

Mining-Induced Seismicity in the Kola Peninsula Mines

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Abstract: Mining-induced seismicity is a reflection of rock geomechanical evolution of geological environment in the natural and man-made systems and in the mining-technical systems. In order to predict and prevent mining-induced seismicity, it is necessary to research geodynamics and stress state of intact rock mass, to determine possible deformations and additional stresses as a result of large-scale rock extraction, conditions of accumulated energy release. For that a geodynamical monitoring is required on every stage of deposit development and a closing. The report considers principal influencing factors of preparation and occurrence of mining-induced earthquakes. Also it estimates precursors and indicators of rock mass breaking point, and experience concerning prediction and prevention of mining-induced seismicity in the Khibiny apatite mines in the Murmansk region, which is the largest mining province.

Key words: Mining-induced seismicity, prediction, precursors, large-scale rock extraction.

1. Introduction

The mining-induced seismicity manifestations are of actuality problem for many world regions with an advanced mining industry, including the Khibiny massif region. An assessment of seismic activity of rock mass and prediction of catastrophic events like rockbursts and mining-induced earthquakes for exploited deposits is carried out using different methods.

In recent years, there has been made a certain progress in understanding a mechanism of source zones creation and realization of dynamic events at mines as a result of complex investigations of mining-induced seismicity manifestations in the mining natural-engineering “Khibiny” system. This permitted to develop methods of prediction of mining-induced seismicity manifestations while developing the Khibiny apatite deposits.

The method is based on a principle of contouring of spatially-temporal areas with increased probability of

hazardous events occurrence. Prediction of seismic events is carried out by simultaneous analysis of prediction criteria using the software “Mining-Induced Earthquakes Prediction System” developed by specialists of the Mining Institute. The following parameters are considered to be rock seismicity characteristics: fractal criterion, dip angle criterion for seismic events recurrence graph, concentration criterion and criterion of fissures’ average length [1]. The mentioned above prognostic criteria take into account different characteristics of seismic regime like spatial location of seismic events, distribution of events by energetic classes, quantity and length of fissures. Influence of determined factors is taken into consideration as well: presence of discontinuous disturbances, stope zone limits and edge of falls. Adaptation of the criteria to conditions of mining natural-engineering “Khibiny” system has shown ambiguity of results concerning calculation of probabilities of catastrophic events occurrence.

2. Literature Review

The most actual problem in mining regions and also in areas of large mining-induced impacts of other sort, for example, under construction of unique hydraulic engineering or underground objects, has been

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so-called induced (mining-induced) seismicity which essentially raises hazard of mining operations and leads to considerable material losses.

As an illustration of catastrophic events in the mining practice, the authors can call large dynamic events on various mines of world (Table 1).

Rockbursts and mining-induced earthquakes have also become real during mining of ore deposits in Russia (Table 2).

The comprehensive information on the deposits

prone to tectonic rockbursts and mining-induced earthquakes is given in the papers [2, 3].

The mining-induced earthquakes can be recorded during opencast mining operations in the high stress rock mass as well (Table 3).

The represented data indicate that tectonic rockbursts occur at the all deposits where they are revealed abnormal high natural stresses in the rock mass whatever the type of tectonic structure (stable shields, mobile platforms and mobile mountain-folded areas).

Table 1 Catastrophic events in the underground mining practice all over the world.

Date	Area	Consequences
January, 1960	Coalbrook, SAR (South African Republic)	Disturbed area about 3.2 km ² , 437 fatalities (underground miners) [1]
March, 2005	Klerksdorp, SAR	$M \approx 5.3$, two miner fatalities [4]
March, 1989	Verra River, Germany	Disturbed area about 6 km ² , destruction of houses in the nearest settlement [5]
January, 1993	Book Cliffs mine, USA	15,000 m ² of pillars destroyed [6]
January, 1995	II Solikamsky mine, Russia	$M = 3.8$, pillars destroyed in 300,000 m ² , surface subsidence up to 4.5 m [7]
February, 1995	Solway mine, USA	$M \approx 5.1$, caused failures about 2 km ² [8]

Table 2 Rockbursts and mining-induced earthquakes on mining ore deposits of Russia.

