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Research on the stability of mine workings and the risk of rock caving at the Zhaysan deposit, Kazakhstan

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Abstract

Purpose. This research aims to predict the stability of mine workings and assess the risk of rockbursts in conditions of insufficient knowledge of the mechanical rock properties at the Zhaysan deposit (Kazakhstan), while taking into account the depth of the rock mass occurrence and quality, as well as the orientation of the mine workings relative to the tectonic stress field.

Methods. The research employs a set of methods: laboratory testing of granitoid and diabase samples, assessment of rock mass disturbance using the Rock Quality Designation (RQD) index, analysis of metasomatically altered rocks, as well as the construction of a simplified 3D geomechanical model using the kriging method. The rock mass strength was predicted using the Hoek-Brown criterion, while the risk of rockbursts was assessed using the Fragility Index (UCS/UTS) and the Canadian method for assessing rockburst potential. The stability of mine workings in different directions was determined by the indicator of weighted frequency of rockfalls and analysis of their ratio with respect to orientation relative to σ_1.

Findings. It has been found that with increasing depth, the average RQD values increase from 60 to 90%, reflecting a decrease in fracturing and an improvement in rock mass quality. However, in fresh granitoids, there remains a high risk of elastic energy accumulation and its release during destruction. The critical depth at which rockburst risk begins has been determined to be approximately 400 m. The rocks altered metasomatically are characterized by reduced strength and fragility, which reduces their susceptibility to bursts, but increases the probability of caving. It has been revealed that the stability of the mine workings depends on their orientation: minimal damage is fixed when coinciding with the direction σ_1 (azimuth ~300°), and the critical is the angle of intersection 45°, after which the volumes of rockfalls increase sharply.

Originality. For the first time for the Zhaysan deposit, laboratory tests, geomechanical parameters (RQD, GSI), analytical strength criteria and analysis of the orientation of mine workings relative to the tectonic stress field were integrated to determine the depth boundary of rockburst hazard occurrence. The necessity of distinguishing between fresh and metasomatically altered granitoids is demonstrated when assessing risks and taking into account the direction of mine workings in project solutions.

Practical implications. The results make it possible to identify high danger zones and depths, starting from which an enhanced monitoring of the stress state of the rock mass and the application of special safety measures are required. The proposed approach can be tailored for similar solid mineral deposits with limited source data, as well as can be used when selecting a safe direction for mine workings in the tectonic stress field.

Keywords: *geomechanics, RQD, rockbursts, stability of mine workings, Zhaysan deposit, tectonic stresses*

1. Introduction

Determining the rock mass burst hazard category at the project stage is necessary for the timely identification of risks and the development of effective safety measures. Lack of information on geomechanical properties, increasing the depth of operations and the influence of the orientation of mine workings relative to the tectonic stress field increases the probability of unpredictable geodynamic processes, which requires the use of more accurate prediction methods.

The relationship between mining depth and rock quality is a key focus of research in mining, especially when mining deep horizons. Studies show that as depth increases, the pressure of overburden rocks increases, which can improve the mechanical properties of the rock mass, increasing its strength and stability. Thus, Lee et al. note that the distribution of stresses in rocks changes significantly with depth, which contributes to the stabilization of the rock mass [1]. Similar conclusions are drawn by Wu et al., which indicate the influence of high geostresses on the deformations of surrounding rocks [2]. According to Zhang et al., at great depths, the behavior of rocks can change from brittle to plastic, which contributes to an increase in structural continuity [3].

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However, this increases the risk of caving and dynamic phenomena, requiring robust monitoring and management [3], [4]. As Kan emphasizes, increased depth is accompanied by increased stress, which complicates the fastening of underground structures [5], while modern high-strength elements help to better control deformations and improve safety [6], which is confirmed by the results of applying modern fastening technologies [7].

Ghazdali et al. demonstrate that numerical modeling effectively assesses stability in low-quality rock conditions, emphasizing the need to tailor mining methods to actual geological conditions [8]. Such studies are consistent with the principles of rational use of rock pressure energy in underground conditions [9] and modern approaches to planning mining operations, taking into account the degree of reserve preparedness [10].

Thus, although deep mining can contribute to improving the strength characteristics of the rock mass, it is associated with a number of engineering risks that require an integrated approach to ensuring the sustainability and safety of mining operations. This is particularly relevant in conditions of weak rocks and weakening zones, which should be identified and monitored [11]. In this case, methods of preliminary rock mass weakening [12], as well as geophysical studies using electrical and radioactive logging, are considered promising, as they provide a more complete understanding of the host rock properties [13].

Although recent studies have significantly advanced the understanding of rockburst mechanisms and rock mass behavior at great depths, their application to specific field conditions, such as those at the Zhaysan deposit, is limited. Sun et al. [14] and Wang et al. [15] propose models for predicting rockbursts, but their effectiveness depends on large marked samples not available for new mines. Zhu et al. [16] and Qin et al. [17] focus on the evolution of stress-strain state with depth, but fail to take into account metasomatic alternations and the transition from brittle to plastic behavior of granitoids. In-situ observations by Zholmagambetov et al. [18], Avdiev et al. [19] and Rojas Perez et al. [20] concern coal and polymetallic deposits that differ in terms of geology. Cortes et al. [21] provide empirical criteria for assessing susceptibility to rockbursts, but without taking into account geological heterogeneity and stress anisotropy.

Thus, there remains a gap in risk modeling for deep, brittle and metasomatically altered granitoids under the conditions of thrust tectonic regimes. The Zhaysan deposit is characterized by limited in-situ data, scarce laboratory testing and complex structural conditions [22]. This research aims to eliminate these limitations by integrating laboratory tests, data-analogs and a simplified rock quality index (RQD)-based geomechanical model to predict rock mass strength and assess rockburst risk.

The Zhaysan ore field is located in southeastern Kazakhstan and is mined by LLP "Zhanashyr Project". One of the factors for conducting the operations was unexpected geodynamic phenomena at the nearby Shatyrkul mine, 25 km from Zhaysan [23]. According to the regulations of the Republic of Kazakhstan, zones with elastic brittle rocks or zones where rockbursts, tremors and shocks have already been observed in similar conditions are considered prone to rockbursts. Such manifestations have been recorded in Shatyrkul, which raises the question: from what depth could they arise at Zhaysan?

The geological structure of the ore field is represented by Upper Ordovician granitoid intrusions (granodiorites and biotite-granites), complicated by diabase dikes. Ore zones are confined to their contacts and are accompanied by a "shirt" of hydrothermally altered rocks of reduced strength, losing stability when waterlogged. No full-scale stress measurements were taken at Zhaysan. Their assessment was performed based on the World Stress Map (2016), according to which a tectonic regime of thrust faulting (TF) prevails in southern Kazakhstan (Fig. 1).

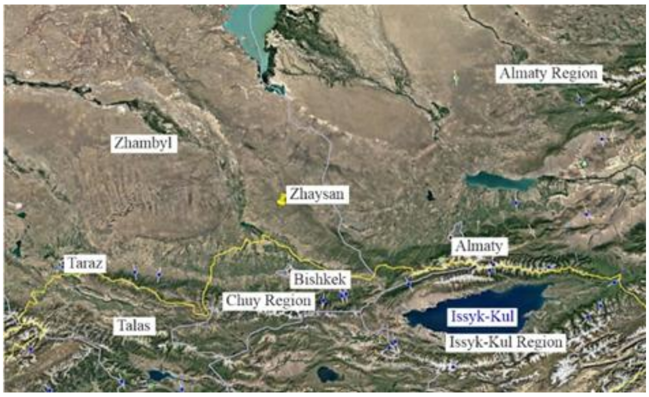

Figure 1. Stress state of the earth's crust in southern Kazakhstan and Kyrgyzstan on the WSM map (coordinates of the Zhaysan mine): N43º32′ E74º25′

The tectonic regime of TF implies the following ratio of principal natural stresses [24]-[26]:

– horizontal tectonic stresses are maximum in value $\sigma_1 = S_{H\max}$; it is precisely their direction of action in the plan that is shown by strokes on the WSM map;

– horizontal stresses $\sigma_2 = S_{H\min}$, acting perpendicular to the maximum stresses, are intermediate in value;

– vertical gravitational stresses from the weight of rock thickness are minimal in value $\sigma_3 = S_V = \gamma H$:

$$S_{H_{\max}} > S_{H_{\min}} > \gamma H \,. \qquad (1)$$

According to the WSM 2016 map (Fig. 1), in southern Kazakhstan, the maximum horizontal tectonic stresses σ_1 act in a submeridional direction, close to the N-S direction.

