ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№6
2025

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

6 (474)

NOVEMBER – DECEMBER 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2025

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan Nº KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: ТОО «Центрально-азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

http://www.geolog-technical.kz/index.php/en/

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OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 6. Number 474 (2025), 209–229

https://doi.org/10.32014/2025.2518-170X.581

UDC 622.24.06:622.248.3

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METHODOLOGY FOR FORECASTING DYNAMIC ROCK PRESSURE MANIFESTATIONS IN UNDERGROUND GOLD MINING

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Abstract: *Relevance of the Study.* Underground mining of gold deposits is carried out under complex geological and geomechanical conditions that increase the risk of dynamic manifestations of rock pressure. The use of mining systems with large open stopes without backfilling, as well as the high degree of rock mass disturbance, leads to stress concentration and the formation of zones of elevated abutment pressure. Developing a comprehensive forecasting methodology that integrates instrumental observations, mathematical data processing, and geomechanical modeling will improve the accuracy of predictions and reduce the likelihood of hazardous situations, making this research important for enhancing the safety and efficiency of underground gold mining. *The purpose of the study* is to develop a methodology for multilevel forecasting of geomechanical processes considering a set of factors influencing the stress–strain state of the rock mass.

The research methods include the development and application of an instrumental measurement system, mathematical data processing, analytical studies, numerical modeling of the stress–strain state of the rock mass, core discing analysis, slot cutting and acoustic emission methods, as well as the use of least squares and group method of data handling (GMDH) to construct predictive relationships. *The results* include the development of a calculation scheme and distributions of principal stresses within the ore body under combined gravitational and tectonic loading; determination of the ratios between horizontal and vertical stresses in the rock mass; and measurements of roof and sidewall deformations in mine workings at active levels of the deposits. It was established that the key factors governing dynamic rock pressure manifestations can be integrated into a single predictive indicator. *The practical significance* lies in the applicability of the developed methodology and predictive indicator for rapid assessment of the geomechanical condition of the rock mass, improving the safety of mining operations, and optimizing mining system parameters in the Zarmitan gold ore zone and similar deposits.

Key words: Zarmitan gold ore zone (ZGOZ), rock pressure, stressed deformed state (SDS), fracturing, acoustic emission (AE)

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ЖЕРАСТЫ АЛТЫН КЕН ОРЫНДАРЫН ИГЕРУ ЖАҒДАЙЫНДА ТАУ ҚЫСЫМЫНЫҢ ДИНАМИКАЛЫҚ КӨРІНІСТЕРІН БОЛЖАУ ӘДІСТЕМЕСІ

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Аннотация. *Зерттеудің өзектілігі.* Алтын кен орындарын жер астында қазу күрделі тау-геологиялық жағдайда жүргізіледі, бұл тау қысымының динамикалық көріністері қаупінің артуына әкеледі. Үлкен ашық тазарту кеңістігі бар, қуыстары толтырылмайтын кен өндіру жүйелерін қолдану, сондай-ақ жыныс массасының жоғары бұзылуы кернеулердің шоғырлануына және көтеріңкі тірек қысымы аймақтарының қалыптасуына себеп болады. Аспаптық бақылауларды, деректердің математикалық өңделуін және геомеханикалық модельдеуді біріктіретін кешенді болжау әдістемесін әзірлеу болжамның дәлдігін арттырып, авариялық жағдайлар ықтималдығын төмендетуге мүмкіндік береді. Бұл зерттеу алтын кен орындарын жер астында қауіпсіз және тиімді игерудің маңызды бағыты етеді. *Жұмыстың мақсаты* — тау жыныстары массивінің кернеу-деформациялық күйіне әсер ететін факторлар кешенін ескере отырып, геомеханикалық үдерістердің көпдеңгейлі болжау әдістемесін әзірлеу. *Зерттеу әдістері* аспаптық өлшеу жүйесін әзірлеу және қолдануды, деректердің математикалық өңделуін, аналитикалық зерттеулерді, массивтің кернеу-деформациялық күйін сандық модельдеуді, кернді дискілеу әдісін, саңылау жасау және акустикалық эмиссия тәсілдерін, сондай-ақ болжау тәуелділіктерін құру үшін ең кіші квадраттар әдісін және аргументтерді топтық есепке алу әдісін қамтиды. *Жұмыс нәтижелері* гравитациялық және тектоникалық күштердің бірлескен әсері жағдайында рудалы дене жазықтығындағы негізгі кернеулердің есептік сұлбасын және эпюраларын құрудан; тау жынысы массивіндегі көлденең және тік кернеулердің арақатынасын анықтаудан; сондай-ақ жұмыс істеп тұрған деңгейлердегі тау қазбаларының төбесінде және бүйір қабырғаларында деформацияларды өлшеуден тұрады. Динамикалық тау қысымы көріністерін қалыптастыратын негізгі факторларды бірыңғай болжамдық көрсеткішке біріктіруге болатыны анықталды. *Практикалық маңыздылығы* — әзірленген әдістемені және болжамдық көрсеткішті массивтің геомеханикалық жай-күйін жедел бағалау, тау-кен жұмыстарын қауіпсіз жүргізу және Зармитан алтын кен аймағы мен оған ұқсас кен орындарында өндіру жүйесі параметрлерін оңтайландыру үшін қолдануға мүмкіндік беруінде.

