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A New Concept of the Mechanism of Rock-Tectonic Bursts and Other Dynamic Phenomena in Conditions of Ore Deposits

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Abstract: In mining technical literature, the prevailing idea is still that rockbursts in open pits and underground mines are caused by gravitational forces produced by the overburden rock mass, put forward in the 20th century by S.G. Avershin and I.M. Petukhov. This concept is the basis for the rules of safe mining at rockburst-hazardous deposits, including modern guidance documents of Rostekhnadzor. Numerous studies of the behavior of a rock mass as a geological medium, the phenomena causing rockbursts in underground workings, the mechanisms of manifestation of rockbursts and rock-tectonic bursts change many ideas. They have now become urgently needed to explain the causes of particularly powerful geodynamic phenomena in mines – rock-tectonic bursts, technogenic earthquakes – phenomena that were practically not observed in the 20th century. Intense geodynamic events in mines (rock-tectonic bursts, technogenic earthquakes), comparable in energy level to natural earthquakes, have once again shown their analogy with natural earthquakes to be studied by seismology. M.A. Sadovsky et al. established the law of self-similarity of seismic process at different scale levels. Based on this law, the relationships established for seismic focuses proved to be applicable to dynamic manifestations of rock pressure at mines. In this paper, further details of this analogy are developed. It shows which forms of dynamic manifestations of rock pressure correspond to which sizes of structural heterogeneity of rock mass. Based on the law of self-similarity of seismic processes at different scale levels, we showed that the energy characteristics of the rock pressure manifestations at mines obey the laws established in seismology.

Keywords: rock-tectonic burst, rock mass, structural heterogeneities, classification, seismic moment, shear modulus.

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Новая концепция механизма горно-тектонических ударов и других динамических явлений для условий рудных месторождений

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Аннотация: В горно-технической литературе до сих пор превалирует представление о том, что горные удары в рудниках и шахтах вызываются гравитационными силами веса массива покрывающих пород, выдвинутое в прошлом веке С.Г. Авершиным и И.М. Петуховым. На этом представлении основываются правила безопасного ведения горных работ на удароопасных месторождениях, в том числе современные инструктивные документы Ростехнадзора. Многочисленные исследования свойств поведения массива горных пород как геологической среды, явлений, вызывающих горные удары в подземных выработках, механизмов проявления горных и горно-тектонических ударов изменяют многие представления. Они оказались в настоящее время настоятельно необходимыми для объяснения причин особо мощных геодинамических явлений в рудниках – горно-тектонических ударов и техногенных землетрясений – явлений, которые в прошлом веке практически не наблюдались. Сильные геодинамические события в рудниках (горно-тектонические удары, техногенные землетрясения), сопоставимые по энергетическому уровню с землетрясениями, в очередной раз показали аналогию этих явлений с естественными землетрясениями, исследованиями которых занимается сейсмология. М.А. Садовским с соавторами был установлен закон самоподобия сейсмического процесса на разных масштабных уровнях. На основании этого закона соотношения, установленные для очагов землетрясений, оказалось возможным применять для динамических проявлений горного давления в рудниках. В настоящей работе развиваются дальнейшие детали этой аналогии. В ней показано, каким размерам структурной неоднородности массива соответствуют те или иные формы динамических проявлений горного давления. На основании закона самоподобия сейсмических процессов на разных масштабных уровнях показано, что энергетические характеристики проявлений горного давления в рудниках подчиняются закономерностям, установленным в сейсмологии.

Ключевые слова: горно-тектонический удар, массив, структурные неоднородности, классификация, сейсмический момент, модуль сдвига.

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Introduction

A rockburst is instantaneous failure of a rock mass alongside a fault or a newly formed technogenic (mining-induced) fracture, causing failure/collapse of pillars and workings, as a rule, over large areas. The new concept is that the instantaneous rock failure during rockburst occurs due to the concentration, around mine workings, of gravitational tectonic stresses existing in the earth crust due to recent orogenic processes. Under the influence of large-scale mining operations, the structural-block medium of rock masses due to the concentration of gravitational tectonic stresses sharply changes to new geodynamic equilibrium; the change is manifested in the form of rockbursts, rock-tectonic bursts and technogenic earthquakes.

