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ASSESSING THE ZONES OF TECTONIC FAULT INFLUENCE ON DYNAMIC ROCK PRESSURE MANIFESTATION AT Khibiny deposits of apatite-nepheline ores

Introduction

Complicated mining and geological conditions are characteristic of the present-day mining practice and in some instances result in the development of tectonic and rock bursts, micro rock bursts, and shocks. The mentioned dynamic rock pressure manifestations (DRPM) result in flow process disruption or more serious consequences and require preventive actions based on effective prediction techniques. However, despite research done in this area, the problem of such phenomena prediction and prevention remains unresolved [1–4] since, among other things, it requires simultaneous account of a lot of factors [5–19]. One of these factors is the influence of tectonic faults, the size of these zones of influence cannot be directly measured and requires advanced study. The analysis of dynamic rock pressure manifestation sites demonstrated that these phenomena generally occur in zones of high rock pressure, i.e. near mine workings [20] and tectonic faults [21]. For instance, when developing the Oktyabrskoye and Talnakhskoye deposits, it was found that the faults of the 1st and 2nd types (according to the VNIMI classification) have the main influence on the development of the zones of abnormal stress and rock burst hazard in the ore deposit and pillars [22]. However, nothing is said about the size and degree of influence of the zones of abnormal stress and rock burst hazard in the ore deposit. Based on the experience of the Kizelovsky basin, Kuznetsk basins, Shurabsky deposit, and Suchansky deposit development, I. M. Petukhov et al. [20] found that within the large faults area there is a 15–20 m wide zone containing rock and coal with weak mechanical properties. The main influence of a tectonic fault on the stress distribution within the coal seam is recorded when mining in immediate proximity to it, especially when drawing close in the course of stoping. However, nothing is said about the degree of influence the zone has. A. S. Batugin [23] found that the tectonophysical conditions for tectonic rock burst and man-induced earthquake manifestations in deposits are as follows: favorable orientation of fault dislocations in a modern or man-induced stress field, the stress field heredity (rock mass readiness for strain by displacement along the existing surfaces of weakness), decrease in the normal compression of fault walls when they enter the zone of geomechanical unloading or when they are flooded, large goaf, and high level of tectonic stresses

Assessing the zones of geologic features influence is a task of dynamic rock pressure manifestation prediction. Under rock pressure manifestations this paper understands rock bursts and micro rock bursts, namely, the coordinates of the recorded damage centers in mine workings and pillars the moment a rock burst or a micro rock burst was recorded. The paper determines the distances from the recorded dynamic rock pressure manifestation points in mine workings to tectonic faults in the rock mass of the Kukisvumchorr apatite-nepheline ore field on the Kola Peninsula. The methods of statistical analysis for the distance value frequency uniformity were used for data processing.

Keywords: tectonic fault, rock burst, dynamic rock pressure manifestations, stability, underground mine, statistics, zone of influence, degree of influence

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in the rock mass. V. N. Filippov [24] determined that dynamic phenomena developed under high stresses redistribution as well with rock burst hazardous rocks, tectonic faults, and ore-rock contacts. The width of hazardous zones around tectonic faults at the Tashtagol and Sheregesh deposits ranges between 5–20 and 65 m, respectively.

Literary sources analysis shows that the sizes of zones of influence differ significantly in different deposits and in different mining and geological conditions. The problem of assessing the zones of tectonic fault influence on dynamic rock pressure manifestation for a particular deposit or groups of analogues is therefore relevant.

The research aims to assess the zones of tectonic fault influence on dynamic rock pressure manifestation.

The following tasks should therefore be solved:

1. an optimal number of intervals within the initial data should be determined;
2. the degree and size of zones of tectonic fault influence on dynamic rock pressure manifestation should be assessed.

Methods of research

The rock mass of the Kukisvumchorr apatite-nepheline ore field on the Kola Peninsula was the object of research. Dynamic rock pressure manifestations were recorded at different elevations of the underground workings of the Kirov mine (**Fig. 1**).

The initial dataset was formed by measuring the lengths of perpendiculars, lowered from the centers of dynamic rock pressure manifestations to tectonic faults. The measurements were carried out on digital horizon-oriented plans.

Methods of mathematical statistics were used for the initial data analysis and the number of ranges into which the initial dataset should be divided:

Fig. 1. The points of the recorded dynamic rock pressure manifestations in the geological structure model of the Kukisvumchorr apatite-nepheline ore field

The Sturges formula [25]:

$$k = 1 + \log_2 n, \quad (1)$$

where n is the number of measuring results for a value complying with normal distribution; k is the number of classes used to build the histogram.

The formula uses the binomial distribution to approximate the normal distribution, which is not always applicable when the number of measurements is less than 200.

The Scott's formula (Scott, 1979) [26]:

$$h = 3.5sn^{-1/3}, \quad (2)$$

where h is the length of the range, s is the standard deviation of the values of a series of measurements.

The Freedman–Diaconis formula (Freedman and Diaconis, 1981) [27]:

$$h = 3.5(IQ)n^{-1/3},$$

where h is the length of the range; IQ is the difference between the upper and lower quartiles.