Түйін сөздер: Зармитан алтын кен аймағы (ЗЗЗ), тау қысымы, кернеулі деформацияланған күй (ТҚКДК), жарықшақтық, акустикалық эмиссия (АЕ)

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МЕТОДОЛОГИЯ ПРОГНОЗИРОВАНИЯ ДИНАМИЧЕСКОГО ПРОЯВЛЕНИЯ ГОРНОГО ДАВЛЕНИЯ В УСЛОВИЯХ ПОДЗЕМНОЙ РАЗРАБОТКИ ЗОЛОТОРУДНЫХ МЕСТОРОЖДЕНИЙ

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Аннотация. Актуальность исследования. Подземная разработка золоторудных месторождений осуществляется в условиях сложного строения массива горных пород, высокой трещиноватости и неоднородности напряжённо-деформированного состояния. Эти факторы существенно повышают вероятность динамических проявлений горного давления. Применение систем разработки с обширными очистными пространствами без погашения пустот, а также наличие нарушенных зон приводит к концентрации напряжений и формированию областей повышенного опорного давления. Необходима методология, объединяющая инструментальные наблюдения, математическую обработку и геомеханическое моделирование, что позволит повысить надёжность прогноза и снизить риск аварий. Цель исследования — разработка многоуровневой методологии прогноза геомеханических процессов с учётом комплекса факторов, определяющих напряжённо-деформированное состояние массива при подземной разработке золоторудных месторождений. Методы исследования включают: инструментальные измерения параметров напряжённо-деформированного состояния; математическую обработку данных; аналитические расчёты; численное моделирование напряжённо-деформированного состояния массива; дискование керна; методы щелевой разгрузки и акустической эмиссии; применение метода наименьших квадратов и группового учёта аргументов для построения прогнозных зависимостей. Результаты. Построена расчётная схема и определены эпюры главных напряжений в плоскости рудного тела с учётом совместного влияния гравитационных и тектонических нагрузок. Определены соотношения вертикальных и горизонтальных напряжений, выполнены замеры деформаций кровли и стенок выработок на действующих горизонтах. Показано, что основные факторы, влияющие на динамические проявления горного давления, могут быть объединены в единый интегральный прогнозный показатель. Практическая значимость заключается в возможности применения методологии для оперативной оценки геомеханического состояния массива, повышения безопасности горных работ и оптимизации параметров системы разработки в условиях Зармитанской золоторудной зоны и аналогичных месторождений.

Ключевые слова: Зармитанская золоторудная зона (ЗЗЗ), горное давление, напряженное деформированное состояние (НДС), трещиноватость, акустическая эмиссия (АЭ)

Introduction. Ensuring the effectiveness of forecasting the condition and properties of a rock mass is the most important problem of the mining industry. A multilevel forecast is based on taking into account many factors that require correct mathematical processing. Traditional approaches to solving this problem do not fully cover the existing realities in the conditions of complex structural deposits of gold ore deposits of volcanogenic genesis. Here, methodology refers to the development and targeted application of measurement, observation, mathematical processing, generalization, modeling, algorithmization, forecasting software, model identification, and evaluation of forecasting results. There is an urgent need to involve new ideas and methodologies in research. Many urgent tasks in the field of studying the stressed deformed state (SDS) of a rock massif in the conditions of underground mining of gold deposits are far from being adequately solved due to the multitude of natural and man-made factors that are difficult to account for.

This problem is becoming particularly important in connection with the deepening of mining operations, where cases of dynamic manifestations of rock pressure are often observed, and seismodynamic effects in the bowels of the earth are increasing. In this regard, the improvement of methods for predicting the stressed deformed state of a rock massif using methods and tools for assessing, monitoring and controlling geomechanical processes occurring in the conditions of underground mining of gold deposits, taking into account geological, mining and technical features expressed in large information arrays (LIA) of data within specific ore fields, is an urgent scientific and technical task (Bychkov et al, 2016).

Worldwide, monitoring and assessment of the geomechanical condition at specific underground mining enterprises is a priori an integral part of the management of safe mining operations. The study of the stressed deformed state of the rock massif contributes to ensuring industrial safety requirements when mining operations at a specific mine developing a gold deposit (Yu, 2014).

One of the solutions to this problem is the development of methods for predicting geomechanical processes during the operation of sections of deposit zones and assessing the stressed deformed state of rock massif in seismotectonically active zones, taking into account the diversity and complexity of safe mining conditions.

Many works are devoted to the assessment of the natural stress state of rock massifs using geophysical and geomechanical methods, numerical modeling methods, where SDS parameters are determined in characteristic sections of the rock massif (Rasskazov et al, 2010, Aitmatov et al, 1987) At the same time, the study of the manifestation of rock pressure in dynamic form during the underground mining of specific gold deposits, the systematization and analysis of existing publications have shown that currently solutions to many important issues have not reached their final goal due to the complex nature of the SDS of the developed rock massifs, the formation of which is associated with numerous natural and technogenic factors (Coutinho, 1999, Mathar, 1998).

To assess the potential safety of mining operations, it is necessary to identify the main factors influencing the manifestation of rock pressure in a dynamic form. These factors are: the presence of rocks with high elastic properties, the effect of significant gravitational-tectonic and geodynamic stresses in the rock massif, the achievement of critical mining depths, and other technogenic processes (Aitmatov, 1987).

Analyzing the methods of measurement and stress assessment, it should be noted that it is impossible to solve many problems of mining geomechanics only by field studies. In recent years, numerical methods, especially the finite element method, have often been used to theoretically study the dynamic manifestation of rock pressure and solve other geomechanical problems. These methods are widely used in calculating the stability of various elements of mining and mining systems and modeling man-made stress fields caused by the influence of mining operations.

Materials and methods. The main factor in predicting geodynamic phenomena is the determination of technogenic effects and the development of stressed deformed fields during the underground mining of non-ferrous metal ore deposits (Adams et al, 2014, He et al, 2022).

Stresses in the earth's crust have a hierarchical block structure, and since vertical stress acts everywhere, and its magnitude is expressed by the density of rocks and the depth from the daytime surface, the hierarchical nature of the structure of the field of natural stress of the rock massif is determined solely by the tectonic state. There are global, regional, local, private, and point-based frameworks of the main stress zones (Sayyidkosimov et al, 2023).

In addition to horizontal and vertical stresses in the rock massif, factors such as the conditions of formation (genesis) of the massif, thermal effects, physical and mechanical properties of rocks, the relief of the earth's surface, the influence of groundwater and surface waters affect the formation of a universal stress field.