Theoretical treatment

The concept is based on the differences in the natural stress state of mineral/mineralized rock masses. In mineralized (ore deposit) rock masses of magmatic or metamorphic origin, a feature of the rock gravitational-tectonic stress condition is prevailing (in magnitude) horizontal stresses (due to recent orogenic processes) over vertical gravitational stresses (caused by overlying rock weight). On contrary, in rock masses of sedimentary origin (coal, salt deposits), due to the relatively weak deformation-strength properties of the rocks and long-lasting rheological processes, gravitational stress condition of the rocks is characterized by prevailing vertical gravitational stress component, caused by overlying rock weight.

Meanwhile, in the modern Russian mining and technical literature, the prevailing idea is still that rockbursts and rock-tectonic bursts in mines are caused by gravitational forces due to overlying rock mass weight. Theoretical substantiation of these ideas is given in studies of S.G. Avershin [1], I.M. Petukhov et al. [2, 3] and others. The concepts on gravitational nature of forces causing rockbursts in mines underly modern instructional documents of Rostekhnadzor [4], which regulate mining operations at rockburst-hazardous ore deposits. The instruction [4] does not even mention tectonic stresses occurring in rock masses. As a result of this, some provisions of the instruction [4] are erroneous and doubtful.

Another basis of the concept is the idea of rock mass as a geological environment of hierarchical block structure, developed by academician M. A. Sadovsky. In accordance with these ideas, rock masses are a hierarchy of geological and structural blocks, as if embedded in each other and separated by inter-block intervals – faults and cracks of different structural levels. There are many rock mass quality designation classifications, but, in our opinion, the most suitable is the classification adopted for foundations of hydraulic structures [5]. This classification is most appropriate for ore deposit rock masses for at least two reasons:

a) the foundations of hydraulic structures in terms of length in horizontal and vertical planes (hundreds of meters, first kilometers) are similar to the dimensions of mine fields, which are similar in size to intersecting structural heterogeneities (fractures, tectonic deformations, faults);

b) the classification is designed for rock masses, i.e., very strong rocks of igneous or metamorphic origin.

Since disjunctive dislocations of different scales should correspond to block structures of appropriate scale, we proposed the following classification of block structures for mine fields, based on the above classification of structural dislocations in hydraulic engineering (Table 1) [6].

Dynamic manifestations of rock pressure in mine workings (rockbursts, rock-tectonic bursts, and other manifestations) can be considered as a response of the geological environment to technogenic intervention. This response depends on many factors, and above all, on the scale of the technogenic impact, structural-block heterogeneity of the rock masses, rock properties, natural stress state of the rock masses, and other factors. The dependence of the forms of rock pressure manifestations on the dimensions of mine workings in case of gravitational-tectonic stress state of the rock masses is shown in Fig. 1.

Table 1

Classification of block structures formed by faults

Block structure designation	Rank (order) of faults confining the block, and block structures	Extent of faults confining the block	Average cross block dimension
Tectonic block	I	Hundreds and thousands of kilometers	500 – 1000 km
Regional geological-and-structural block	II	Tens and hundreds of kilometers	50 – 100 km
	III	Several kilometers and first tens of kilometers	5 – 10 km
Local geological-and-structural block	IV	Hundreds and first thousands of meters	500 – 1000 m
	V	>10 m	50 – 100 m
Fracturing block structure	VI	1 – 10 m	5 m
	VII – VIII	< 1 m	< 1 m

