mining operation is in an area of increased gas hazard, requiring measures for degassing or methane control.

$$f_{\delta P}(x) = \begin{cases} 0.2, & 8.0 > f_{\delta P}, \text{ relatively safe;} \\ 0.5, & 8.0 < f_{\delta P} < 10.5, \text{ moderate activity;} \\ 0.8, & 10.5 < f_{\delta P} < 12, \text{ close to critical;} \\ 1.0, & f_{\delta P} > 12.5, \text{ critically high rate.} \end{cases} \quad (12)$$

The studies on the influence of moisture on the mechanical properties of coal are presented in reference [4]. The results of these studies are important for assessing the gas-dynamic hazard as one of the factors in the release of energy during the disturbance of the massif.

Expert evaluations of the impact of coal moisture W from past GDP in the basin show that if the coal has a very low moisture content $W < 6\%$, it is more susceptible to disintegration and releases free, adsorbed methane more quickly. Dry or semi-dry

coals have lower cohesion, which, combined with other factors (such as increased ground pressure and fracturing), contributes to sudden outbursts. With higher moisture, the coal pores and fractures are partially “filled” with water, slightly reducing the tendency for immediate gas-dynamic manifestation.

$$f_W(x) = \begin{cases} 0 & f_W > 7.0; \\ 0.3, & 5.0 < f_W < 7.0; \\ 0.6, & 3.0 < f_W < 5.0; \\ 1.0, & 3.0 > f_W. \end{cases} \quad (13)$$

The gas content of the coal seam is one of the factors influencing the intensity of GDP. When the gas content exceeds a certain critical level X_b , the seam is considered “over-saturated” with methane, which can lead to a sudden release of gas when mechanical unloading occurs on the coal mass. The higher the gas content relative to the norm, the stronger the energy potential for an outburst.

$$f_X(x) = \begin{cases} 0, & 10.0 > f_X; \\ 0.5, & 10.0 < f_X < 14.0; \\ 0.8, & 14.0 < f_X < 18.0; \\ 1.0, & f_X > 18.0. \end{cases} \quad (14)$$

The gas pressure P in the seam is determined through degassing wells, including reservoir wells, or by calculation. If the pressure exceeds a certain threshold value P_b , the risk of a sudden outburst increases significantly. This is because, at high pressure, methane is ready for rapid avalanche-like release when a fracture or structural weakness forms in the face area.

$$f_P(x) = \begin{cases} 0, & 5.0 > f_P; \\ 0.5, & 5.0 < f_P < 10.0; \\ 0.8, & 10.0 < f_P < 12.0; \\ 1.0, & 12.0 > f_P. \end{cases} \quad (15)$$

The gas-dynamic index I_{GD} is defined in a scoring (interval) format—it is the sum of the weighted functions $f_j(x_j)$, where each function converts the actual value of the parameter x_j into a number from 0 to 1 based on pre-established intervals and scores. This sum is then divided by the number of criteria (five).

3.3. Risk Assessment of GD Based on the Integral Index

The provided examples are taken from the “Catalog of sudden coal and gas outbursts of the Karaganda coal basin”, 2018 [18]. Below is the table characterizing the coal seams at the site of the outburst.

Let us consider the coal and gas outburst at the Kazakhstan mine on 20 April 2012, in the D6-Kassinsky seam, with a mining depth of 524 m and a gas drainage tunnel 312-D6-v (Table 6).

The description notes the presence of geological disturbances, so $f_A = 0$, as there is no information available; the dip angle i is similarly treated as the amplitude of the dislocation, $f_i(i) = 0$; “weak rock layers” and “kaolinitization” indicate reduced strength, assuming the thickness of such a layer is greater than 0.3 m, then $f_{soft} = 1.0$ “strong fracturing” gives $f_{frac} = 1.0$; “the outburst site: strong fracturing, kaolinitized, weak...”, so we take the minimum value of the fragmentation zone based on the following scale: $f_{Wd}(W_d) = 0.3$. Thus, the tectonic index I_T for the D6 seam is 0.6; the gas-dynamic index I_{GD} for the D6 seam is 0.96. The total index $I_{total} = \alpha I_T + \beta I_{GD}$ (with α and β equal to 0.5) equals $0.7775 \approx 0.78 > 0.6$.

Table 6. Characteristics of seams at the site of the outburst.