Similar results obtained in the neighboring region of Kyrgyzstan using tectonophysics methods showed that in the area of the Shatyrkul and Zhaysan mines, maximum tectonic (horizontal) stresses act in a northeastern direction, coinciding with the direction of the ore zones. The results of in-situ measurements presented in [19], provided estimates of natural horizontal stresses $\sigma_1 = 3.1\,\gamma H$; $\sigma_2 = 1.9\,\gamma H$, while the minimum stress caused by the gravitational pressure of rock thickness is $\sigma_3 = \gamma H$.

These results show that at the Shatyrkul and Zhaysan mines, the maximum tectonic (horizontal) stresses along the strike of the ore zones σ_1 can exceed the vertical pressure of the overlying stratum γH by 3 times. At depths of H = 500-600 m, as envisaged in mining projects, high tectonic stresses can create burst-hazardous situations in strong, elastic, brittle granitoids not altered by hydrothermal metasomatosis.

To clarify the predicted and estimated geomechanical situation at the Shatyrkul and Zhaysan mines in the mined-out mine workings, it is necessary to conduct research and development work to determine the susceptibility to rockbursts.

2. Research methods

The research employs a set of geomechanical methods, including analysis of the geological peculiarities of the deposit and in-situ measurements, using approaches to geomechanical characteristics of rock both at the surface and underground [27]. The stress state was assessed based on tectonic-physical data and laboratory strength tests [28]. The structure and fracturing of the rock mass were determined using RQD and then interpolated using Multi-Gaussian kriging [29], [30], which made it possible to construct a 3D geomechanical model [31]. The stability prediction of mine workings was performed using numerical stability modeling, including analysis of the influence of fracturing [32]. Based on the results, recommendations were developed for managing rock pressure and ensuring the stability of mine workings.

2.1. Mechanical properties of rocks

The Zhaysan mining project [33] uses Protodyakonov's strength indices (PSI): for sulphide ores, f = 8-10; for oxidized ores, f = 8-9; and for granites, f = 9-11. Thus, host rocks are considered stronger than ore, but the scope of the initial research is unknown, which needs to be verified. Kazakhmys practice has shown that using inaccurate data on rock strength in projects can lead to negative consequences [34], [35].

At the current stage, the properties of the rocks have been studied to a limited extent: only 100 samples of granites, granodiorites and diabase have been tested for compression and tension. The small sample collection (4-7 samples per test) does not allow for reliable differentiation between rock types based on strength or assessment of changes in strength with depth. In addition, the reduction in strength in metasomatic zones requires clarification. The results are summarized in Table 1.

Table 1. Properties of the rocks at the Zhaysan deposit

Rocks	Granodiorite	Diabase	Granite	Average
True density, g/cm^3	2.70	2.77	2.65	2.71
Bulk density, g/cm^3	2.68	2.76	2.63	2.69
Elasticity modulus, 10^4 MPa	4.5	4.6	4.2	4.5
Poisson's ratio	0.14	0.14	0.14	0.14
Compressive strength, MPa	99	77	87	86
Number of samples	7	6	5	6
Tensile strength, MPa	7.7	7.6	8.6	8.0
Number of samples	7	4	4	5
In a water-saturated state, MPa	87	64	68	74
Softening factor	0.88	0.83	0.78	0.86
Fragility	13	10	10	11

The average compressive strength of Zhaysan granitoids is 80-100 MPa, which corresponds to strong rocks (R4) according to the ISRM classification [36], [37]. They soften little when waterlogged, have a high modulus of elasticity and a brittle nature of destruction, which makes them prone to rockbursts at high pressure [38]-[40].

The lack of factual data on Zhaysan is compensated by the results of studies at the Shatyrkul deposit, which is similar in terms of conditions (hydrothermal genesis granitoids, steeply dipping ore zones, tectonic regime of thrust faulting The Shatyrkul experience demonstrates the need to distinguish between unaltered (fresh) and metasomatically altered granitoids. As a result of hydrothermal metasomatosis, strong minerals are replaced by sericite and chlorite, which reduces the strength and elasticity of rocks to a clay-like state and increases their tendency to soak. Tests on 104 samples revealed a bimodal distribution of UCS, reflecting the existence of two types of rock: strong, unaltered rock and metasomatically altered rock with medium strength. The average UCS was 110 MPa with a high variation factor (56%), indicating significant mass heterogeneity.

A comparison of the average UCS values for Zhaysan and Shatyrkul using Student's t-test [26] (significance level 1%) confirmed a statistically significant difference between the samples (Table 2): the strength of Zhaysan rocks is lower than that of Shatyrkul rocks. At the Shatyrkul deposit, the conditional boundary between unaltered and metasomatically altered granitoids is determined by a strength of UCS ≈ 120 MPa. Dividing the initial statistics into two groups allows us to assess the strength of each type of rock. The results of the comparison are presented in Figure 2 and Table 3.

Table 2. Comparison of rock strengths at the Zhaysan and Shatyrkul mines

Parameters	Shatyrkul (1)	Zhaysan (2)
Number of tests	104	18
Uniaxial compressive strength (UCS), MPa	110	87
Standard deviation S_d, MPa	50	29
Student's t-statistic	$T = \frac{UCS_1 - UCS_1}{\sqrt{\frac{Sd_1^2}{n_1} + \frac{Sd_2^2}{n_2}}}$	
	$T = 2.81$	
Number of degrees of freedom $n_1 + n_2$	120	
Level of significance α	0.01	
Critical value of Student's t-test	$t_\alpha = 2.62$	
Result of comparison	$T > t_\alpha$	

The strength of metasomatically altered rocks in the "shirt" around ore zones is on average 2.2 times lower than that of the original granitoids. According to the PSI classification, they are divided into two categories of strength. Dividing the initial heterogeneous statistics into two sample sets reduced the variation factors to an acceptable level, which statistically confirmed the difference between the two types of rock (fresh and altered).

The experience of the Shatyrkul mine shows that the main rock pressure manifestations occur when driving mine workings in metasomatites with reduced strength and high fracturing. To minimize them, at the design stage, it is advisable to locate capital and preparatory workings in unaltered rocks of greater strength and less disturbance.

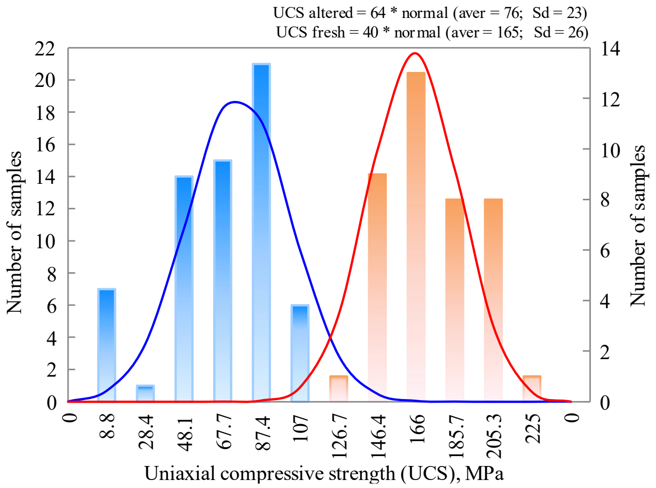

Figure 2. Difference in strength between metasomatically altered (blue) and unaltered rocks (red) at the Shatyrkul deposit

Table 3. Comparison of the properties of hydrothermally altered and unaltered rocks at the Shatyrkul deposit

Rock strength indicators under uniaxial compression (UCS)	rocks	
	altered	unaltered
Number of tests	64	40
Average strength, MPa	76	165
Root mean square deviation, MPa	26	23
Variation factor	34%	14%
Strength category according to PSI	7 (medium strength)	16 (very strong)

2.2. Rock mass fracturing

The fracture system prediction was made based on research results at the similar Shatyrkul deposit. The polar diagram of the rock mass fracturing, constructed in the Dips programme, is shown in Figure 3. Based on 702 measurements, three main systems have been identified:

– 1 m – steeply dipping fractures (Dip = 75-90º), coinciding with the strike and dip of the ore zone, the most extensive and widespread;

– 2 m – oblique fractures (Dip = 40-55º), consistent with the strike but with reverse dip, cutting longitudinally;

– 3 m – steeply dipping fractures (Dip = 65-90º), crossing ore zone strike at nearly right angle, transversely intersecting.