Date	Area	Consequences
April, 1989		Breakup of the main drifts, damage of the surface infrastructure, $M \approx 4.2-4.3$ [9]
July, 1989	Kirovsky mine, JSC (Joint Stock Company) "Apatit", Russia	$M \approx 3.0$ [10]
November, 1993		$M = 2.0-2.5$ [10]
December, 1993		$M = 2.0-2.5$ [10]
October, 2010		$M = 3.4$ [10]
October, 1984	Northern Ural and South Ural bauxite mines	$M \approx 3.0$ [11]
May, 1990		$M \approx 3.5-4.0$ [12]
August, 1984	Tashtagolskoe iron-ore deposit, Gornaya Shoriya, Russia	$M \approx 3.0-3.5$ [13]
August 17, 1999	Umbozero mine, Russia	$M = 4.0-4.2$, drifts and pillars breakup in 600,000 m ² , damage ≈ 210 mln. rubles

Table 3 Catastrophic events in the world's opencast mining practice.

Area	Consequences
Wappingers Falls, New York	$M \approx 3.3$, The event occurred under the open-pit floor (0.5-1.5 km deep) with length more than 1.0 km. The high horizontal stresses were recorded on the deposit close to surface (up to 50 m) [14]
Cacoosing Valley, near Reading, PA	During 1992-1997, a range of mining-induced earthquakes were recorded in the open workings, directly below a quarry, $M \approx 4.3$ was registered, with fracture activation at the depth up to 2.0 km directly under the mining operations [14]
Belchatow region in Poland	$M \approx 4.6$ open-pit coal mining having dimensions 1 km ² × 2 km ² and 100 m depth [14]
Lompoc diatomite mine, California, USA	From 1981 to 1995, there had experienced four seismic events with $M \geq 3$, the length of the open pit excavation exceeded 1,000 m. On the pit bench appeared a fracture in the zone active by tectonic events [14]
BHP Billiton Nickel Wests nickel deposit, Australia	Progress of seismic events was registered under the open-pit when operating in the rock mass with high horizontal stresses [15]
Vyborg region, Leningradskaya Oblast, Russia	Seismic shocks and dynamical cleavage of plates occurred in the granite open pits, caused by high horizontal stresses acting. The pits depth was 30-50 m [16]
Tsentralny mine, JSC Apatite, Russia	The events with $M \geq 3.0$ were recorded on October 26, 1995, September 24, 2004 and May 25, 2009 [8, 17-19]

The mining-induced earthquakes occur, as a rule, at the deposits where the large areas are excavated, and significant volumes of rock mass are extracted and removed. According to Melnikov et al. [20], geodynamical behaviour of regional geological environment is disturbed only under extraction of certain volume of the rock mass and creation of overstressed zone having considerable area. Then arises a situation which is similar to one of forming and realizing induced seismicity during water reservoirs filling [21].

The tectonic rockbursts can be regarded at a first approximation as foreshocks or aftershocks of the mining-induced earthquakes. At that, as the experience shows the depth in the high stressed rock massive where tectonic rockbursts occur is minimal. This fact indicates that natural stress field is indeed the first course of tectonic rockbursts and mining-induced earthquakes with mining-induced event being a trigger.