Mine, Seam	Kazakhstanskaya, D6	Kuzembaeva, K10
Seam thickness, m	5.5	4.2
Thickness at the outburst location, m	5.5	4.1
Dip angle, degrees	From +3 to −12	From +4 to +11
Gas content, m ³ /t	20	16
Gas pressure, kgf/cm ²	12	Data unavailable
Moisture content, %	2.27	5.89
Surrounding rocks	Argillites in the soil (1.2–1.5 m), medium-strength aleurites (40 m), sandstone (2–5 m)	Roof: argillite 2–6.25 m, aleurite 4.5 m, sandstone up to 20.7 m. Soil: argillite 5.8 m, aleurite 6.8 m.
Strength coefficient	0.28	0.33
Initial gas emission rate, conditional units	10	20
Geological conditions at the outburst location	Strong fissility, kaolinized, weak, prone to collapse and caving	The geological disturbance at the outburst location, coal seams, and surrounding rocks have reduced mechanical strength and unsatisfactory stability, which may result in the collapse of roof rocks, the formation of domes, and increased gas emissions.

An analysis of the total index calculations for Seam D6 in relation to gas-dynamic events (GDEs) at the Kazakhstan mine shows that even with low (or borderline) ΔP values, the total index $I_{total} > 0.7775$ categorizes the zone as “highly hazardous”. This is due to a high tectonic index, which incorporates characteristics such as the presence of a weak interlayer, high fracturing, a high gas-dynamic factor, low coal strength $f = 0.28$, high seam gas content, and high gas pressure. An outburst occurred at this site on 20 April 2012, and the model (with $I_{total} > 0.6$) would have formally classified the area as “highly hazardous”. This case demonstrates that a high tectonic index (≈ 0.6), combined with significant gas-dynamic indicators ($I_{GD} = 0.96$), raises the total index I_{total} to a level consistent with a “high-risk” zone. The real-life occurrence of an outburst supports the adequacy of this multi-criteria approach to calculating the integrated index.

The analysis of the total index calculations for the D6 seam in the Kazakhstan mine shows that even with a low (or borderline) ΔP , the overall indicator $I_{total} > 0.7775$ classifies this zone as “particularly dangerous”. This is explained by the high tectonic index, which includes characteristics of the weak layer, high fracturing, and a high gas-dynamic factor, as well as the low coal strength of $f = 0.28$ u.e., high gas content in the D6 seam, and high gas pressure. The outburst in this area occurred on 20 April 2012, where formally, at $I_{total} > 0.6$, the model would classify it into the “particularly dangerous” category. From the calculation of this example, we see that the high tectonic index (≈ 0.6), combined with significant gas-dynamic factors ($I_{GD} = 0.96$), raises the I_{total} to the “particularly dangerous” zone level. The actual outburst case confirms the adequacy of the integral index calculation and the validity of such multi-criteria calculations.

Let us consider an example of the GDP at the T. Kuzembaev mine on 20 August 2011, seam K10, with a mining depth of 607 m, ventilation shaft 37-K10-V.

In the description of the GDP location, it is noted that there is a geological disturbance, but the amplitude is not specified. For calculation purposes, an amplitude range of 2 to

4 m is used, so $f_A = 0.5$. The dip angle of the fault, i , is taken as 45° , so $f_i(i) = 0.5$. The roof and floor rocks have reduced stability, with local deformations (collapses, formation of “domes”), and the crushing zone ranges from 5 to 10 m: $f_{Wd}(W_d) = 0.5$. The roof and floor rocks are of “reduced strength”, and the thickness of the weak layer is assumed to be from 0.1 to 0.3 m, so $f_{soft} = 0.6$. Intense fracturing zones f_{frac} , which form a “free gas collector” and “domes”, are assumed to be $f_{frac} = 0.7$. The tectonic index I_T for the K10 seam at the T. Kuzembaev mine is calculated as ≈ 0.585 .

For the calculation of the gas-dynamic index I_{GD} , measured values from the GDE zone were used (Table 6): coal strength $f = 0.2 \Rightarrow f_f = 1.0$; $\delta P = 20 \Rightarrow f_{\delta P} = 1.0$; moisture content $W = 5.89\% \Rightarrow f_W = 0.3$; gas content $X = 16 \Rightarrow f_X = 0.8$; $_{3H}$ gas pressure P was not specified, so average values were assumed for a seam depth of 607 m $\Rightarrow f_P = 0.5$. The gas-dynamic index for Seam K10 is approximately ≈ 0.72 .