Currently, the strength index, as well as other physical and mechanical characteristics of rocks determined on samples, is considered a random value obeying certain laws of distribution. It is assumed that each point of the rock massif can be characterized by distribution parameters obtained from a number of sample tests, provided that the number of tests is large enough.

Summarizing a brief overview of methods for assessing the variability of factors forming the SDS of a rock massif, it should be emphasized that the choice of a particular assessment method or criterion for the uniformity of the indicator under study must be made from the standpoint of the physical meaning of the indicator itself. Assessing the degree of randomness of individual values of an indicator and identifying patterns of its manifestation can be successful only if a thorough analysis of the causes of variability, the degree of their impact on the indicator and the degree of randomness is carried out. Only under these conditions will it be possible to develop principles and criteria for assessing the degree of uniformity of breed indicators in each specific case.

It is characteristic that areas of increased fracturing are associated with tectonic disturbances and form zones of structural weakening. In areas of transverse or diagonal orientation of weakened zones to the worked-out space, significant rock blocks are observed to collapse, the separation of which occurs along the dislocators of the disturbance, provided that these zones are worked out.

A characteristic feature of the host rocks of the Zarmitan deposit is their intense tectonic disturbance. At the same time, as the depth of mining increases, the degree of tectonic disturbance increases. The rocks of undisturbed zones are rocky, and in zones of tectonic disturbances they are semi–rocky.

The structural features of the deposits, the interrelationship of the deformation and strength characteristics of rocks with their petrographic composition have been revealed in the deposits of the Zarmitan gold ore zone. In the case of stress distribution and the manifestation of rock pressure in a dynamic form, the fracturing of rocks has a great influence on the stability of underground mining structures. Comprehensive studies included the determination and static processing of the elements of the occurrence of cracks, their linear parameters, the distance between them, the nature of the crack surface, the description and analysis of cases of displacement, collapse, rock formation and other elements of the dynamic manifestation of rock pressure (Sayyidkosimov et al, 2023). Cracks with a steeper or reverse drop may be the boundaries of the shear area and the locations of the most likely roof collapses of the treatment workings. With regularly expressed fracturing, it is possible to predict the direction of relative displacement vectors and possible angles of rock fractures. The more fractured the array is and the greater its intensity, the lower the strength properties and the lower the coefficient of structural weakening (Sayyidkosimov et al, 2023).

The structural disturbance of the massif was assessed according to three types of fracturing of rocks: weakly fractured, medium-fractured and strongly fractured. The stress state of the array from moderate to high was taken into account. According to the Palstrom classification, the geological quality index of the rock mass was determined, which ranged from 30 to 17.6 for weak and medium-fractured rocks, which corresponds to the high quality of the massif. For highly fractured rocks, the quality index of the massif was 6.3 (Palmström et al, 2017, Palmström, A. 2017). According to the conditions of occurrence, the nature of the distribution and variability of the mineralogical composition of rocks, it can be divided into a number of structures. The bulk of the ore in the deposits of the Zarmitan gold mining zone is represented by gold-bearing quartz veins and sulfide ores.

The structural model of the rocks was obtained from laboratory tests of rock and ore samples in conjunction with an analysis of the causes of variations in indicators, including a study of the mineralogical composition and fracturing of the rock in a piece and in kind.

Mining practices in the mines of the Zarmitan gold zone show that ores and rocks are prone to brittle fracture when loaded and are capable of accumulating potential energy during deformation.

Studies of the stressed deformed state of the rock mass during the exploitation of deposits, typical for regions where large faults and horizontal compression are observed, have shown that under similar conditions with the Charmitan deposit at a depth of 100-200 m, horizontal stresses are in the latitudinal direction Y = (3.2-4.0)uN, meridian X = (2.6-2.8)uN, vertical Z = l,8N. Steep-lying ore bodies (at an angle of 70°) have been studied at the Zarmitan deposit during the excavation of reserves by a mining system with ore storage and collapse of the underlying rocks (Sosnovskaya et al, 2019).

The main geomechanical feature of all applied mining systems at the Zarmitan mine is the leaving of an open unfilled developed space and security interstory and interblock pillars. After working off the blocks, it is difficult to excavate the interstory and interblock security pillars from the raises. Due to the high tension created in the rear sight during the excavation of the sub-floor, these rear sights often suddenly collapse in a dynamic form. As a result, conditions are created for the formation of increased reference pressure. With the depth of excavation of reserves and the increase in the span of the developed space, the manifestation of rock pressure increases, both in static and dynamic forms (Tyupin, 2019).

Results and discussion. The stress state of the rock massif was estimated in the mining workings of the existing horizons of the mines of the Zarmitan gold ore zone using slot discharge, acoustic emission (AE) and numerical modeling using the finite element method. Measurement of deformations in the roof and walls of mine workings by reference points and paired reference points of embedded profile lines with a frequency of once a quarter. The control of geomechanical processes was carried out in the most stressed areas by instrumental measurements of deformations and stresses in mining workings and treatment chambers.

The use of the slot discharge method allows you to obtain information about the stress in a section of about 1 m. This method is based on fixing the deformations of the walls of the workings formed during the formation of the gap. Considering that the discharge zone of the rock massif is in the range of three times the size of the gap, the length of which is 0.3 m. The method is used in weakly cracked, strong, elastic ores and rocks, provided that no deformation zone is created near the mine. By the method of slot discharge, the stresses in the sides of the workings are set - horizontal and vertical - acting along the axis of the workings (*RD 06-329-99, 1999,* Kuzmin, 2014).

The stresses at the Charmitan deposit operating in the rock massif were determined in the area of the drift along ore body No. 17 in the mine located parallel to the ore structures, and in the 6001 trench at the horizon of +540m. At the Gujumsay deposit, the research was carried out on an active horizon of +660 m in the area of ore body 53, substory drift No. 1. The measurement results are shown in Table 1.