In the section to the dip constructed using the DFN module, the first and second systems with average dip angles of 81 and 53º are distinguished (Fig. 3). These systems cause kinematic instability in the drifts running along the strike of the ore zone, which is manifested in intense block rockfalls from the roof and walls. Preventing such caving by means of fastening is extremely difficult, costly and unsafe.

Similar fracture systems (at least the main ones) are to be expected at the Zhaysan mine. Consequently, problems with maintaining drifts along the strike of the ore zones will be similar. Measures to ensure the stability of the drifts should be similar. In order to predict the stability of mine workings and substantiate the parameters of mining measures to protect the drifts, the mine geomechanics engineer must continuously map the disturbance of the rock mass by fractures during the process of driving. It is necessary to measure the elements of fracture occurrence (angle and azimuth of dip using a mining compass), their lengths, distances between fractures in systems, degree of roughness, presence of an aggregate and signs of weathering.

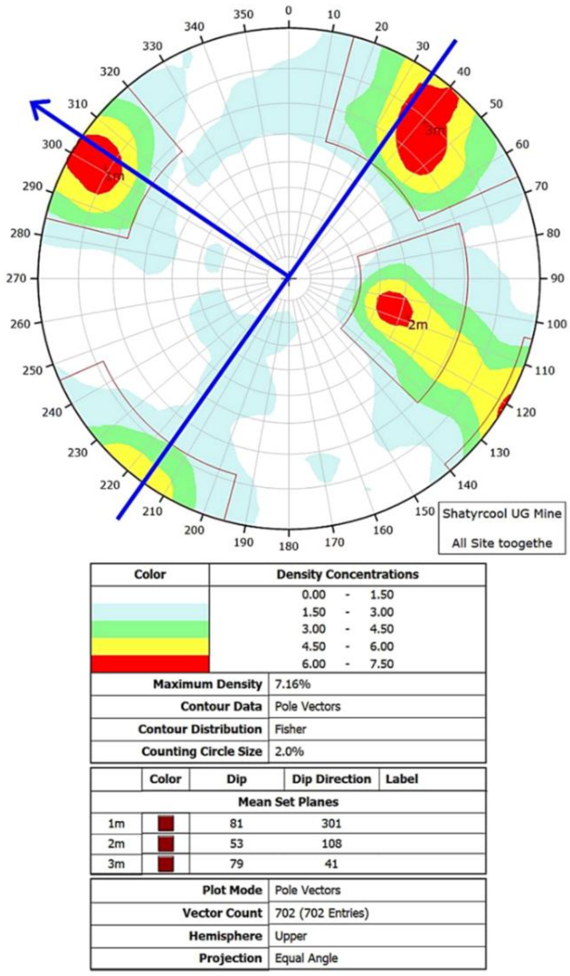

Figure 3. Rock mass blocks falling into the drifts along the strike of steeply dipping fractures under the action of their own weight

2.3. Rock mass disturbance index RQD

Additional exploration of the Zhaysan deposit determined geomechanical index of rock disturbance RQD in the course of geological description of the core. This index is used in almost all modern geomechanical calculation methods. It is determined by core intervals. As a rule, this is the length of the drilling run. In 47 wells with indices C (11 pcs.), WAI (16 pcs.), ZH…Tech (20 pcs.) with a diameter of HQ, 5409 core intervals with a length of 1-3 m have been described. RQD statistics are provided in Figure 4.

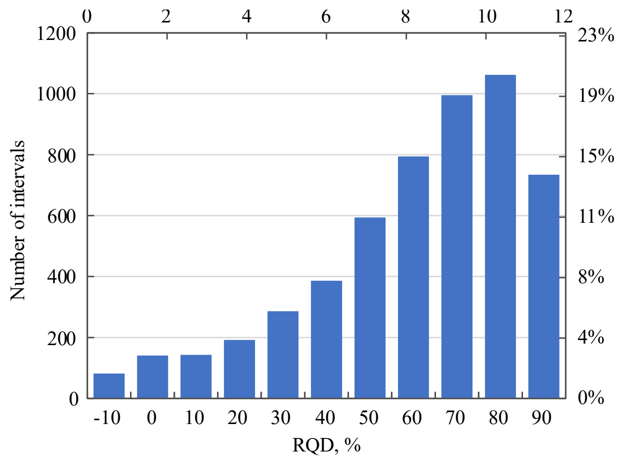

Figure 4. RQD histogram at the Zhaysan deposit

The distribution has an inverse logarithmic normal form. It is asymmetrical: high values dominate (RQD = 100-60%); their share is 68%. The "tail" of low values fades in the range RQD = 50-0%. This type of histogram is typical for strong, weakly disturbed rocks with relatively thin zones of tectonic disturbances with low RQD values.

With an asymmetric distribution, the average index value underestimates the rock mass quality. The modal (most common) value is more objective. At Zhaysan: average RQD = 67%, modal – RQD = 85%. The modal value of RQD is used as a boundary condition when creating a block geomechanical model of the deposit.

With increasing depth, the mass disturbance by fractures decreases slightly, as the average RQD values increase slightly (Fig. 5). This means that the greatest problems with mine working stability may be observed at the highest horizons.

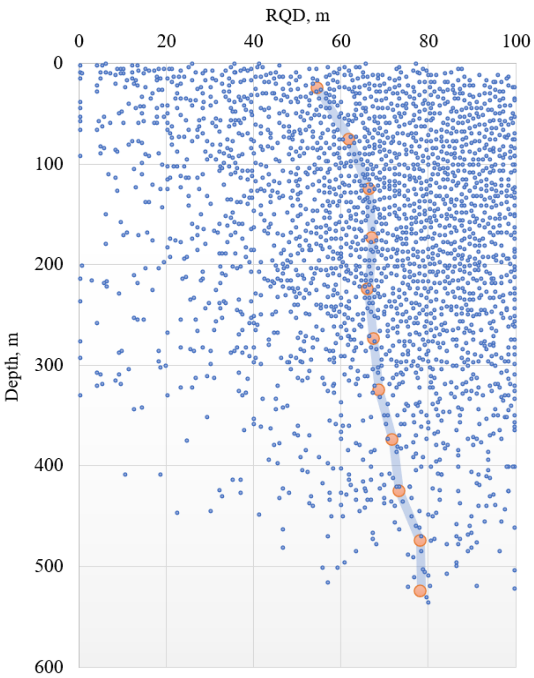

Figure 5. RQD change with depth at Zhaysan deposit

This observation is important because it refutes the common assumption that deeper horizons automatically pose a greater geotechnical hazard. On the contrary, the data obtained indicate that the upper, more near-surface levels may require increased attention when planning support structures due to the presence of weaker and severely disturbed rocks. In this regard, operational strategies should take into account the need to strengthen fastening at the early deposit mining stages.

2.4. Block geomechanical model of the rock mass at the Zhaysan deposit

2.4.1. Source data

The geological structure of the deposit was thoroughly studied and depicted on plans of 1040-470 m horizons and sections 7, 9, 11, 13, 15. This data in 2D format was used to construct a 3D model in Leapfrog software with reference to coordinates and marks. The results of core description of 47 wells drilled in 2018-2020 were used to fill the geomechanical block model. Only one parameter was determined – RQD, which, given the insufficient study of rock properties and fracturing of the mass, allows only a simplified model to be created. The coloring of wellbores with RQD values is shown in Figure 6.

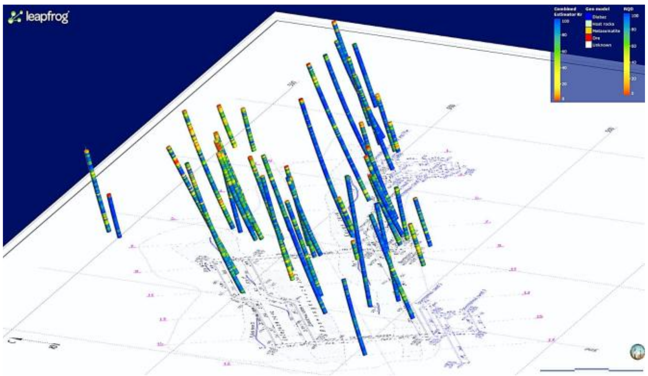

Figure 6. Geomechanical database for core samples from exploration wells

2.4.2. Geological model of the deposit

The geological shell of the created 3D model has the following dimensions: West-East – 2200 m; North-South – 1400 m; in depth – 520 m. It should be noted that the mass has been more or less explored up to an altitude of 770 m.