The final index is calculated as $I_{total} = \alpha I_T + \beta I_{GD}$ (with $\alpha = \beta = 0.5$) resulting in ≈ 0.65 (>0.6 , categorized as a “highly hazardous zone”).

In the total index calculations for Seam K10, some parameters (e.g., fault dip angle, gas pressure) were taken as “average” (0.5) due to the lack of precise measurements. This choice is justified to avoid nullifying the contribution of these variables. However, it should be noted that if a further analysis reveals a steeper fault dip ($>30^\circ$) or significantly higher pressure, the final index would increase even further.

Using average values in the absence of reliable data is a reasonable conservative approach—it does not reduce the contribution of unknown criteria to zero, but also does not equate them to the maximum level. Therefore, the calculation of $I_{total} \approx 0.65$ reflects the likely condition of the rock mass, indicating that even with moderate estimates of several parameters, the situation in Seam K10 qualifies as “highly hazardous”. If subsequent refinement reveals more extreme values, the integrated index could be significantly higher, further confirming the critical risk of sudden outbursts.

3.4. Applicability and Limitations of the Methodology

The proposed algorithm has been calibrated using data from the Karaganda coal basin but can be adapted to other deposits, provided a number of prerequisites are met. Accurate spatial interpolation of parameters requires an exploration grid with a spacing of no more than one borehole per approximately 200 m²; with sparser drilling, semivariogram parameters should be refined locally. Real-time measurements of gas-dynamic factors (gas emission rate, reservoir pressure, coal strength, and moisture content) should preferably be conducted at intervals no greater than every 10–12 m of mining advance, as longer intervals significantly reduce the reliability of the I_{GD} index.

The weighting coefficients used in the calculation of the tectonic and gas-dynamic indices are empirically derived from historical outburst statistics; for a new mine site, they must be recalibrated either based on a dataset of at least 25 documented cases or from the results of pilot monitoring at three or more production faces.

It should also be noted that in areas of high seismic activity, fault geometries may change more rapidly, increasing forecast uncertainty; in such conditions, it is recommended to shorten the model update cycle and incorporate microseismic monitoring data.

4. Discussion

The algorithm for calculating the total index I_{total} is based on the results of 3D modeling of the coal seam structure, which identifies previously undetected tectonic disturbances. These disturbances are then used to calculate the tectonic index I_T and the gas-dynamic index I_{GD} as part of a risk assessment for gas-dynamic phenomena (GDP) using a systems approach. The most valuable aspect of the proposed method is its ability to simultaneously

account for structural-geological (amplitude, dip angle of the dislocation, fragmentation zone, weak layers, and fracturing) and gas-dynamic (ΔP , f , W , X , P) factors.

The integral risk assessment provides a more objective picture since local tectonic features can greatly amplify the danger, even when the “average” gas-dynamic parameters appear relatively moderate. As an example of the sensitivity of the total index to the amplitude of the faulting, the dependence of I_T on amplitude A is demonstrated while other factors are fixed. Figure 12 shows that the amplitude varies from 1 to 5 m, with other tectonic and gas-dynamic parameters fixed at average levels (e.g., $\Delta P = 10$, $f = 0.6$, etc.). It is observed that at $A \approx 2$ m, the total index is approximately 0.72 (indicating a “moderately dangerous” state), while with an increase in amplitude to 5 m, I_{total} reaches 0.78, moving closer to the “particularly dangerous” zone $I_{total} > 0.6$. This demonstrates the significant impact of faulting disturbances on the overall risk of sudden coal and gas outbursts.