The uneven stress distribution in the massif is caused by a complex tectonic structure, in particular, blocky rocks limited by systems of cracks and disturbances, as well as mountainous terrain. The actual vertical stresses of the rock massif are almost equal to the gravitational stresses from the weight of the overlying rocks, equal to γH according to the Geim and amount to 10.26 MPa for the Charmitan deposit at the horizon of +540m, where γ is the volume weight of the rocks, 2.7 t/m^3, H is the depth of development from the surface – 380m. The horizontal stresses on the considered horizon, directed along the strike of ore bodies, are 1.4-1.6 times higher than the vertical stresses. The maximum values are the stresses acting across the strike of ore deposits, which are 2.5-3.5 times higher than the vertical stresses (Ruchkin et al, 2014).

Table 1. Characteristics of the initial stresses of the rock mass of the deposits of the Zarmitan gold mining zone

Place of measurement	Stress	Theoretical stress according to A. Geim $\sigma_v = \sigma_l = \sigma_v = \gamma H$, MPa	Tectonic stresses according to field measurements	
			Results of stress determination by slotted discharge method, Mpa	
Charmitan deposit				
The horizon is +540m in strike	vertical	10,26	3,95	3,87
	horizontal		15,30	
Horizon +540 m across to strike	vertical	10,26	3,85	7,6
	horizontal		29,1	
Gujumsay deposit				
The horizon is +660m in strike Горизонт	vertical	7,02	3,7	4,2
	horizontal		15,4	

Note: σ_v – vertical stress, σ_l – longitudinal stress, σ_t – transverse stress, σ_h – horizontal stress, σ_v – vertical stress.

The excess of horizontal stresses of σ_h over vertical stresses can be explained by the presence in the massif, along with gravitational stresses, significant stresses of tectonic origin, supported by modern neotectonic movements of the Earth's crust, as well as a significant redistribution of stresses due to the left voids, unfilled chambers. The presence of the latter was previously established in other ore deposits of Central Asia by I.T. Aitmatov, N.G. Yalimov, V.R. Rakhimov, K.D. Vdovin, G.A. Markov, and others (Aitmatov, 1987).

According to the results of experimental studies, the variation of stresses on the workings contour has been established. Vertical stresses range from 3.0 to 4.0 Mpa, horizontal stresses range from 15.0 to 30.0 Mpa. The main factor in this data spread seems to be the presence of several crack systems and, consequently, the blocky structure of the rock mass.

To assess the dynamic manifestation of rock pressure at the Zarmitan mine, a geophysical method was used using the SB-32M Sapphire instrument, which allows recording acoustic emission pulses in the high-frequency range via two channels with different amplitude levels. To assess the strength of the rock mass based on the obtained indicators, the parameters of the AE process were calculated.

Graphical results of minute-by-minute AE measurements are shown in Figures 1-4, which combines four measurements of AE parameters carried out sequentially at one section of the mine in opposite sides. At the last measurement, the category "Dangerous" was obtained.

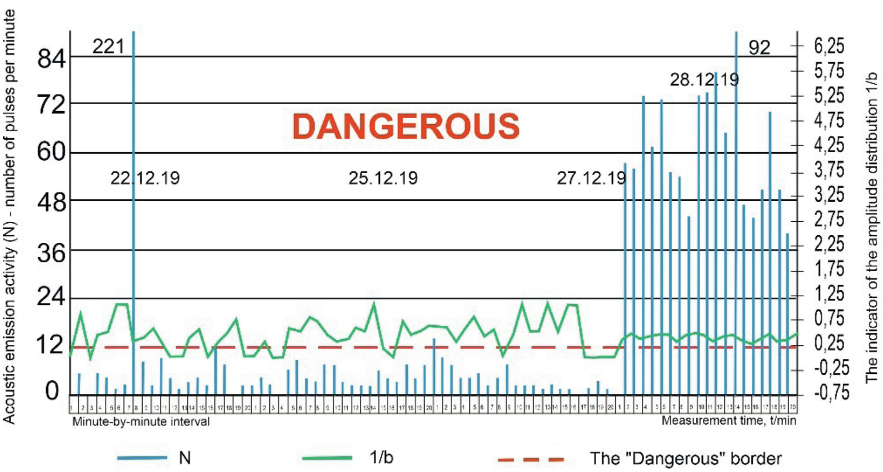


Figure. 1. Minute-by-minute graph of AE measurements in crosscut 6001 at the 540 m horizon. (N is the number of pulses per minute, 1/b is an indicator of the amplitude distribution of pulses, - - - the boundary of the establishment of the "dangerous" category)

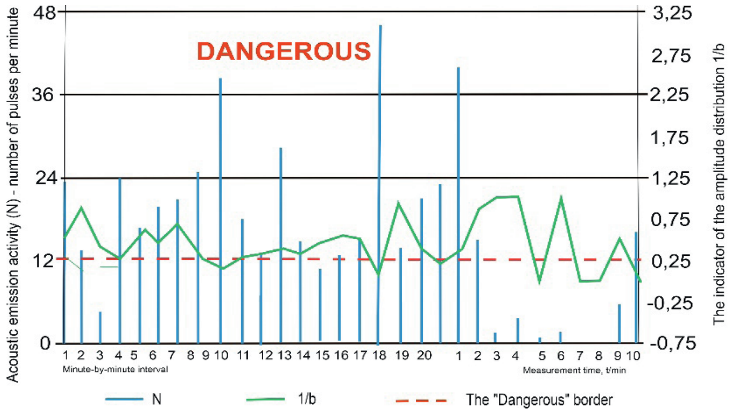


Figure. 2. Minute-by-minute graph of AE measurements at the +540 m level.
Block 60128–129.