According to existing conceptions [22], mining-induced earthquakes are similar to the natural ones, but differ by the behavior of seismic energy released under the mining-induced factors influence. The factors are characterized by a large number of foreshocks (or tectonic rockbursts) prior to a maximal earthquake, by slow decrease of aftershocks, and increased seismic magnitude due to shallow location of an earthquake source. For mining-induced earthquakes to occur during mining operations a combination of a set of conditions is required as follows [23-29]:

(1) high level of horizontal tectonic stresses in the rock mass determined by a corresponding tectonic—physical environment (i.e., existence of zones with heavy gradients of the most recent tectonic movements rates);

(2) existence of friable high-strength rocks with tectonic discontinuities within a working zone;

(3) favorable geomorphologic environment (massifs relief);

(4) large-scale mining (excavation area, working depth, volume of excavated and removed rocks);

(5) blasting impact in driving workings and ore breaking.

Manifestation of the most recent movements results in redistribution of stresses in the earth crust which has an impact on separate blocks behaviour, and the latter is expressed in slow (creep) or stick-slip (shocks) movement on faults.

3. Geological Condition

Human engineering activity can be considered to be an additional external impact on the complicated chain of natural interrelated processes acting as trigger for accumulated elastic energy releasing. Due to cascade energy release close to geo-mechanical mine space the total level of natural stresses in the rock mass decreases, and maturing of the largest possible earthquake for the region is of low-probability. In the zone of mining-induced impact where considerable rock mass volumes are excavated and removed and considerable mined-out spaces are formed (Fig. 1), the rate of rocks deforming increases compared to natural one (sometimes in order of magnitude) [20, 21] and large dynamical impacts from bulk blast are superposed.

This leads to the disturbance of source formation process (maturing source time), early initialization of weaker shocks due to the contacts failure between blocks or interaction of contiguous fractures and faults. Energy released in a mining-induced earthquake is proportionate to volume of mined-out space and can not exceed energy of maximum natural earthquake for the area of interest. To search precursors of the large dynamical events and control efficiency of preventive measures the systems of geodynamical monitoring are created, including the Khibiny apatite-nepheline mines [17].

4. Instrumentation and Monitoring

The geodynamic monitoring system at Khibiny mines

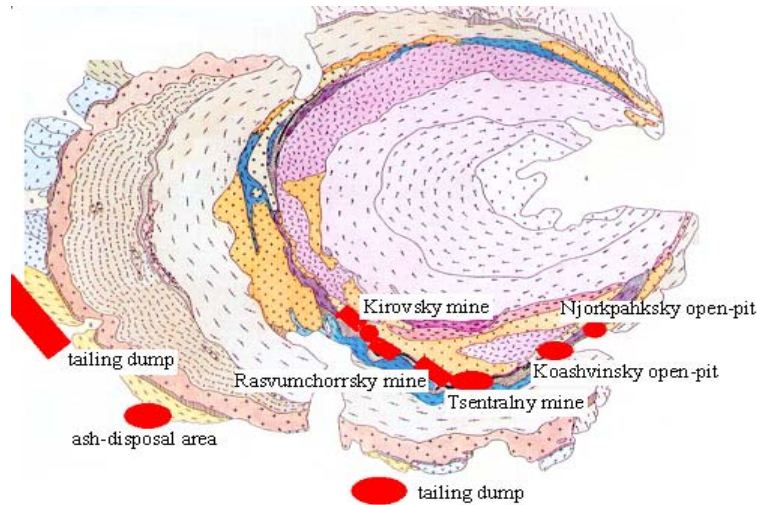


Fig. 1 The chart of natural-technical system “Khibiny”.

consists of three major blocks: monitoring of stresses and deformations, seismic monitoring and seismologic control. The first subsystem includes stresses measurements by unloading method, periodical leveling and light distance measurements, continuous deformation control by quartz strainmeters and dipmeters.

The seismic monitoring is carried out in active and passive mode, including seismic transmission of source zones in the Khibiny massif with use of industrial blasts as a source of elastic vibrations, and seismic tomography and transmission in the mining

workings on the high stressed mine field’s parts.

The largest dynamic events in the Khibiny massif as well as mining-induced and natural earthquakes are registered by the seismic station “Apatity” belonged to the Kola Branch Geophysical Survey Russian Academy of Sciences which is a part of the united seismic stations system of the northern Europe.