The classification quality functionals method was used to substantiate the number of ranges the initial dataset was divided into [28]:

$$Q: \Theta \rightarrow R, \quad (3)$$

where Q is the set of all possible class systems.

The weighted sum of intraclass variances was used as a classification quality functional for a given number of classes k :

$$Q_1(S) = \sum_{i=1}^k \sum_{X_j \in S_i} d^2(X_j, \bar{X}(I)), \quad (4)$$

Fig. 2. Dependence between the number of the recorded dynamic rock pressure manifestations and the distance from the tectonic fault to the rock pressure manifestation site

where $\bar{X}(I) = \sum_{i=1}^n \frac{X_i}{n}$; d is the feature space metric $Sp(X)$; $S = (S_1, S_2, \dots, S_k)$ is some fixed categorization of observations $X_1, X_2, \dots, X_n$ into a given number k of classes $S_1, S_2, \dots, S_k$.

D. A. Rodionov's statistics v_k was used to analyze the dataset values homogeneity (rock burst frequencies) within the ranges [29]:

$$v_k = \frac{n-1}{kn(n-k)} \sum_{j=1}^m \frac{\left[(n-k) \sum_{i=1}^k x_{ij} - k \sum_{i=k+1}^n x_{ij} \right]^2}{\sum_{i=1}^n x_{ij}^2 - \frac{1}{2} \left(\sum_{i=1}^n x_{ij} \right)^2}, \quad (5)$$

where k is the number of the observation, after which the threshold divides the set of observations into two parts, $k = 1, 2, \dots, n-1$; n – rows (number of observations); m – columns (number of features); x_{ij} is the object-feature matrix entry.

The SECTIONS software [30] was used for statistical calculations.

Research results

Based on the analysis of mining-geological conditions and dynamic rock pressure manifestation recording results, a variational series of distances from the manifestations to tectonic faults was formed (Table 1), and the number of recorded rock pressure manifestations was plotted against the distance from the tectonic fault to the rock pressure manifestation site (Fig. 2).

The paper considers the issue of tectonic faults influence that extends beyond their boundaries, so the DRPM number values recorded directly in tectonic faults $d = 0$ m (null zone) were excluded from the initial dataset. The values of the variational series starting from $d = 2$ m were therefore accepted for further analysis.

Table 1. Distances from the tectonic faults to the recorded dynamic rock pressure manifestation sites

d, m	0	2	4	5	6	7	9	10	14	16	19	22	23	24	29	30	32	33	34	35	39	43	47	48
n	13	2	2	2	1	2	3	1	1	2	1	2	1	2	1	1	1	1	3	1	2	3	1	1
d, m	52	53	54	56	57	70	71	77	87	92	96													
n	2	1	1	3	2	1	1	1	1	1	1

Fig. 3. Dependence between the values of functional $Q(S)$ and the number of dataset categorization ranges (a) and the values of functional increments (b)

To solve the first problem, we calculated the range number values for different means of initial dataset categorization (Table 2).

The method of classification quality functionals was used to objectively determine the number of ranges the initial dataset should be divided into. The initial dataset in row d of Table 1, starting from $d = 2$ m, was sequentially divided into 1, 2, ..., 9 ranges, for which the values of the functional $Q(S)$ were calculated. The results are presented in Table 3 and Fig. 3, a. It can be seen from the figure that functional is slightly changed when the initial dataset is divided into 3 intervals and more.

To clarify the optimal number of categorization ranges, the functional values increment graph was plotted (Fig. 3, b). It can be seen from the figure when the initial dataset is divided into 3 intervals and more, the functional increment is two decimal places. So, with a further categorization of the dataset into 4, 5, 6, etc. ranges, the functional values scarcely differ. It is therefore rational to categorize the entire initial dataset into no more than 3 ranges (zones) (Table 2).

To objectively assess the zones of tectonic fault influence, frequency values homogeneity was statistically analyzed according to Rodionov's criterion (4). The following values have been obtained (Tables 4, 5).

Table 2. Defining the number of initial dataset categorization ranges

Method	The length of the range h , m	The number of the ranges k
The Sturges formula		7
The Scott's formula	23.2	4
The Freedman–Diaconis formula	21.7	4
Functional under $\alpha = 0.05$		3

Table 3. The values of the normalized functional and its increments

Normalized value $Q(S)$	The number of the range $dQ(S)$	Increment dQ
1		
0.345257	2	0.654743
0.166574	3	0.178683
0.128763	4	0.037811
0.102374	5	0.026388
0.069	6	0.033374
0.047163	7	0.021837
0.031648	8	0.015515
0.026204	9	0.005444

Table 4. The sizes of the zones of tectonic fault influence under $\alpha = 0.1$ and $c^2 = 2.71$

Zone number	The number of the recorded dynamic rock pressure manifestations, m	Zone width l , m	m/l	w
1	9	7	1.286	0.17
2	3	1	3	0.39
3	29	48	0.6046	0.08
4	5	2	2.5	0.33
5	6	27	0.2226	0.03
		Total	7.6126	1

Considering the number of ranges calculated earlier, as well as the values of w (Table 4), the decision was made to combine the 1st and 2nd, as well as the 3rd and 4th zones (Table 6).