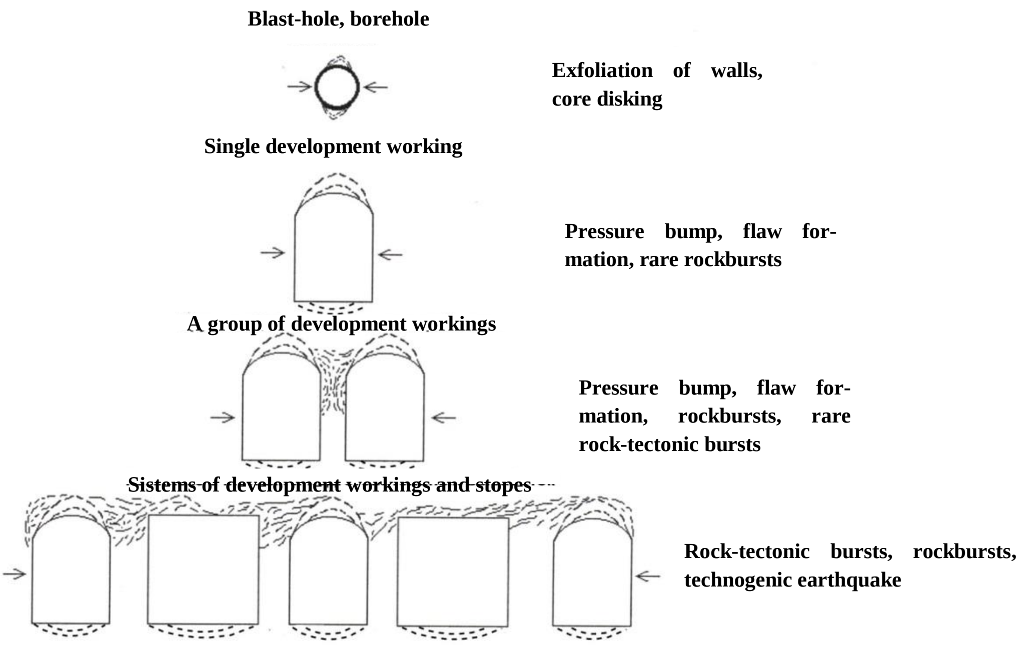


Fig. 1. Model of development of rock pressure dynamic manifestation forms with increasing scale of mining operations in conditions of gravitational-tectonic stress state of rock masses

Table 2

Forms of extreme dynamic manifestations of rock pressure corresponding to the scale of geological structures activated by mining

Rank (order) of geological structure	Scale of mining operations (workings), activating the structure	Characteristic size of mine workings, m	Form of dynamic manifestations of rock pressure
VII – VIII	Blast-hole, borehole	$10^0 – 10^1$	Exfoliation of walls, core disking
VI	Single working, twinned working	$10^2 – 10^3$	Pressure bump, flaw formation, rockburst
V – IV	Systems of development workings and stopes	$10^4 – 10^6$	Rock-tectonic burst, rockburst, technogenic earthquake

Thus, the proposed classification of structural block heterogeneity of rock masses allows ranking blocks of the most common sizes for mines. It enables practical implementing the concept of M. A. Sadovsky on the model of the hierarchical-block geological environment as applied to the problems of mine exploitation.

Analysis of materials. Theory development

Any dynamic manifestations of rock pressure are changes of the geological environment to new geodynamic equilibrium under the influence of mine workings and stresses occurring in this environment. Magnitude of the change depends on the size of mine workings in the rock mass, the rock stress state, the dimensions of geological and structural (block) heterogeneity of the rock mass, and other factors. In the previous, XX century, too little attention was paid to the analogy of rockbursts and seismic phenomena in the earth's crust, since rockbursts in Russian mines had relatively low energy level [7]. And only in the end of the last century – the beginning of this century, when severe rock-tectonic bursts with the released seismic energy magnitude of $E = 10^{10}$ J began to happen in mines of Russia, South Africa, Poland, and other countries, analogy of these phenomena with earthquakes was revealed [8, 9, 10].

To characterize energy of earthquakes, in seismology and mine seismicity, the concept of seismic moment in the focus is used [9]:

$$M_0 = GS\delta, \qquad (1)$$

where M_0 is seismic moment, N·m; G is shear modulus of rocks mass, MPa; S is fracture area, m^2; δ is amount of displacement in the focus, m.

When describing low-energy rockbursts in mines, such event parameters as the fracture area S and the displacement value δwere not previously determined. And only when rock-tectonic burst energy in mines got close the level of natural earthquake energy, researchers began measuring these parameters, by analogy with earthquakes. Table 3 presents the mentioned parameters for some of the severest rock-tectonic bursts in Russian mines [11]. Fig. 2 shows the geometric illustrations of mechanism of these rock-tectonic bursts.

No other examples were found in domestic mining literature, since these parameters were not measured when examining consequences of the events in mines.