The Khibiny rock massif seismicity control within the UKM (United Kirovsky) and Rasvumchorrsky mines is managed by JSC “Apatite” seismic station with the using of AMSMS (automated monitoring systems of mining-induced seismicity) (Fig. 2).

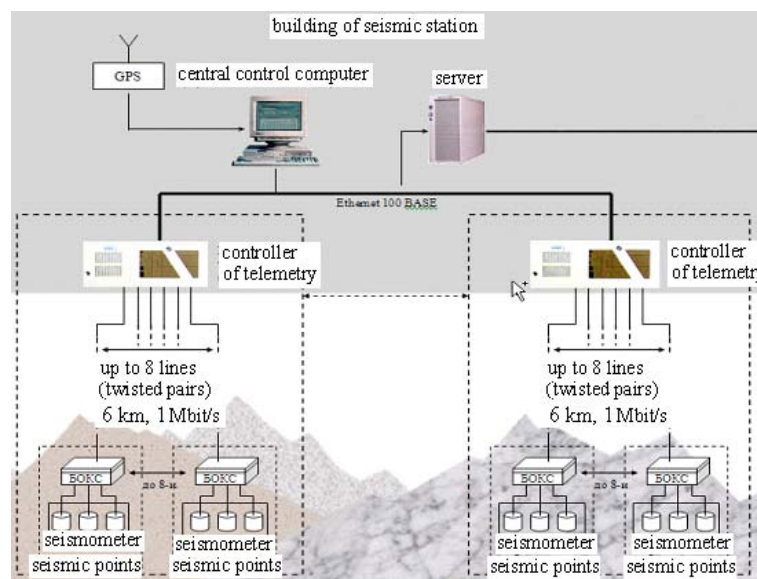


Fig. 2 Layout of AMSMS of geophysical monitoring center JSC “Apatit”.

UKM is monitored by AMSMS-UKM system installed on the base of TSG (telemetric system of seismic information gathering) made by SIE "Systemotechnika" (Ivanovo). Seismic points of AMSMS-UKM are located in the underground workings. The distance between them is 300-400 m. The seismic point contains a three component seismometer, a telemetric box, an electrical power unit and accumulators to provide uninterrupted power supply in the power cutoff. Telemetric box provides frequency filtering of seismometer's signals, preamplification, analog-to-digital conversion and data transmission on a seismic controller. Concentrators unite signals from different blocks to transmit data through one radio-frequency cable. The seismic network uses seismometers made by The Schmidt Institute of Physics of the Earth (Moscow), such as S 1073 accelerometers and S 2123 velocimeters. At that, the velocimeters are installed in the outlying districts to register seismic waves from remote sources. The results of the regional prediction are transferred to the mine SPPRB (service of prediction and prevention of rockbursts).

The Rasvumchorrsky mine subsystem AMSMS-R manages a zone of joining with an open-pit, an ore pass No. 6, and a northern-western highwall of the Tsentralny mine. It contains a network of seismic points deployed in the underground mine workings, cable communication lines and a telemetry controller. To connect the seismic points with seismic station building a radio frequency cable is used. Range of boxes communication Geos kft (Hungary) without retranslation is 1,000 m. Surface program—hardware complex AMSMS-R is located in the mine administration building, and is a remote automated centre of seismic data gathering and preliminary scrapping. The files of wave forms of seismic events registered by AMSMS-R are transferred through fiber-optic communication lines into the seismic station where they are processed by a geophysicist. The results of the regional prediction are transferred to

the SPPRB.