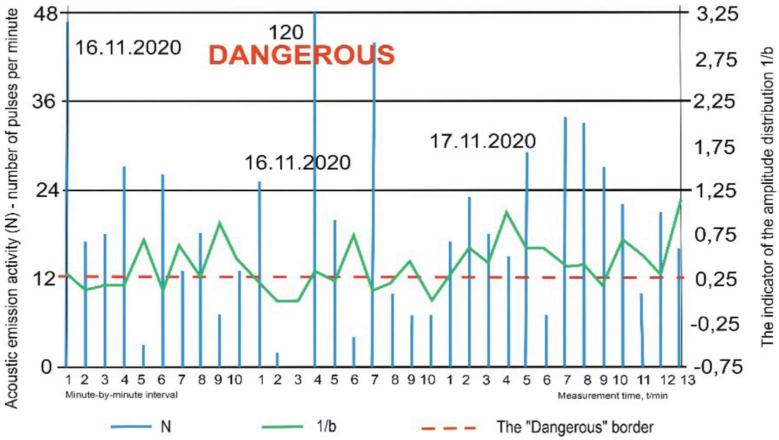


Figure 3. Minute-by-minute graph of AE measurements at the +540 m level.
Block 60127–128.

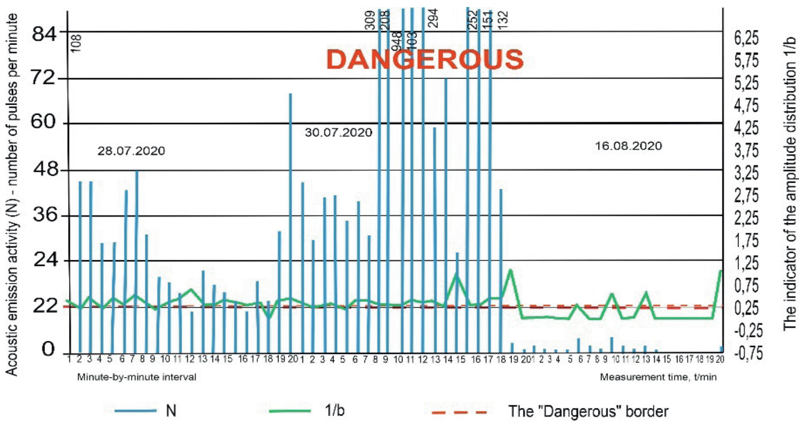


Figure 4. Minute-by-minute graph of AE measurements for July 27, 28, and 30, 2020, in the drift at the +540 m horizon.

All measurements of AE parameters using the SB-32M (Sapphire) instrument were carried out according to the compiled measurement manual. For each measurement, the following were indicated: the characteristics of the site, the time frame of measurement relative to blasting operations, and the external signs to be recorded. The SB-32M device allows recording acoustic emission pulses in the high-frequency range via two channels with different amplitude levels. To assess the strength and impact hazard of the rock mass, the parameters of the AE process are calculated based on the obtained indicators.:

– on the first channel, we get the average activity of N0.15 for a 20-minute measurement (eighty intervals of 15 seconds);

– by the ratio of the values in channels 1 and 2, we obtain an indicator of the structural distribution of pulses b.

The 1/b curve, highlighted in green in Fig.1, is an indicator of the amplitude distribution of pulses, i.e. a characteristic of the unstable state of a section of a rock massif.

Based on the experience of conducting research on the impact hazard of ore deposits, the installation criteria for the category of impact hazard according to AE parameters were adopted for the Zarmitan mine. The "DANGEROUS" category for medium-strength rocks corresponds to the parameters: N0.15 $\geq$ 3; b $\leq$ 4. The red dotted line marks the boundary of the "dangerous" category. Accordingly, all indicators registered above this limit will be classified as a dangerous category for mountain impacts. These studies were conducted jointly with specialists from the Ural branch of JSC ARSRSI (All-Russian Scientific Research Surveying Institute) and according to the methodology proposed by them.

Analysis of AE measurements shows frequent occurrences of zones classified as hazardous. After several recorded manifestations at the +540 m horizon in blocks 60107–127, 60127–128, and 60128–129, monitoring based on AE data was carried out. In block 60128–60129 (November 16–17, 2019), elevated activity categories were obtained, indicating intense brittle microfracturing processes and the onset of dynamic failure conditions. Measurements were also performed in stoping chambers and in blocks with stored ore, where rock pressure hazards likewise occur.

The minute-by-minute AE activity graph (Figure 2) shows spikes ranging from 30 to 120 impulses per minute, reflecting periodic increases in stress concentration and indicating an unstable state of the rock mass. In block 60127–60128 (Figure 3), two measurements demonstrated an overall trend toward decreasing AE activity, with short-term spikes up to 40 impulses.

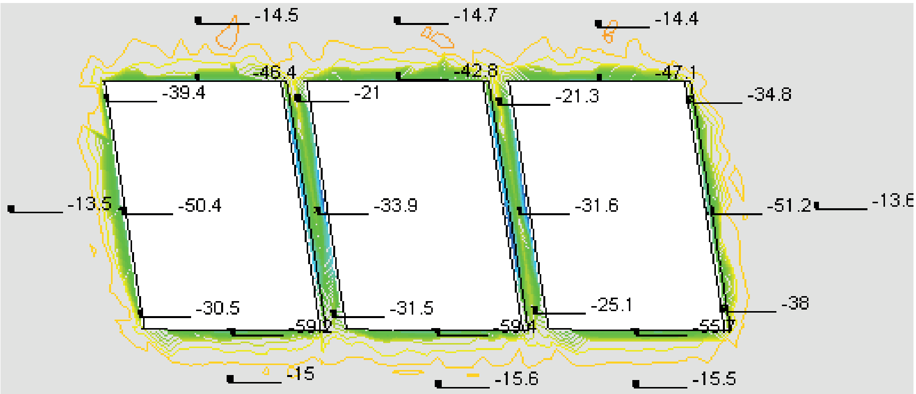
During the driving of r.t. 1a drift and inter-drift crosscuts in the zone of tectonic fractures, hazardous categories and dynamic manifestations were also recorded. Similar indications were observed in the stoping chamber during drilling. The AE graph for the eastern part of the r.t. 1a drift (Figure 4), combining measurements from July 28, July 30, and August 16, 2020, shows a significant decrease in AE activity by mid-August—down to zero values.