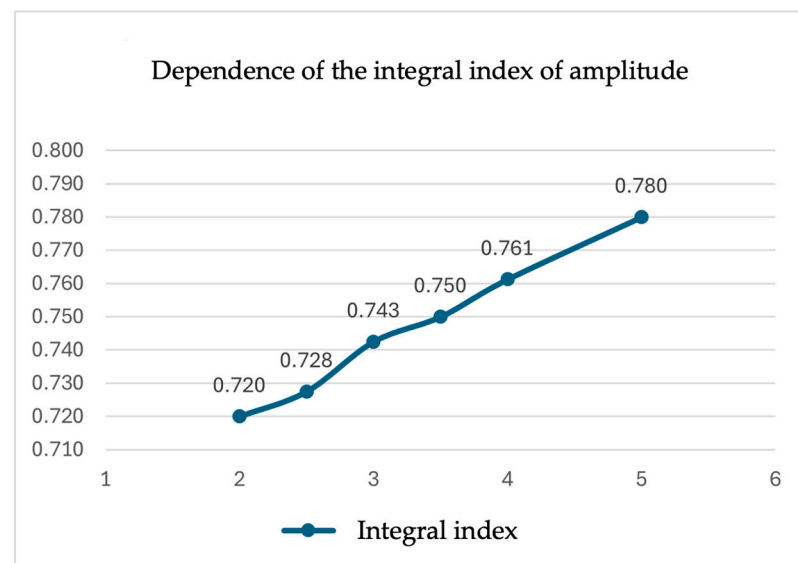


Figure 12. Graph of the dependence of the total index I_{total} on the displacement amplitude A .

The significant influence of the tectonics of the coal seam and the associated changes in mechanical properties and gas conditions on the risks of gas-dynamic phenomena (GDP) provides a foundation for using an integral approach. In practice, this approach is especially useful in cases where in the adjacent zone, individual factors have moderate values, but when combined, they become dangerous [1,2].

The expert assessment of previous gas-dynamic events (GDEs) in the coal basin allows for the determination of optimal α and β values (or within the indices themselves—weights w_A , w_i , w_{Wd} , w_{soft} , etc.), which provides universality to the proposed methodology. In mines with a pronounced gas abundance (where δP and X are initially high), it makes sense to increase β , while in areas where the main issue is related to fault tectonics and frequent small faulting, α should be increased. Figure 13 shows the dependency of the final index I_{total} on the value of the coefficient α , with the condition $\beta = 1 - \alpha$. Fixed values of $I_T \approx 0.55$ and $I_{GD} \approx 0.75$ were adopted for the calculations. It is evident that at $\alpha = 0$ (full priority given to gas dynamics), the final index is about 0.75, and as α increases, the contribution of the tectonic block increases and I_{total} decreases, reaching approximately 0.55 when $\alpha = 1$.

This approach demonstrates how sensitive the result is to the “redistribution” of weights between the tectonic index I_T and the gas-dynamic index I_{GD} . In conditions of high gas occurrence, increasing β (strengthening the influence of I_{GD}) may be justified,

while in areas with complex tectonics, increasing α might be more appropriate. This makes the methodology more flexible and adaptable to real geological and mining conditions.

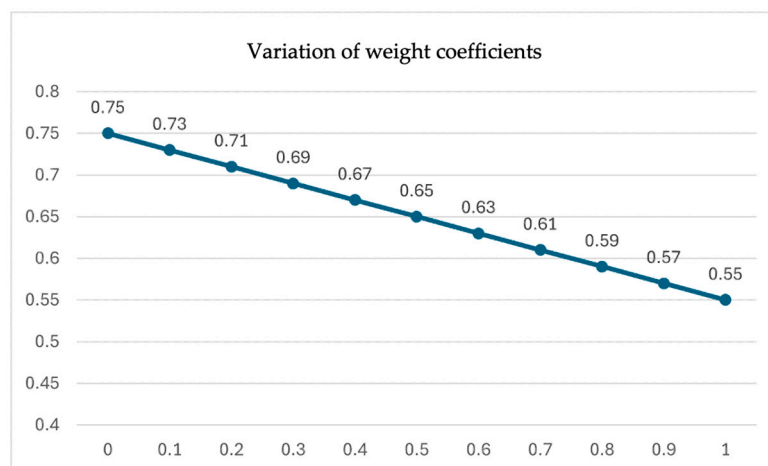


Figure 13. Dependence of the index I_{total} on the value of the coefficient α .

The convenience of interpreting the ranges established based on expert assessments $I_{total} < 0.3$, $0.3 \leq I_{total} < 0.6$ and $I_{total} \geq 0.6$ allows for quick evaluation of whether the borehole is in a safe, moderately dangerous, or particularly hazardous zone. Experience shows that for taking operational measures against blowout protection, the three-level integral risk assessment system for the GDP in coal mines is more effective compared to when single threshold checks are used [4].