A general view of the geological model of the Zhaysan deposit is shown in Figure 7. It uses the following mass types:

– host rocks are represented by fresh granites and granodiorites;

– metasomatically altered host rocks;

– diabase dikes;

– ore bodies.

Figure 7 shows the coloring of rock types. Figure 8 shows a geological model section, for example, along line 11-11.

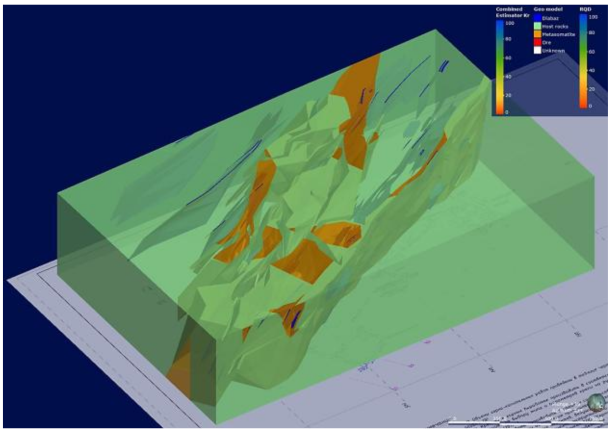

Figure 7. General view of the geological model of the Zhaysan deposit

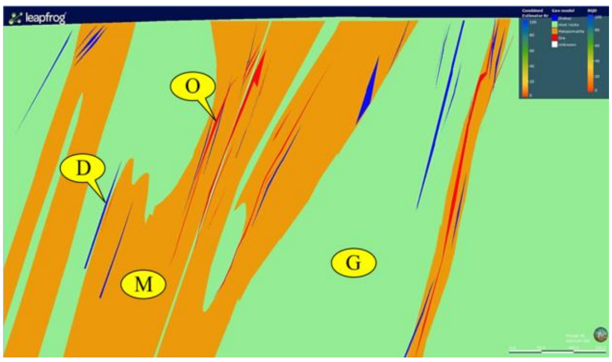

Figure 8. Geological model section along line 11-11: O – ore bodies; D – diabase dikes; M – metasomatically altered rocks; G – altered (fresh) granitoids

2.4.3. Geomechanical model of the deposit

The current stage of geomechanical study of the Zhaysan deposit can be called initial (Scoping Study). Therefore, due to the lack of source data on ore and rock properties, fracturing and the natural stress state of the mass, it is not yet possible to construct a complete block model of the mass filled with such important indices as:

– Rock mass rating (RMR) according to Bieniawski;
– Barton's quality index (Q);
– Hoek's geological strength index (GSI) for fractured rock mass;
– strength of fractured rock mass.

So far, only a simplified geomechanical model of the deposit can be constructed. It uses the rock mass disturbance index (RQD), as it determines the Geological Strength Index (GSI) of fractured rock mass [41]:

$$GSI = \frac{52 J_r / J_a}{1 + \left(1 + J_r / J_a\right)} + \frac{RQD}{2}, \tag{2}$$

where:

J_r, J_a – Barton's indices characterizing the roughness of fractures and their filling or weathering.

The geological strength index (GSI) is used to calculate the strength of fractured rock mass. For this purpose, the generalized Hoek-Brown criterion is used [41]:

$$\sigma_1 = \sigma_3 + UCS \cdot \left(m_b \cdot \frac{\sigma_3}{UCS} + \right)^a, \tag{3}$$

where:

UCS – rock strength under uniaxial compression in undisturbed samples;

m_b – Hoek-Brown parameter, depending on rock type (similar to the internal friction angle in the Coulomb-Mohr strength criterion):

$$m_b = m_i \cdot \exp\left(\frac{GSI - 100}{28 - 14D}\right), \tag{4}$$

where:

m_i – parameter determined by the rock strength certificate based on triaxial compression tests on samples;

s – Hoek-Brown parameter (analog of adhesion in the Coulomb-Mohr strength criterion):

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right), \tag{5}$$

where:

D – parameter that takes into account the reduction in strength due to damage to the rock mass caused by blasting operations.

The Hoek-Brown generalized strength criterion for fractured rock mass determines the limit values of the maximum principal stresses σ_1 in a volumetric stress state (under the action of minimum principal stresses σ_3). This criterion is used to calculate the safety factor in numerical modeling of geomechanical situations. RQD is also the basis for calculating the quality index of the Q mass according to Barton [41], [42].

2.4.4. Simplified geomechanical model of the Zhaysan deposit

To fill in the block model, RQD values were interpolated using the Kriging method in 3 passes [42]. Each of them used its own variogram parameters (Table 4). This allowed for a more accurate RQD interpolation in areas where the density of the source data is higher. The first two passes used a variable orientation of the search ellipsoid based on the main fault planes at the object. For the third pass, the global trend was used, set by the average values of the dip of the two main fault zones: Dip = 69.4º; Dip Direction (Azimuth) = 327º. The resulting passes are combined into a block model.

Table 4. Parameters of RQD search ellipsoids using the Kriging method

General information		Dimensions/radii of the ellipsoid variation			Ellipsoid axes			Variable orientation
Name	Values	Maximum	Intermediate	Minimum	Dip angle	Dip azimuth	Strike azimuth	
Kr, RQD 1 pass	RQD	373	224	74.5	–	–	–	Faults with variable orientation
Kr, RQD 2 pass	RQD	700	500	250	–	–	–	Faults with variable orientation
Kr, RQD 3 pass	RQD	800	600	400	69.4	327	1.03	–

At the outer boundaries of the interpolation volume, a modal value of RQD = 85% was assumed. Visual verification of interpolation realism did not reveal any inconsistencies with the source data. The block model of the mass with block dimensions of 10×10×10 m is filled with interpolated RQD values. Figure 9 shows an axonometric view of the mass RQD block model.

At the Zhaysan mine, the current density of accumulated geomechanical data at 970 m horizon (for example) is shown in Figure 10. The Leapfrog software was used to construct RQD distribution sections, including section 11-11 (Fig. 11). High RQD values (blue tones) correspond to more stable rock masses, while low values (yellow-orange tones) indicate medium and low stability.

To analyze the change in RQD with depth using the block model, horizontal sections (Swath) were made at 10 m intervals, and the average value of the parameter was calculated for each section.

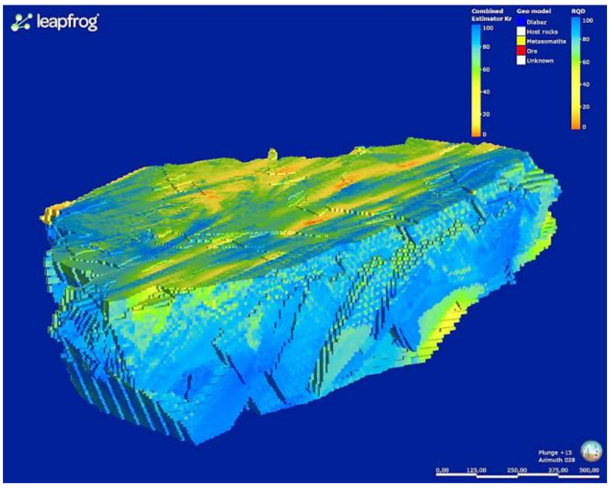

Figure 9. Block 3D model of the mass RQD at the Zhaysan deposit

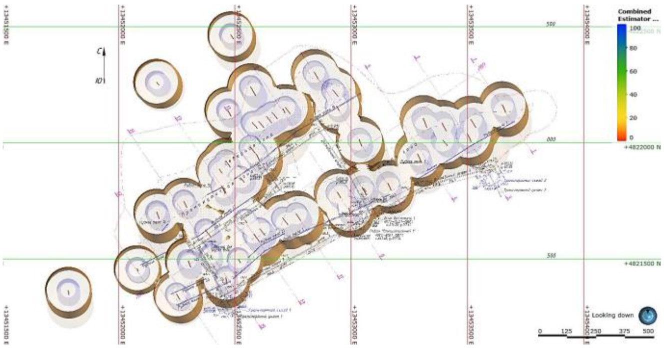

Figure 10. Density of geomechanical GDD data at 970 m horizon: blue cylinders with a radius of 50 m around the wellbore; olive cylinders with a radius of 100 m

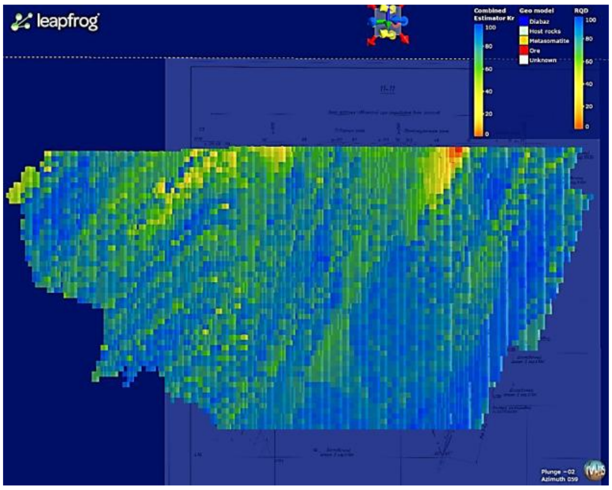

Figure 11. RQD distribution in section 11-11

Figure 12 shows the dependence of RQD on depth: the black line represents the data for the wells, the red – the interpolated values of the model.