The practice of conducting experiments shows that the main factors of increasing the dynamic manifestation of rock pressure during excavation are the zones of influence of tectonic disturbances and the reference pressure of cleaning operations, the concentrators of which are the interfacing of workings, the shape of the inter-heading pillars and the failure of workings.

Numerical methods are increasingly being used to study rock bumps and theoretical solutions to various geomechanical problems, among which the FEM finite element method and the BEM boundary element method should be highlighted. These methods are especially widely used in modeling technogenic stress fields caused by the influence of mining operations, as well as in calculating the stability of various elements of mining systems and workings.

The assessment of changes in the stress deformed state of the rock massif was performed using numerical simulation using the finite element method. Mathematical modeling of the SDS array was performed in the COSMOS/Works program, a finite element analysis system integrated into the SolidWorks three-dimensional design environment, which allowed us to obtain a tool for calculating and optimizing structures consisting of a large number of parts. The general idea of the finite element method (FEM) is to move from the differential equations of continuum mechanics to a system of linear equations with respect to the displacements of the vertices of the elements. The complexity of solving practical problems consisted in the need to solve high-order equations, in entering and outputting large amounts of data by elements, and in interpreting such results.

The calculation scheme (Figure 5) and the diagrams of the main stresses (σ_1, σ_2, σ_3) in the plane of the ore body (OB) (Figure 6) were obtained on the basis of model studies of the SDS of the massif with excavation blocks under the combined action of gravity and tectonics.



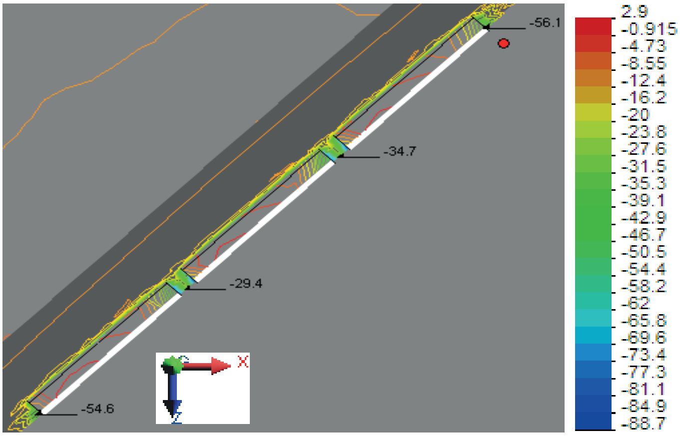
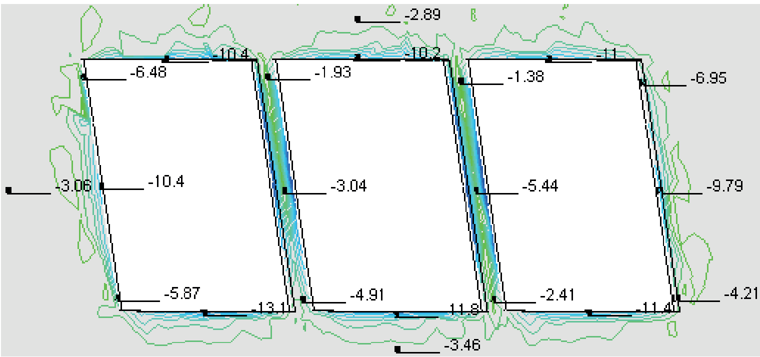


Figure 5. Horizontal stresses along the X-axis in the middle section of the pillars. Σ_3, Mpa. Top and front views



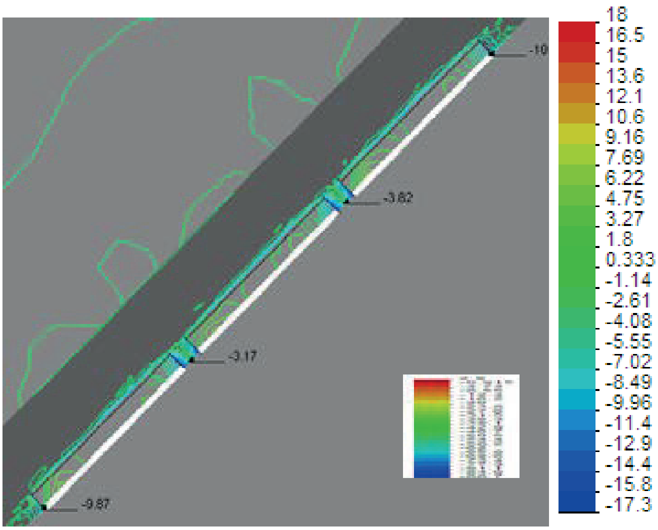


Figure 6. Stresses along the Z axis $\boldsymbol{\sigma}_2$, MПa. Top and front views

It follows from the model shown in Figure 6 that the stresses in the vicinity of the treatment units increase markedly compared to the intact array. In the middle of the lateral faces of the host rocks, compressive stresses are 4 times higher than the stresses of points far from the faces. In the pillars, the stresses are also compressive, increasing towards their middle. In the middle of the ceilings of the extreme excavation blocks, the compression stresses exceed the corresponding values of the average excavation block, reaching 47.1 MPa. The maximum compression of 88.7 MPa corresponds to the middle of the left side of the right block. The ratio of the element size to the power of the ore body: 8.2. Therefore, the average stresses are relevant (Table 2).

Table 2. The average values of σ_3, MPa on the faces of the excavation blocks

	Block	Left	Middle	Right	Block	Left	Middle	Right
Facets	Footwall	-14.7	-16.3	-14.1	Right wall	-40.9	-42.8	-33.3
	Hanging wall	-14.8	-15.7	-15.2	Roof	-33.2	-34.5	-32.8
	Left wall	-33.4	-42.5	-43.1	Floor	-34.4	-36.7	-33.1

It is characteristic that along the boundaries of the treatment units, the reserve coefficient is less than 1, and at a small distance from the boundaries it increases to 2 or more. At the points of the middle horizon in the pillars, where maximum stresses were observed, the margin coefficient is less than 0.5. The exceptions are the ceilings and the soles of the blocks, the weakest elements are the pillars and the lateral boundaries of the array.