The prospects for further development of the system are linked to the combined use of the calculation of the stress–strain state of the rock mass (for example, FLAC3D, UDEC) to assess the “stress concentration” coefficient, which formally reflects how close the seam zone is to the critical level. The consideration of petrographic characteristics in the risk of GDP is associated with an increased vitrinite composition, the presence of sulfides in coal, as well as microstructural properties that affect the rate of methane adsorption and desorption, which is important for forecasting at greater seam depths. Seismic monitoring, acoustic or microseismic methods used to detect sources of coal-rock mass destruction, enhance the effectiveness of GDP risk assessment using an automated mode based on software.

As practical recommendations, it is suggested to conduct the following: adaptation of scales at each coal mine (or even at different horizons of a single mine), as the scales for f_A , f_i , etc., may differ; calibration of boundary values and intervals based on local accident statistics, avoiding figures that might be irrelevant; monitoring and reassessment of weights by adjusting them as information on sudden blowout incidents accumulates.

The proposed algorithm, which includes the construction of a 3D tectonic model of the coal seam and the calculation of an integral index, provides a comprehensive view of the situation regarding the state of the coal seam zone, where faulted tectonics and gas saturation of the rock mass interact, significantly increasing the likelihood of sudden blowouts. This multi-criteria approach has proven its practical value in international practice, and our research, with prospects for further development based on expanded data (geomechanics, petrography, microseismicity), is capable of predicting the emergence of GDP risks in critical coal seam zones with high accuracy.

5. Conclusions

The novelty of the proposed method for assessing the risk of sudden coal and gas outbursts lies in the integrated use of geological and gas-dynamic factors for predicting gas-dynamic phenomena. These factors are derived from a 3D model that reflects the geological

conditions of coal seam occurrence and characteristics of tectonic disturbances, as well as from expert assessments of gas-dynamic parameters based on past outburst events in the basin. The integral characterization of tectonic and gas-dynamic components increases the probability of accurate risk evaluation and substantiates mine planning measures for hazard prevention. Moreover, the expert selection of criteria for tectonic and gas-dynamic indices can be refined for specific hazardous seams or areas of the deposit, based on regulatory documentation annually issued by mining enterprises that classify coal seams according to their outburst hazard level.

Practical testing of the proposed methodology on real cases of sudden blowouts in the Karaganda Basin mines shows that the combined use of the 3D model of coal seams with identified tectonic faults weakened zones of the coal seam, and the integral indicator that includes both tectonic and gas-dynamic blocks in a single composite index allowed for the assessment of the risk of GDP. The integral indicator correlates well with the actual development of emergency situations. It is important to note that the proposed method is not reduced to any single group of features, as in the case of seam D6, where high gas occurrence and low coal strength played a decisive role, while in another case (seam K10), the combination of moderate geological data with extreme values of δP was more significant. Additionally, unaccounted-for pressure P and the uncertain power of geological disturbances may have further increased the actual risk assessment for GDP manifestation.

The results of the calculations and their comparison with actual coal and gas outbursts confirm the need for a comprehensive (multi-parameter) risk assessment. The tectonic block (I_T), obtained based on the 3D model of the coal seam, identifies local hazardous zones due to factors such as the displacement amplitude, fragmentation zones, and fissility. The gas-dynamic block (I_{GD}) takes into account the specific characteristics of low coal strength, high values of δP , gas content, and others. This integral approach is especially important in conditions of deep coal seam deposits and mining, where even minor tectonic disturbances under elevated gas pressure can significantly increase the likelihood of a sudden outburst of coal and gas, with the potential for spontaneous ignition of finely crushed coal and dust in the outburst zone.

The prospects for further development are linked to the possibility of complementing the proposed methodology with more detailed geomechanical variables (stress–strain state calculations, petrographic features) and automating the calculation of I_{total} . This will allow for a more accurate assessment of outburst hazards at significant depths and in complex seam structures, as well as strengthen industrial safety through more comprehensive and timely predictions of sudden outbursts.

Author Contributions: Conceptualization, methodology: V.P. and A.M.; resources: A.Z. and S.I.; investigation: A.M., A.G. and N.S.; project administration: A.G. and K.K.; editing: R.M. and S.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. BR24993009).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data from this study are available within the article.

Conflicts of Interest: Author Andrey Golik was employed by the company LLP «I-GEO KAZAKHSTAN». The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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