By finally integrating the null and the 1st zones we get the following dimensions of the zones and the degree of tectonic faults influence within them (Table 7).

Conclusions

The article provides statistical analysis data for the distances from tectonic faults to dynamic rock pressure manifestations recorded in the rock mass of the Kukisvumchorr apatite-nepheline ore field. Based on statistical calculation

Table 5. Homogeneous zones according to D. A. Rodionov's criterion under $\alpha = 0.1$

$\alpha = 0.1$	d, m	2	4	5	6	7	9	10	14	16	19	22	23	24	29	30	32	33	34	35	39	43	47	48	52	53	54	56	57	70	71	77	87	92	96
$\gamma = 2.705543$	m	2	2	2	1	2	3	1	1	2	1	2	1	2	1	1	1	1	3	1	2	3	1	1	2	1	1	3	2	1	1	1	1	1	1

Table 6. The size of the zones of tectonic fault influence after zones integration

Zone number	The number of recorded dynamic rock pressure manifestations m	Zone width l , m	m/l	w
1	12	9	1.333333	0.59
2	34	48	0.708333	0.319
3	6	27	0.222222	0.0989
Total	52		2.263889	1

and comparative analysis, it was found that the number of ranges the initial dataset should be divided into varies from 3 to 4. Based on the dataset homogeneity criterion, according to D. A. Rodionov's method, the sizes of the zones of tectonic fault influence on dynamic rock pressure manifestation were assessed. The sizes of the zones and the degree of influence were as follows: the 1st zone is 9 m wide with the degree of influence 0.8, the 2nd zone is 48 m wide with the degree of influence 0.15, and the 3rd zone is 27 m wide with the degree of influence 0.05. Zones of influence gradation with the corresponding degree of influence should be considered as new results. Despite the fact that the sizes of the zones were determined for particular mining-geological conditions, they can be used to predict dynamic rock pressure manifestations at every Khibiny apatite-nepheline deposit of the Kola Peninsula.

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Table 7. Sizes of the zones of influence after the null and the 1st zones integration

Zone number	The number of recorded dynamic rock pressure manifestations m	Zone width l , m	m/l	w	Rounded value w
1	25	9	3.125	0.78	0.8
2	34	48	0.68	0.16	0.15
3	6	27	0.222	0.05	0.05
Total	52		4.027	1	1

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GEODYNAMIC INTERPRETATION OF MODERN GEODYNAMIC MOVEMENTS IN THE SOUTHERN PART OF THE YENISEI RIDGE (IN APPLICATION TO THE PROBLEMS OF UNDERGROUND ISOLATION OF RADIOACTIVE WASTE)

Introduction

In 2019, at the Yenisei site (Nizhne-Kansk massif, southern part of the Yenisei Ridge), the construction of an underground research laboratory (URL) began to substantiate the final decision on its geological suitability for the disposal of high-level radioactive waste (HLRW) [1, 2]. The international and Russian documents regulating the safety of handling HLRW state that the main barrier guaranteeing the safety of HLRW isolation for their entire period of radiobiological hazard (up to 100 thousand years) is the geological environment [3–5]. The modern international practice of choosing a site for HLRW disposal is based on a systematic analysis of a set of properties, phenomena and processes that affect the preservation of the insulating properties of the massif [6, 7].

The main danger is associated with large-scale geodynamic processes and phenomena [8, 9], the impact of which on a structurally disturbed massif leads to the

The results of geodynamic interpretation of the results of GNSS observations of present-day movements and modeling of the stress-strain state of the upper part of the Earth's crust in the area of the construction of an underground research laboratory to substantiate the safety of disposal of high-level long-lived radioactive waste in granite-gneiss rocks of the Nizhne-Kansk massif are presented.

The kinematic model of the area made it possible to assess the directions of block movements of large structural blocks. The greatest movement gradients were noted in the west, between the underground research laboratory site and the contact between the Siberian Platform and the West Siberian Plate along the Atamanovsky Fault. Local zones of stress concentration have been identified, in which destruction of the rock mass in the near-contour zone of underground workings is most likely.

Analysis of models and results of GNSS observations showed that the structural-tectonic block, in which the construction of the underground research laboratory is planned, is in relatively calm geodynamic conditions. Present-day movements determine the regime of sublatitudinal compression in azimuth close to 100–110° at the underground research laboratory construction site. A systematic analysis of geological and geophysical data made it possible to obtain new knowledge about the kinematics and stress-strain state of the rock mass in the southern part of the Yenisei Ridge, necessary to ensure the geoecological safety of isolation of high-level radioactive waste in the granite-gneiss rocks of the Nizhne-Kansk massif.

Keywords: geodynamics, present-day crustal movements, GNSS, zoning, radioactive waste, Yenisei Ridge

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