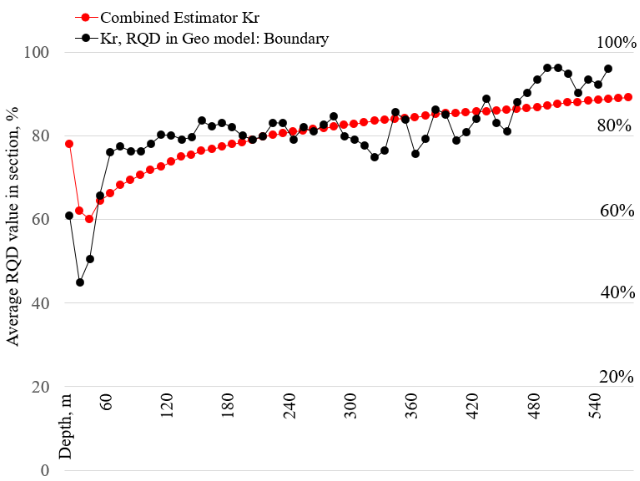

Figure 12. Increase in RQD with depth

2.5. Theoretical basis of the research

The research employs a comprehensive theoretical approach based on proven models and criteria of rock mechanics. RQD is used to assess the fracturing and structural continuity of the rock mass; based on this, the GSI was calculated using Barton's empirical formula. GSI values were used in the generalized Hoek-Brown criterion to determine the maximum strength of the rock mass. The susceptibility of rocks to rockburst was assessed using the Fragility Index (UCS/UTS) associated with Griffith's theory of brittle fracture, and the risk level was classified according to the Canadian Rockburst Program methodology.

The stress state was analyzed using Bruno-Kirsch's analytical solution, adapted to the conditions of thrust tectonic, to calculate the induced stresses on the mine working contour. A simplified 3D model of the mass was constructed using the kriging method based on RQD values, which made it possible to predict the distribution of strength and stability. This integrative approach takes into account both the physical-mechanical properties of rocks and structural peculiarities, even when source data is limited, as in the case of the Zhaysan deposit.

3. Research results

The observed values and their approximation in the model show an increase in average RQD values with depth: from 60% at a depth of 60 m to 90% at a depth of 540 m. This is a very important fact: the rock mass quality improves with reduced mining operations, as the average rock mass disturbance caused by fractures decreases. This fact gives reason to hope that at the deep horizons of the Zhaysan mine, the increase in rock pressure will be compensated by an increase in the rock mass quality (strength, stability).

3.1. Prediction of mine working stability

For strength prediction, we use the generalized Hoek-Brown criterion (3). In it, the fracturing characteristics of the rock mass are described by the GSI. Based on the analogy with Shatyrkul, the fracture roughness will be characterize by index $J_r = 3$, and weathering/filling of fractures – by index 1.5. Then, using Formula (1), obtain GSI = 35 + 0.5·RQD (Table 5).

Table 5. Dependence of the geological strength index (GSI) on the RQD index

RQD	100	90	80	70	60	50	40	30	20	10
GSI	85	80	75	70	65	60	55	50	45	40

The main factor affecting rock mass strength is the intensity of fracturing, expressed by the RQD. This dependence is the basis of a simplified geomechanical model and emphasizes that the behavior of the rock mass is determined not only by the properties of the monolithic rock, but also by its structural state. Therefore, project solutions – the size of mine workings, support spacing, blasting parameters – should take into account local RQD variations.

Fracture parameters such as roughness (J_r) and filling/weathering (J_a) generally vary less. Usually, the average J_r value for the entire deposit is used in calculations, whereas J_a varies in weathered and metasomatically altered rock zones compared to unaltered (fresh) granitoids. Geomechanical mapping can be used to clarify these differences, which will allow the model to be brought up to standard level using the RMR, GSI and *Q* indices.

Fracturing reduces not only strength, but also the stiffness of the rock mass (modulus of deformation). Figure 13 shows the dependences of these parameters on GSI and RQD, calculated according to the Hoek-Brown criterion in the RocLab software with rock properties: UCS = 87 MPa, $m_i = 30$, $E_o = 45$ GPa, without taking into account blast damage ($D = 0$).

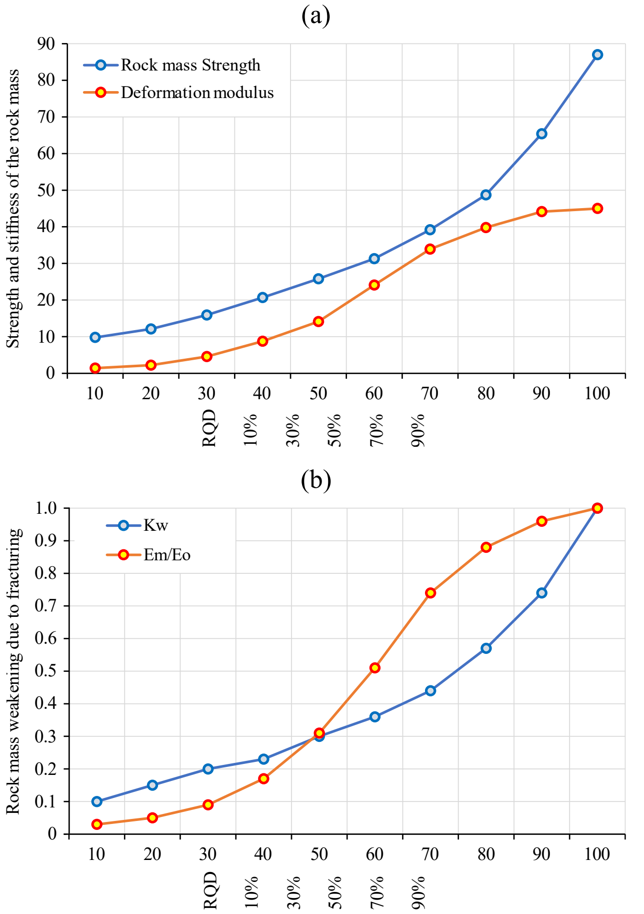

Figure 13. Reduction in strength (a) and modulus of rock mass deformation (b) due to fracturing

The higher the intensity of fracturing, the greater the fracture frequency, the lower the RQD and GSI, and the lower the strength and deformation modulus of the rock mass. In an engineering context, this emphasizes that the behavior of a rock mass is determined not only by the strength of the pillar, but also to a large extent by its structural state. When planning, it is necessary to take into account local variations of the RQD index when selecting the dimensions of mine workings, support spacing and blasting methods.

3.2. Expected forms of instability in mine workings

Mine workings are considered stable if, during the entire service life, there are no rockfalls, caving or significant contour displacements, that is, the project dimensions and section shape are maintained, ensuring the safety and technological feasibility of operations. The loss of stability can be manifested in the form of caving along fractures and weak contacts, or crushing of rock under the influence of high stresses. Based on the experience of the Shatyrkul mine, at Zhaysan, rockfalls are most likely to occur along steeply dipping fractures in drifts driven along the strike of strong rock and ore zones. An example of this is the rock mass caving onto the Robolt installation in the drill-loading drift at the 700 m sublevel, northern portal No. 6, recorded on May 19, 2021 (Fig. 14).

The analysis of the stability of mine workings has confirmed that the orientation of mine workings relative to tectonic compression has no less important influence than the physical-mechanical properties of rocks. With identical strength characteristics, the volumes of roof rockfalls vary significantly depending on the angle of intersection with σ_1.