Given the law of self-similarity of seismic processes at different scale levels, established by M. A. Sadovsky et al. [12], dynamic manifestations of rock pressure in mines can be considered as seismic events in a rock mass. Extrapolating Table 3 data, these events can be characterized by the following parameters (Table 4).

Table 4 presents data obtained on the basis of the law of seismic processes self-similarity at different scale levels. In particular, it is known [13] that in the event of large earthquakes of intensity 7–8, the length of the faults reaches tens to hundreds of kilometers, and displacements along the faults achieve several meters. Therefore, the parameters of rock pressure dynamic manifestations in mine workings, whose energy level is several orders of magnitude lower than that of large earthquakes, look quite plausible.

Knowing the characteristics of focus of dynamic phenomena in mines (see Table 4), one can estimate the energy characteristics of these phenomena by formula (1). Rock shear modulus G is generally not measured when determining mining operation details. Therefore, let us determine its value from the well-known relationship established in geophysics [14]:

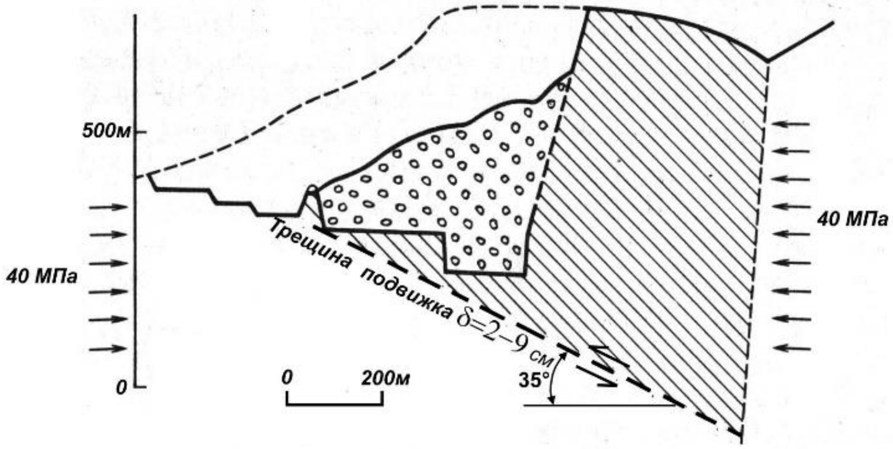
$$G = \frac{E}{2(1+\nu)}, \qquad (2)$$

where E is rock modulus of elasticity, MPa; ν – Poisson's ratio of rocks.

Table 3

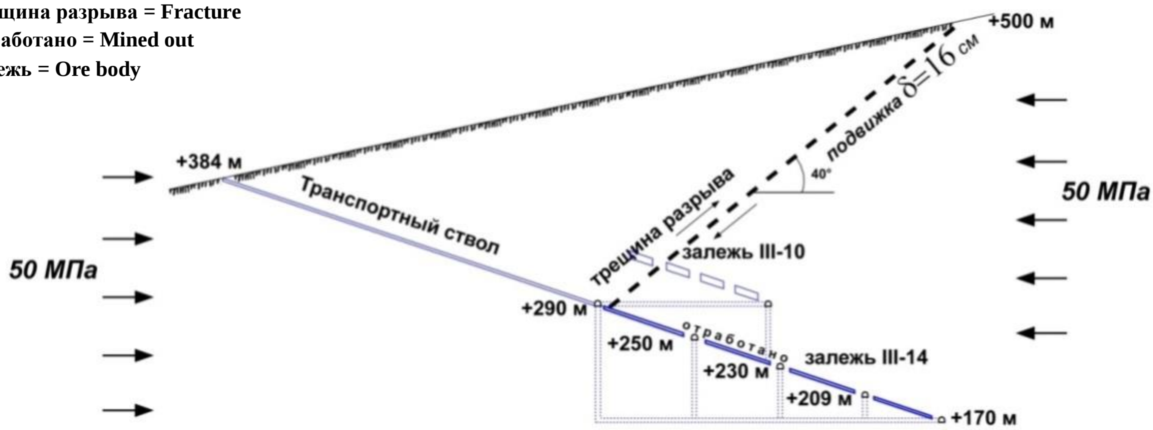
Parameters of some of the most severe rock-tectonic bursts (RTB) in mines