Analysis of seismic events flow shows that at least half their sources are internal destructions in the rock in situ which are not manifested in the mine workings and this fact was also noted at the northern Ural bauxite mines [30]. The main factors determining manifestations of the seismic events in the massif rock as well as rockbursts and mining-induced earthquakes are zones of concentration of natural stresses in the intact massif, stresses nearby stope faces and tectonic disturbances, bulk blasts and inflows in the mine workings. The large technological blasts in a number of cases induce an event of mining-induced aftershock seismicity since they act as trigger mechanisms for different dynamic events in the massif rock.

Analysis of the investigations performed to date has shown that the parameters of seismic behaviour of rock massif and rock deformation behaviours are the most perspective predictive precursors of tectonic rockbursts.

Disturbance process develops in space and time, and so criteria of seismic prediction, first of all, must take into account just space-time parameters of micro-seismicity. At that are used single one-parameter criteria such as tangents of angle of seismic events recurrence graph, concentration parameter, parameter of fractal dimension of seismic events spatial distribution, average length of fractures and etc..

Prediction effectiveness by separate criteria, as a rule, exceeds slightly prediction effectiveness by random guessing. World experience and the authors' investigations show that the complex analysis of different precursors increases greatly the prediction reliability [19].

5. Case Study

Fig. 3 shows a distribution according to years of a number of seismic events registered at the Rasvumchorrsky and United Kirovsky mines of JSC

“Apatit” for this period. The graph shows decline of values in 2007 as against 2006 both for this mines. A less number of events at the Rasvumchorrsky mine were registered in 2010. This can be related to failure of some seismic points (and as a result recording abilities of the monitoring system decreased). Currently a reconstruction of AMSMS-R is being carried out.

The Kukisvumchorrsky side of UKM presents decrease of values till 2009 and almost double increase of those in 2010. It is connected with a fact that since the end of 2008 and during 2009 the mining operations were less intensive than in 2010. The Uksporsky side of UKM does not record considerable changes of a number of events starting from 2007.

Also the distinctions are noticed according to total energy released in the mines (Fig. 4). At the Rasvumchorrsky mine, the value of total energy released did not exceed 10^8 J in 2006 but since 2007

there are recorded values higher 10^8 J. The Uksporsky side of UKM demonstrates a decline of values on two orders of magnitude in 2010 as against 2006.

The diagram made for the Kukisvumchorrsky side of UKM demonstrates a slight increase in 2007 related to a fracture intergrowth in the hangwall and partial failure of the roof rocks. Then you can see a gradual decline till 2009 and a maximum peak in 2010. This peak is related to a mining-induced earthquake with $E = 10^9$ J recorded on October 21, in the mining zone of the Kukisvumchorrsky side. The foreshocks prior to the main event in this region were not registered. The aftershocks were noticed for a week after the main event.

Figs. 5a-5c presents monthly distribution of a number of events and total released energy for the Rasvumchorrsky mine, the Kukisvumchorrsky and Uksporsky sides of UKM. As can be seen, all the mines record the increase of seismicity level during the periods of rain and intensive snow melting.

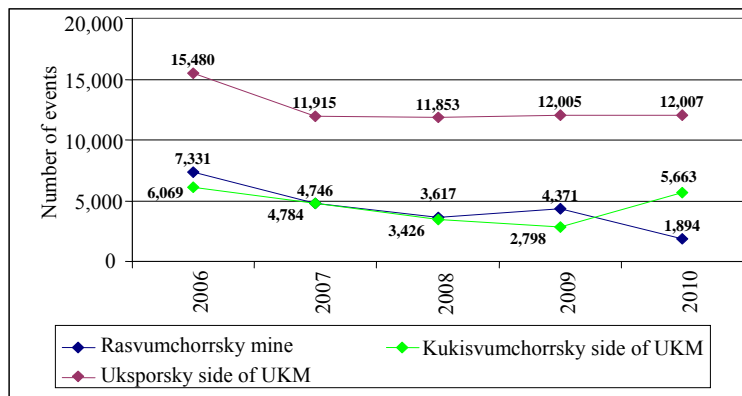


Fig. 3 Number of registered seismic events by years.