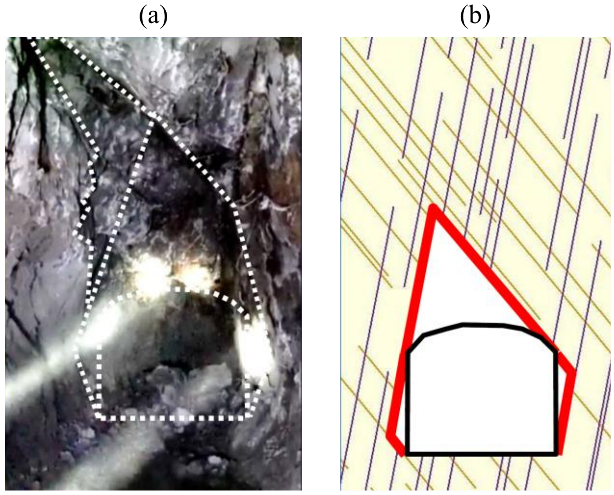

Figure 14. Caving in the drill-loading drift at the 700 m sublevel, northern portal No. 6 at Shatyrkul mine on May 19, 2021: (a) field photo; (b) schematic interpretation

This confirms the need to integrate stress field analysis into the geomechanical substantiation of project solutions.

Practical analysis has shown that the direction of mine workings relative to the field of tectonic stresses directly determines their stability. An in-situ analysis of 39.8 km of drifts showed that the largest volumes of rockfalls occur at an angle of intersection with the direction $\sigma_1 \geq 45°$. Minimal damage is recorded when driving mine workings along σ_1 (azimuth ~300°). This is explained by the increase in circumferential stresses in the roof as the angle of intersection with σ_1 increases. For quantitative assessment, the weighted frequency of rockfall parameter was used, taking into account both the length and power of the destruction. The results are presented in Figure 15.

The caving occurred in the fastened part of the drift together with roof bolts. There is a coincidence in the general outline of the caving zone contour with the network of steeply dipping fractures. It is clear that the height of the caving zone is much greater than the length of the roof bolts. It is quite common for rock blocks to fall from the drift sides that are not fastened. After the side cleavages, which are usually ignored at first by the responsible persons, there is an increase in the width of mine workings with the subsequent roof caving. Rock cleavages from the sides of the drifts have repeatedly led to incidents at the Shatyrkul mine.

Also, on April 7, 2020, there was a caving of the sides and roof of the mined-out and fastened ventilation drift at 705 m horizon over a length of 21 m, with a volume of 109 m^3 (Fig. 16). The drift was driven horizontally along the strike of the rock thickness and the most developed fractures of bedding 1 and along the intersecting fractures 2, along which wedge-shaped rockfalls occurred from unfastened sides and fastened roof.

The forms of block rockfalls along fractures when driving drill-loading drift along the strike of the rock thickness, generated by the Unwedge software based on specified fracture systems are shown in Figure 17.

The Unwedge program was used to calculate the volumes and heights of the roof rockfalls from drill-loading drift when changing the direction of its driving relative to the strike of the ore and thickness of the host rocks (Fig. 18).

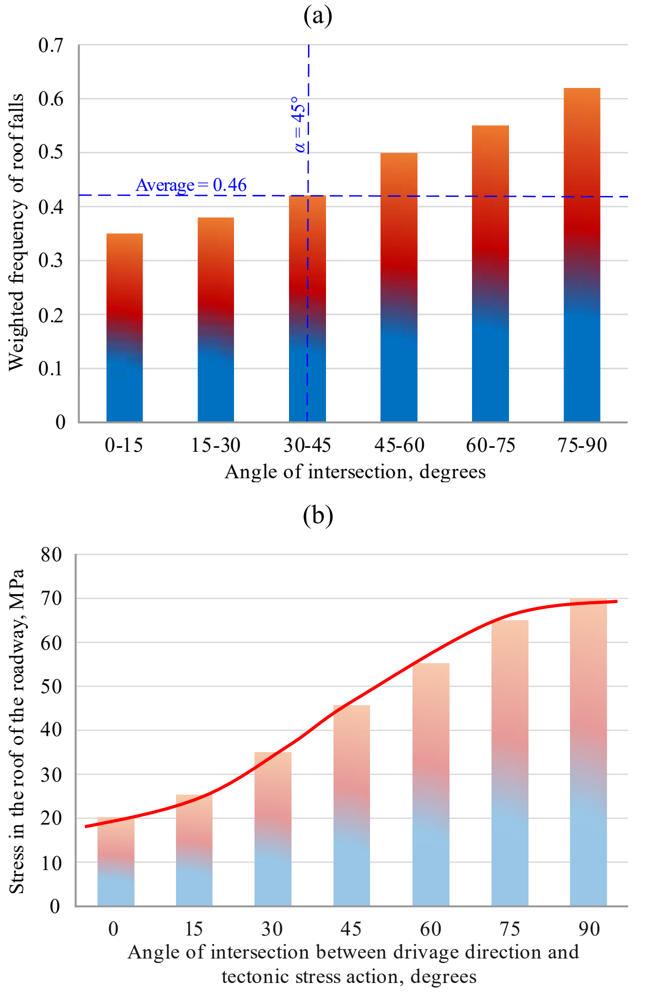

Figure 15. Dependence of fracture formation parameters and stress state of the mass on the angle of intersection: (a) weighted frequency of roof falls; (b) stress in the mine-working roof

Figure 16. Wedge-shaped rockfall in a ventilation drift at 705 m horizon at the Shatyrkul mine on April 7, 2020

The results of the kinematic analysis of rockfalls show:

– the largest volumes of rockfalls occur when driving a drift along the strike of the rock mass;

– when driving mine workings along the strike of steeply dipping rocks, the height of the roof rockfalls is maximum;

– when the drift axis deviates from the strike of the rock thickness, the volumes of the rockfalls and their thickness (maximum height) decrease sharply;

– the larger the cross-sectional area of the mine workings (its dimensions), the greater the volume and height of the rockfalls.

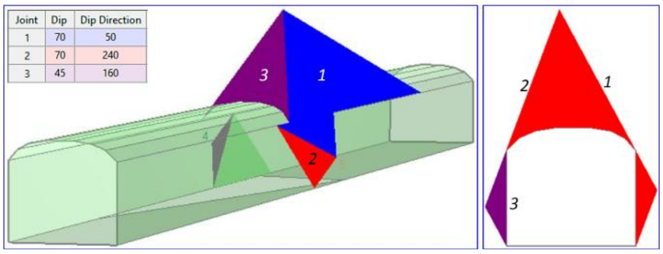

Figure 17. Geometry of possible rockfalls when driving drill-loading drift along the strike of the ore and host rocks along fractures: 1 – the most highly developed system, consistent with the dip of the rock thickness; 2 – longitudinal cutting system with reverse dip; 3 – transverse cutting system

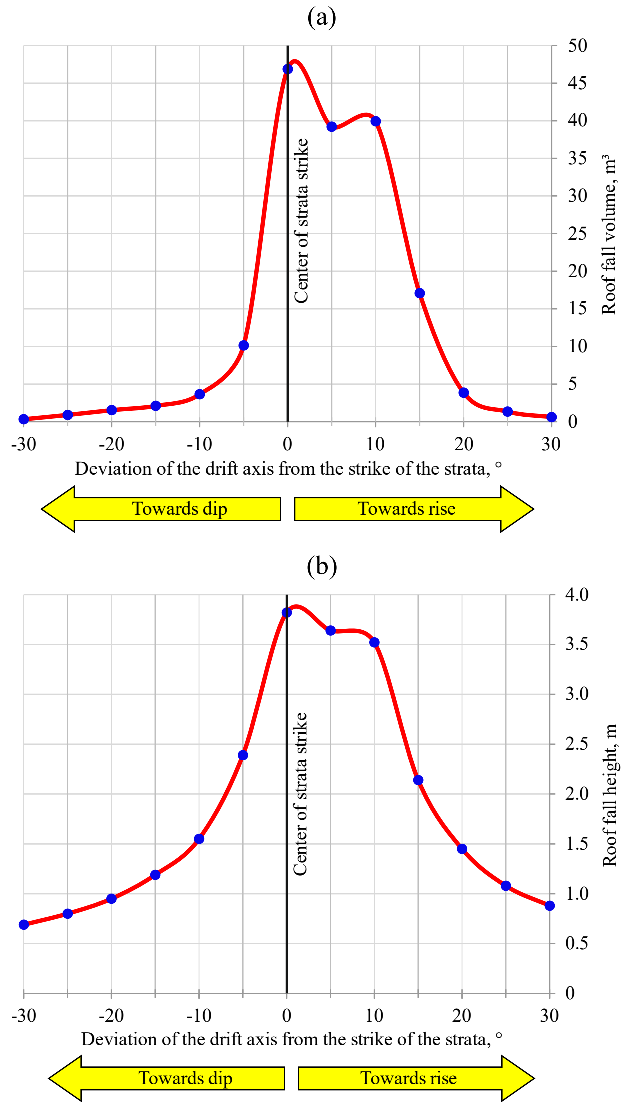

Figure 18. Dependence of the volume and height of roof rockfalls from drill-loading drift workings on the direction of their driving relative to the strike of the ore and the thickness of the host rocks: (a) rockfall volumes; (b) rockfall height

Similar processes and phenomena should be expected at the Zhaysan mine. Their nature is the kinematic instability of rock blocks formed by systems of steeply dipping fractures. The conditions for their rockfalls under the action of their own weight are determined by kinematic analysis. For this, it is necessary to specify the orientation of the fracture systems, the shear resistance along the fractures (adhesion and friction angle), the section and direction of the mine working drivage.