Mine, deposit	Event date	Event parameters		Focal parameters	
		Magnitude, M_L	**Energy class, *k***	**Displacement area, S, m^2**	**Displacement amount, cm**
Kirovsky (Khibinsky apatite)	16.04.1989	4.3	10.5	220 000	2 – 9
Umbozero (Lovozersky rare metal)	17.08.1999	5.0	11.8	~500 м × 500 m = 250,000	16



Трещина = Fracture
Подвижка = Displacement
Транспортный ствол = Hoisting shaft
Трещина разрыва = Fracture
Отработано = Mined out
Залежь = Ore body

a



b

Fig. 2. Schemes of the mechanism of rock-tectonic bursts at the Kirov mine (*a*) and the Umbozero mine (*b*)

Table 4

Parameters of dynamic manifestations of rock pressure at mines

Manifestation types	Energy parameters		Focal parameters	
	Energy, J	Energy class, *k*	Characteristic amount of the displacement area, m^2	Estimated displacement amount, cm
Rock-tectonic burst, tech-nogenic earthquake	$10^9 – 10^{12}$	9 – 12	100,000	10
Rockburst, pressure bump	$10^5 – 10^8$	5 – 8	100	1.0
Borehole wall failure	$10^0 – 10^1$	1 – 2	0.1	0.1

Table 5

Estimation of the magnitude of seismic moment in the focus of rock pressure dynamic manifestations

Form of dynamic phenomena	Fault/Fracture area, m^2	Displacement amount, m	Rock shear modu-lus, t/m^2	Seismic moment, t·m
Rock-tectonic burst	100,000	0.1	2,400,000	$2.4 \cdot 10^9$
Rockburst, pressure bump	100	0.01	2,400,000	$2.4 \cdot 10^6$
Borehole wall failure, core disking	0.1	0.001	2,400,000	$2.4 \cdot 10^2$

We can calculate, in particular, shear modulus for the rocks of Lovozersky rare metal deposit (nepheline syenites: lujavrite, urthite, foyaite): $E = 6 \cdot 10^4$ MPa; ν = 0.25. Shear modulus calculated by formula (1) will amount to:

$$G = \frac{60000\text{MPa}}{2.5} = \frac{6000000\text{t/m}^2}{2.5} = 2.4 \cdot 10^6\text{t/m}^2.$$

Now all the parameters included in formula (1) have been determined, and the seismic moment magnitude in the focus can be used to estimate the energy of rock pressure dynamic manifestations in mine workings. The results of such estimations are given in Table 5.

In Table 5, the calculations were implemented using the value of rock shear modulus $G = 2.4 \cdot 106$ t/m^2, being typical for hard rocks, in particular, for the rocks of the Lovozersky deposit. The obtained values of seismic moment for various forms of rock pressure dynamic manifestations correspond to those actually observed in mines, in particular, the energy characteristics of rockbursts and rock-tectonic bursts [7] and the estimates of these phenomena by other authors [15, 16].

The data presented allow confirming the law of self-similarity of the seismic process at different scale levels, established by M.A. Sadovsky et al. The rock pressure dynamic manifestations in mines (rockbursts and rock-tectonic bursts, pressure bumps, etc.) are the forms of self-organization of geological environment when affected by mining operations. The data presented allow confirming the fact that the form and energy of dynamic phenomena in mines depend on many factors, primarily the scale of technogenic impact on rock masses, their stress state, structural-block structure, rock properties, etc.

Conclusion

1. Rational and the most relevant for mine conditions classification of hard rock mass structural-block heterogeneity based on the classification of ruptural structures (faults, fractures, etc.) in hard rock masses, adopted in hydraulic engineering, is presented.

2. The dependence of the forms of rock pressure manifestations in mine workings on the dimensions (scale) of technogenic intervention in the rock mass and the dimensions (scale) of the rock mass structural heterogeneity activated by mining operations is presented.

3. Based on the law of self-similarity of the seismic process in rock masses at different scale levels, the energy parameters of various manifestations of rock pressure are estimated. The estimated energy parameters of the rock pressure manifestations correspond to actual data on rockbursts in mines.

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