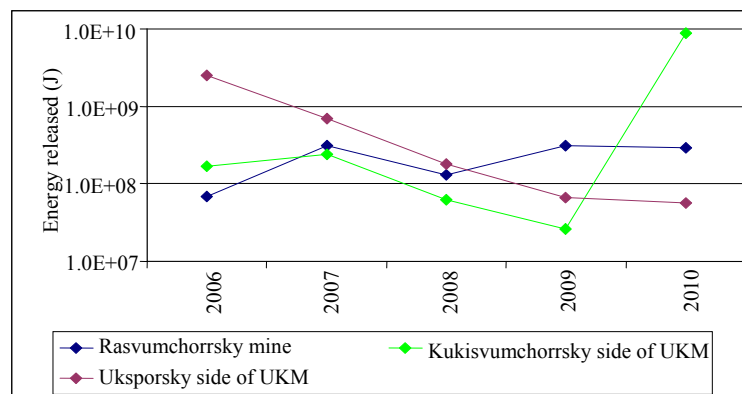
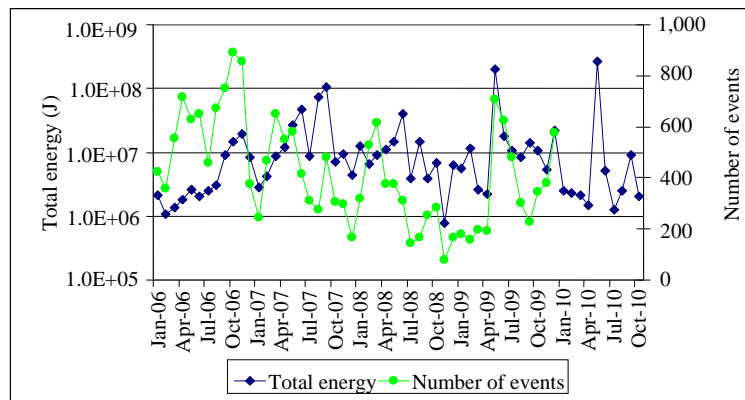
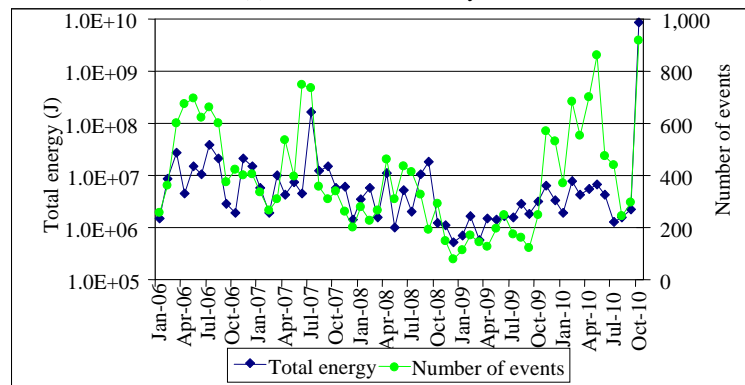


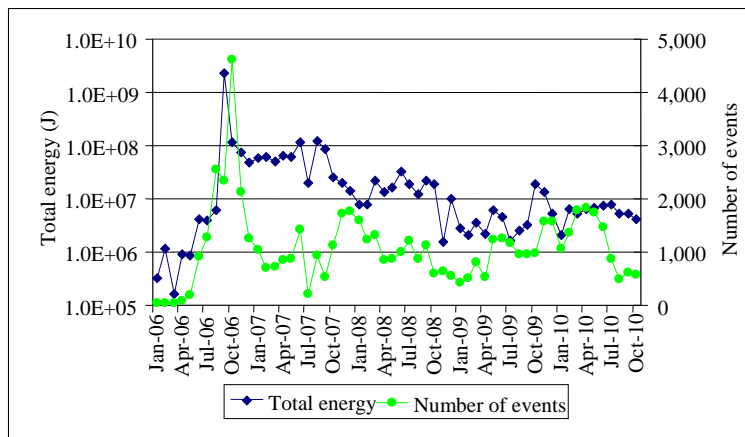
Fig. 4 Total energy released.