The SDS of an intact massif was studied under the combined action of gravity and tectonic compression stress of 12 MPa directed at an angle of 45.5° to the strike of the RT and taking into account three excavation blocks in the studied zone. A special feature of this task is that the capacity of the excavation unit is almost 33 times smaller than its other two sizes and 8.2 times smaller than the size of the final element.

Thus, the excavation unit is like a narrow slit in an array and is a stress concentrator.

In the vicinity of the treatment units, the maximum horizontal stresses $\boldsymbol{\sigma}_3$ noticeably increase compared to the untouched array. In the middle of the lateral faces of the host rocks, the compressive stresses are 4 times higher than the stresses of the points far from the faces. In the rear sights, the stresses are also compressive, increasing towards the middle of the rear sights. In the middle of the ceilings of the extreme excavation blocks, the compression stresses exceed the corresponding values of the average excavation block. The concentration coefficient for average stresses is: in the pillars 3.23, in the ceiling 2.63, in the soil 2.8.

Along the boundaries of the treatment units, the safety margin coefficient is $n<1$, and at a small distance from the boundaries it increases to $n>2$. At the points of the middle horizon in the rear sights, where maximum stresses were observed, $n<0.5$.

The main reason for the strength violation is the magnitude of the tectonic stress, since the strength of the enclosing massif under the action of gravity alone is beyond doubt. In this case, it is necessary to perform more accurate experiments on measuring horizontal stresses in the array containing the ore body. Research on the refinement of the strength properties of the host rocks is also relevant.

During the development of the deposits of the Zarmitan gold mining zone, with increasing depth of development, there is an intense manifestation of mining pressure, which negatively affects the safety and efficiency of mining operations.

The conducted impact hazard study is based on an assessment of the stress state and physico-mechanical properties of rocks in the reference pressure zone by the geomechanical method. The core disketing method is based on the ability of the core of brittle rocks to collapse into discs under the influence of high stresses (Kuzmin, 2014).

The essence of the method is core drilling of an advanced well and core extraction. The degree of rock-bump hazard of an array is judged by the nature of core destruction, that is, by the number of convex-concave fragments of the extracted core (disks) per unit length.

As is known, the core disketing method comprehensively characterizes the state of an array, which is related both to the magnitude of stresses acting in the array and to the strength properties of the ore (rock), which determine the tendency of ores (rocks) to brittle core fracture into discs, and the thickness of the discs is evidence of the level of stress of the array.

The thickness of the discs into which the core is destroyed depends on the magnitude of the stresses acting in the array normal to the axis of the well and on the diameter of the core. The higher the acting stresses, the more intense the process of disk formation and the smaller the thickness of the core disks.

To predict the rock-bump hazard and assess the strength of the array, a Diamec 232 drilling rig was used with a drilling mode: rotation speed of the drilling shaft 350-450 rpm; feed force up to 1 MPa; drilling speed 1-2 cm/min according to the instructions (Kuzmin, 2014).

The core wells from which the core was taken were drilled in the workings of the Gujumsay and Zarmitan mines, which are outside the zone of influence of the cleaning works.

Drilling operations were carried out at the Gujumsay field at a horizon of +660m, in the 660-1 trench and in the drift along ore body No. 51b, where a fan of wells with a diameter of 49 mm was drilled at the drilling site.

The drilling sites at the Charmitan deposit were selected according to the following principle: one in the development of the ore structures laid across the strike, the other in the development, along the strike of the ore structures. Drilling operations were carried out in the 7004 kverschlag of the +480m horizon and in the drift along the 1a ore body. The research results are shown in Tables 3 and 4.

Table 3. Maximum stresses acting on the workings circuit at the Gujumsay and Charmitan fields

№	Deposit, horizon, mine working	X_{max}, cm	t_{min}, cm	t_{min}/d	$\sigma_{max}/\sigma_{сж}$	h, см	X_{max}/h	σ_{com}, MPa	σ_{max}, MPa	$\sigma_{vert}=\gamma*H$, MPa	$\sigma_{uc}=\sigma_{max}*0{,}2$, MPa
1	Gujumsai, crosscut hor.+660-1	254,2	1,1	0,28	0,60	320	0,8	49,02	29,4	7,02	5,87
2	Gujumsai, crosscut hor. +660-1 (inclined borehole 45 degrees)	310,1	0,7	0,18	0,85	320	1,0	49,02	41,7	7,02	8,33
3	Gujumsay, a drift along ore body 51b	228,2	1,3	0,33	0,54	300	0,8	49,02	26,3	7,02	5,25
4	Charmitan, crosscut №7004 hor.+480 m	35,3	2,4	0,62	0,39	300	0,1	51,8	20,2	11,88	4,03
5	Charmitan, a drift through the ore body 1a; hor.+480 m	According to the drilling results, core disking was not detected.									

Note: σ_{com} - compressive stress, σ_{uc} - uniaxial compression

Table 4. Результаты расчета горизонтальных напряжений и и вертикального напряжения

№	Deposit, horizon, mine working	$\sigma_{верт}=\gamma*H$, MPa	σ_1, MPa	σ_2, MPa	$\sigma_3=\gamma*H+\lambda*\sigma_1$, MPa
1	Gujumsay, hor.+660m, crosscut +660-1	7,02	22,66	19,22	14,57
2	Gujumsai, horizon.+660m, drift along the 51b river	7,02	22,66	19,22	14,57
3	Charmitan, crosscut №7004 hor.+480	11,88	21,73	18,03	19,12
4	Charmitan, hor.+480, drift through ore body 1a	According to the drilling results, core disking was not detected.			