When planning mining operations, it is advisable to take into account the direction of tectonic stresses. It is optimal to drive mine workings along σ_1 (azimuth ~300°), within the ±15° sector, where the roof stability is higher and the volume of rockfalls is below average. Critical is considered to be an angle of intersection ≥ 45°, at which stability decreases sharply. If it is impossible to maintain the σ_1 direction, it is advisable to project the drifts in a zigzag pattern, reducing the average angle of intersection. Analysis of actual sustainability confirms the effectiveness of this approach.

Based on these data, a diagram for projecting the directions of mine workings in the field of tectonic stresses is proposed, reflecting the critical angle of intersection and distinguishing the “favorable” and “prohibited” sectors for the orientation of mine workings (Fig. 19).

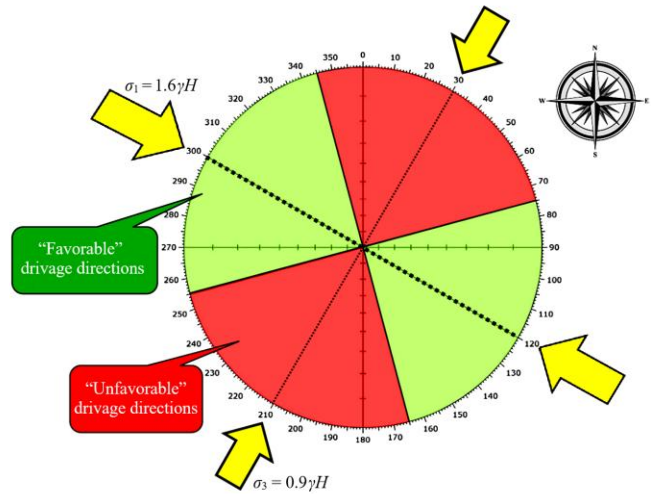

Figure 19. Diagram for projecting mine workings at the Zhaysan mine, taking into account tectonic stresses

3.3. Rockburst hazard prediction

The classic method for assessing rockburst hazard involves two stages: determining the rock susceptibility to rockbursts and assessing the stress level sufficient to cause a rockburst [43], [44]. Ores/rocks are considered prone to rockbursts if they deform elastically (accumulate potential elastic deformation energy) up to the point of failure and exhibit brittle failure behavior (release accumulated elastic energy rapidly during failure with small deformations). All hard rocks are elastic. The brittle ones are those that have a decay modulus (*M*) greater than modulus of elasticity (*E*).

The modulus of elasticity (*E*) is determined prior to rock failure using standard “soft” presses in all conventional laboratories. To determine the decay modulus (*M*), it is necessary to record deformations in a superlimiting state during the sample destruction process. And this is only possible on “hard” presses, which are much more complex, massive and expensive than “soft” presses. Obtaining data on the rock decay module for a wide range of deposits has proved to be quite problematic due to the limited availability of “hard” tests. Therefore, to indirectly assess the susceptibility of rocks to rockbursts without determining the decay modulus, the Fragility Index K_{xp} = UCS/UTS is used. The criterion for the susceptibility of rocks to rockbursts is $K_{xp} > 10$. This criterion is a consequence of Griffith’s brittle fracture criterion [45], [46]. According to this, under tensile stress conditions, the ratio of compressive strength UCS to tensile strength UTS should be equal to UCS/UTS = 8; under volumetric compression conditions, it should be equal to UCS/UTS = 12. The average figure expresses the condition of brittle fracture of rocks at a Fragility Index UCS/UTS > 10.

The results of long-term research in Canada (Canadian Rockburst Program) have shown that it is reasonable to assess the risk of rockbursts by a cumulative indicator – rockburst potential, which takes into account both the UCS of the rock and the Fragility Index (UCS/UTS). The higher the strength, the more elastic energy accumulates until failure, and the brittleness index reflects the tendency of the rock to dynamic failure (spalling) [47]. All available data on the properties of rocks at the Zhaysan deposit are plotted on a diagram of rockburst hazard levels (Fig. 20).

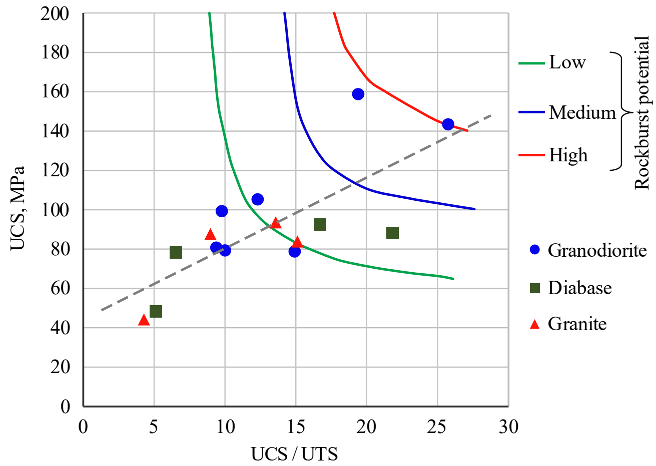

Figure 20. Assessment of the rockburst hazard potential of Zhaysan rocks based on laboratory test results; dotted line: trend line K_{xp} = 0.14 UCS

According to the results of tests on samples from the Zhaysan deposit, 53% of rocks have no potential for rockbursts, 33% demonstrate a low or medium level, and only 14% demonstrate a medium to high level. The greatest potential is characteristic of strong and brittle granitoids that have not undergone metasomatosis. Metasomatically altered rocks surrounding ore bodies have reduced strength and brittleness, and, therefore, are not prone to spalling. This highlights the importance of geological mapping with differentiation between fresh and altered rocks when assessing risks and planning to construct support.

Analytical dependence ($K_{xp} \approx 0.14$ UCS) confirms the direct correlation between strength and brittleness [48]. Given this, the critical depth at which the risk of rockbursts begins is estimated to be between 390 and 420 m (at UCS = 120-130 MPa, $\gamma = 0.027$ MN/m^3, $\lambda_1 = 3$). The final accepted boundary – 400 m, is based on calculations by the Bruno-Kirsch equation and corresponds to the level at which the stresses on the contour of mine workings reach 70% of the rock mass strength [49], [50].

The results obtained are critically important for planning safety measures, as they determine the depth from which specialized methods of counteracting rockbursts are required. From this level, enhanced monitoring (such as microseismic systems), adaptive fastening systems and de-stressing methods should be applied to reduce the risk of dynamic events.

In general, the research results form a deep-specific view on geomechanical risks at the Zhaysan deposit. They demonstrate that weakening of the mass in the upper horizons and increased stress with depth pose a double threat. The applied model allows identifying transition zones and developing differentiated strategies of fastening along the vertical section of the mine space.

4. Discussion

The research conducted on the quality of the rock mass at the Zhaysan deposit demonstrates a regular increase in rock mass stability with depth, which is consistent with previously published data from other authors on the influence of increased rock pressure on improving mechanical properties of rocks. In particular, the increasing strength and stability of the rock mass with increasing depth is confirmed by the identified increase in the average RQD value: from 60% at the upper horizons to 90% at a depth of over 500 m. This is consistent with the conclusions of Zhang et al. that increasing the mining depth contributes to rock mass stabilization due to the transition of rocks from brittle to plastic characteristics. In addition, in zones where rocks change, there is an increased sensitivity to water exposure, which is confirmed by laboratory tests under saturation conditions. Although no direct hydrogeological modeling was performed as part of this research, the identified weakening effect of interaction with water indicates a significant influence of groundwater on mechanical stability at depth. This needs to be taken into account in future multiphysics modeling.

Practical recommendations show that the control of the geometry of mine workings, in particular by avoiding placing them along the strike and using a zigzag pattern direction, helps to reduce the probability of rockfalls and increase stability.

A critical discrepancy with the predictions of previous studies has been revealed in the context of the rockburst hazard. If according to data in [47] the mass strength at great depths ensures the accumulation of significant elastic energy, but at the Zhaysan deposit, this effect manifests itself irregularly and mainly in unaltered granitoids. The experimental data obtained indicate that only a limited proportion of rocks (about 7%) have a high rockburst hazard potential. This significantly limits the applicability of generalized predictive models, such as the Canadian methodology proposed, without taking into account specific local geological conditions.

The limitations of the research are related to the small volume of laboratory tests, the lack of instrumental monitoring of stresses, and insufficient data for a complete 3D model. It should also be noted that there are no in-situ measurements of stresses at the Zhaysan deposit, which are replaced by analogies from the neighboring Shatyrkul mine. This limits the reliability of conclusions made about the stress state and rockburst hazard.

The results of this research are consistent with previously published studies, which indicate that at great depths, the rock mass quality can increase due to compaction under the influence of rock pressure and a reduction in the degree of fracturing. Thus, Zhang et al. [3] and Zhu et al. [16] showed that with increasing depth, the behavior of the rock may change from brittle to plastic, which contributes to increased stability of the rock mass. Similar patterns associated with the increase in rock strength with depth have also been confirmed at the Zhaysan deposit.

At the same time, this research differs from previous works in its approach to accounting for metasomatic alternations. Unlike earlier models assuming homogeneous lithological behavior with depth, our results emphasize that metasomatically altered zones retain low strength and brittleness even at significant depths, as confirmed by comparison with data from the Shatyrkul deposit. This conclusion indicates the limitations of existing generalized predictive models, such as those proposed by Sun et al. [14] and Wang et al. [15], which do not take into account local geochemical changes in rock.

Furthermore, while in studies such as Rojas Perez et al. [20], the depth, at which rockburst risk begins in hard rocks, varies between 1200-1500 m, then in our case it is shown that under the influence of high tectonic stresses in thrust tectonic conditions, the risk of rockbursts occurs already at a depth of about 400 m. This discrepancy highlights the importance of taking into account local stress state, which is often ignored in universal predictive models.

The data obtained confirm that the orientation of mine workings relative to the tectonic stress field has a significant influence on their stability. With identical strength characteristics, stability decreases sharply when the angle of intersection with the direction σ_1 is greater than 45°. The empirical diagram (Fig. 19) allows the substantiation of "prohibited" and favorable" project sectors, which is consistent with the calculated dependence between the direction of mine working and the weighted frequency of rockfalls (Fig. 15). These results complement the traditional approach to stability prediction, taking into account the orientation of mine workings in a stressed rock mass.

Thus, the presented research confirms the general trend of increasing mass quality with depth, but also reveals critically important exceptions related to geological heterogeneity and stress orientation. This requires calibrating of predictive models to specific structural conditions.

Along with depth and strength, metasomatic alternations and tectonic anisotropy are key factors. Promising areas for further research include expanding the mechanical testing base, introducing hydrogeomechanical monitoring, and direct in-situ stress measurements to improve the accuracy of stability and reliability predictions for project solutions.

5. Conclusions

The research analyzes the quality of the rock mass and changes in the risk of rockbursts with depth at the Zhaysan deposit (Southeastern Kazakhstan). To compensate for the limited amount of in-situ data, an integrative methodology is used, including laboratory tests, the use of analogues, and the construction of a simplified geomechanical model based on the RQD index.

It is shown that the average RQD value increases with depth (from 60 to 90%), reflecting a decrease in fracturing and an improvement in the strength characteristics of the rock mass. However, when horizontal tectonic stresses dominate, the risk of rockbursts remains. The use of the Fragility Index (UCS/UTS) in conjunction with the Canadian method for assessing rockburst potential has determined the depth of the risk onset at about 400 m. Metasomatically altered rocks are characterized by reduced strength and low susceptibility to rockbursts, whereas fresh granitoids remain vulnerable to dynamic manifestations.

Practical analysis has shown that the orientation of mine workings has no less influence on stability than the physical-mechanical properties of the rock mass. Maximum stability is achieved when the mine working axis coincides with the direction of σ_1 action (azimuth ~300°), minimum stability is achieved at an intersection angle of 90°, and the critical value is an angle of 45°. The constructed stability diagram (Fig. 19) distinguishes between "favorable" and "prohibited" directions for placing mine workings, providing a basis for sound project solutions.

Unlike generalized models, which mainly take depth into account, the present research emphasizes the need for a comprehensive consideration of geological heterogeneity, metasomatic alternations, and stress field orientation. In the future, it is recommended to expand the laboratory base, introduce microseismic monitoring, and develop numerical modeling. The proposed approach can be used to assess risks at similar hard mineral deposits with limited source information.

Author contributions

Conceptualization: MB; Data curation: AR; Formal analysis: GS, AO; Funding acquisition: MB, ST; Investigation: AR, SI; Methodology: MB; Project administration: MB, AO; Resources: GS; Software: AR, ST; Supervision: MB, SI; Validation: GS, XX; Visualization: AR; Writing – original draft: MB, AO; Writing – review & editing: MB, GS, SI. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Дослідження стійкості гірничих виробок та ризику обвалення гірських порід на родовищі Жайсан, Казахстан

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Мета. Прогнозування стійкості гірничих виробок та оцінка ризику гірських ударів в умовах недостатньої вивченості механічних властивостей порід на родовищі Жайсан (Казахстан), з урахуванням глибини залягання, якості масиву та орієнтації виробок щодо поля тектонічних напружень.

Методика. У роботі застосовано комплекс методів: лабораторні випробування зразків гранітоїдів та діабазів, оцінка порушеності масиву за показником RQD, аналіз метасоматично змінених порід, а також побудова спрощеної тривимірної геомеханічної моделі методом кригінгу. Прогноз міцності масиву виконаний за критерієм Хоека-Брауна, ударонебезпечність оцінювалася за індексом крихкості (UCS/UTS) та канадською методикою оцінки потенціалу гірських ударів. Стійкість виробок у різних напрямках визначалася за показником виваженої частоти вивалів та аналізу їх співвідношення з орієнтацією відносно σ_1.

Результати. Встановлено, що зі збільшенням глибини середні значення RQD зростають від 60 до 90%, що відображає зниження тріщинуватості та покращення якості масиву. Однак у свіжих гранітоїдах зберігається високий ризик накопичення пружної енергії та її вивільнення при руйнуванні. Критична глибина початку гірничоударного ризику визначена на рівні близько 400 м. Метасоматично змінені породи характеризуються зниженою міцністю та крихкістю, що зменшує їх схильність до ударів, але підвищує ймовірність обвалень. Виявлено, що стійкість виробок залежить від їхньої орієнтації: мінімальні ушкодження фіксуються при збігові з напрямом σ_1 (азимут ~300°), а критичним є кут зустрічі 45°, після якого різко зростають обсяги вивалів.

Наукова новизна. Вперше для родовища Жайсан виконано інтеграцію лабораторних випробувань, геомеханічних показників (RQD, GSI), аналітичних критеріїв міцності та аналізу орієнтації виробок відносно поля тектонічних напружень для визначення глибинної межі виникнення гірничоударної небезпеки. Показано необхідність розрізнення свіжих і метасоматично змінених гранітоїдів при оцінці ризиків та урахуванні спрямованості виробок у проєктних рішеннях.

Практична значимість. Результати дозволяють визначити зони підвищеної небезпеки та глибини, починаючи з яких необхідним є посилений моніторинг напруженого стану масиву та застосування спеціальних заходів безпеки. Запропонований підхід може бути адаптований для аналогічних родовищ твердих корисних копалин з обмеженими вихідними даними, а також використовуватися при виборі безпечного напрямку виробок у полі тектонічних напружень.

Ключові слова: *геомеханіка, RQD, гірничі удари, стійкість виробок, родовище Жайсан, тектонічне напруження*

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