Based on the calculations performed, the ratio of the main stresses acting in the massif in relation to the vertical stress should be determined.:

At the Gujumsay deposit:

- the main maximum horizontal stress acting across the strike of ore structures is $\sigma_1=3.23*\gamma*H$, MPa;

- the intermediate horizontal stress acting along the extension of ore structures is $\sigma_2=2.74*\gamma*H$, MPa;

- the vertical stresses acting in the array are minimal and amount to $\sigma_3=1.00*\gamma*H$, MPa.

At the Charmitan deposit:

- the main maximum horizontal stress acting across the strike of ore structures is σ_1=1.83*γ*H, MPa;
- the intermediate horizontal stress acting along the extension of ore structures is σ_2 =1.52*γ*H, MPa;
- the vertical stresses acting in the array are minimal and amount to σ_3 =1.00*γ*H, MPa;
- the performed calculations show that the maximum and intermediate horizontal stresses in an intact array have similar values in magnitude.

For the first time, the methods of least squares and group accounting of arguments of the MGAA were used to predict geomechanical processes.

The least squares method (LSM) is used to construct approximation relationships between the measured parameters of the rock mass and the observed geomechanical manifestations (deformations, stresses, displacements). Its application makes it possible to identify statistically significant factors influencing the stress–strain state of the rock mass, to build stable regression models, to smooth out inaccuracies and noise in instrumental measurements, and to obtain quantitative predictions of rock-mass behavior under changing mining conditions. Thus, LSM serves as a fundamental tool for deriving primary mathematical relationships.

The GMDH method (Group Method of Data Handling) is a model self-organization algorithm that automatically selects the most significant variables and forms the optimal model structure. Unlike traditional regression, GMDH builds the model step by step, from simple to more complex, eliminates insignificant or weakly influential factors, prevents overfitting, and ensures high forecasting accuracy under complex and nonlinear dependencies. This is especially important in geomechanics, since processes such as stress redistribution, the formation of concentration zones, and the occurrence of dynamic phenomena often exhibit nonlinear behavior.

Using LSM and GMDH together makes it possible to identify the key factors of geomechanical manifestations, obtain statistically stable dependencies from measurement and monitoring data, construct a model capable of capturing nonlinear processes within the rock mass, and provide a multi-level forecast in which LSM results form the foundation and GMDH acts as a mechanism for refining and optimizing the model structure. This approach increases the accuracy and reliability of predicting dynamic manifestations of rock pressure.

Given the importance of obtaining reliable predictions, the next step is to assess how accurately the developed models perform in practice. The accuracy of the forecast is usually judged by the magnitude of the forecast error—the difference between the predicted and actual values of the variable under study (Suchenko, 2004). In practice, the problem of forecasting accuracy is often solved in situations where the true value of a random variable is unknown. To determine the joint heuristic and stochastic errors, the value of the function is evaluated depending on the forecast horizon.

$$\mu(l) = \sqrt{1 + \frac{1}{l_0} + \frac{(2l + l_0 - 1)^2}{l_0^2 - 1}} \quad (1)$$

where l is the forecast distance; l_0 is the length of the initial dynamic range.

If we keep in mind that absolute errors are superimposed, then taking into account systematic and stochastic errors, the total errors in estimating the predicted indicator are expressed as follows:

$$\mu_{general} = \Delta + \sqrt{1 + \frac{1}{l_0} + \frac{(2l+l_0-1)^2}{l_0^2-1}tm}, \quad (2)$$

where t is the confidence level, Δ is the absolute prediction error, $\Delta = |P_i - A_i|$ is defined as the difference between the true value of the indicator P_i and the predicted A_i; m is the standard deviation of the forecast,

$$m = \pm\sqrt{\frac{\sum\delta^2}{n}} \quad (3)$$

where n is the number of indicators.

The coefficient of discrepancy characterizes a measure of the quality of the forecast

$$V = \frac{\sqrt{\sum(P_i - A_i)^2}}{\sqrt{\sum A_t^2}} \quad (4)$$

An indicator of the value of a forecast is not only its reliability, but also its usefulness in solving production problems.

Conclusion. The main factors of the conditions for the formation of the manifestation of rock pressure in a dynamic form are, in priority order; natural stresses in the rock mass; structural heterogeneity of the rock mass; stress-strain state of the rock mass around the mine workings; physico-mechanical properties of rocks in the massif; fractured-tectonic state of the rock mass; mineralogical composition and content of minerals and harmful components in the ore, which can be combined in an indicator of the coefficient of structural weakening of the rock.

At the Zarmitan and Gujumsay mines, which exploit the deposits of the Zarmitan gold ore zone, the recorded forms of rock pressure are: collapses of interblock and interstory pillars, rock layers in areas of converging ore bodies, dislocations of the host rocks in the worked-out space, deformations of the walls of shupurs and wells, shooting, cracking, silks during mining.

It has been established that with an increase in the depth of mining operations, conditions are created for the formation of increased reference pressure in both static and dynamic forms.

It has been experimentally proved that the main factors of increasing the dynamic manifestation of rock pressure during mining are the zones of influence of tectonic disturbances and the reference pressure of cleaning operations in excavation chambers and work on partial excavation of room fender pillars.

It is determined that in the presence of neotectonic movements and seismotectonic activity, the direction of tectonically compressive and tensile stresses in the rock mass of the Zarmitan mine is oriented in a northeasterly direction and the vertical component of the stresses is 2.5-2.8 times higher than the calculated ones, and the horizontal stresses exceed the vertical stresses by 1.3-1.4 times.

It has been experimentally confirmed that the information obtained on core disking is a complex characteristic of the rock massif, reflecting both the strength properties of ore and rock, as well as the degree of their fragility, as well as the magnitude of stresses in the array. The obtained values of horizontal and vertical stresses acting in the rock mass should be taken into account when designing the lower horizons of the Gujumsay and Zarmitan mines.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 15.12.2025.
Формат 70х90$^{1}/_{16}$. 20,5 п.л.
Заказ 6.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142