(a) The Rasvumchorsky mine



(b) The Kukisvumchorsky side of UKM



(c) The Uksposky side of UKM

Fig. 5 Monthly distribution of values of total energy released and a number of events for the JSC “Apatit” mines.

For the period under study there were recorded the following events:

On July 12, 2008, a micro rockburst was recorded at the Rasvumchorsky mine caused by high tectonic stresses acting in the massif rock, existence of bearing pressure zone due to stoping operations at the working level, and under bearing pressure of overlying rocks console. The event resulted in the total ore outburst

approximately 15 m³. On October 14, 2008, another micro rockburst was recorded at the Rasvumchorsky mine. The event was also caused by high tectonic stresses acting in the massif rock, existence of zone with bearing pressure due to stoping operations at the overlying working level, impact of non-caved overlying rocks, and close location of drill haulage crosscuts. The seismic event caused destructions with

total volume of 20 m² on the 30 m section;

On February 4, a tectonic rockburst was registered at the Rasvumchorrsky mine which was induced by shearing of weakly spreustein rocks but heavily fragmented rocks along the steeply inclined shallow zone (0.2 m). As a result 20 m² area of the monolith concrete excavation support was disturbed;

On May 13, 2009, a micro rockburst was registered at the Kukisvumchorrsky side of UKM. It was caused by influence of stress concentration zone formed close to a boundary of stoping zone, an existence of monchikite dyke, and changing of rock massif stress strain state due to ore drawing on the underlying level. After this seismic event a 12 m² rock mass outburst was recorded in the 8 m of mine with disturbance of sprayed concrete excavation support;

On May 25, 2009, an increase of seismic activity in the Khibiny massif was registered at the mine Tsentralny area. The seismic event with $E = 5 \times 10^{10}$ J occurred at 12:05 p.m.. The increased seismicity in the region of interest is caused by a long mining-induced impact during mining operations at the Plato Rasvumchorr and Apatitoviy Tsirk deposits. The seismicity activation was induced by a temporary decrease of the rocks strength in the zones with tectonic disturbances because of water filling during snow melting. The source of the mining-induced earthquake was rock shearing along a fault in the Draznyashchee Ekho valley;

On November 18, 2009, at the Rasvumchorrsky mine a micro rockburst was registered within an mine located in the zone of bearing pressure from the boundary of overlying level breaking and stoping operations at the level. The rockburst occurred during drilling wells unloading line. As a result of the event there occurred a rock mass outburst by total volume 10 m³ in the mine. The seismic event was triggered by loading of the border part of unloading line in the highly-stressed rock mass.

At the end of 2010 the background level of seismicity according to the mines made up:

- (1) the Rasvumchorrsky mine— 3×10^4 J;
- (2) the Kukisvumchorrsky side of UKM— 7×10^3 J;
- (3) the Uksporsky side of UKM— 6×10^3 J.

For the Rasvumchorrsky mine and Uksporsky side of UKM the background level was calculated on the beginning of November 2010. For the Kukisvumchorrsky side of UKM the background level was calculated on the beginning of October 2010.

In October, there occurred a mining-induced earthquake, therefore, one can observe a sudden increase of energy characteristics of seismic behavior for the Kukisvumchorrsky side. Average value of energy released during October was 9×10^6 J.

6. Conclusions

So, mining-induced seismicity is a reflection of evolution of the geological environment stress strain state in the natural-technical systems as well as tectonic seismicity is a consequence of accumulated high stresses discharging in the separate lithosphere parts. The changing of parameters of mining-induced seismicity at the apatite mines because of increasing the depth and volume of mining operations and corresponding complication of the geomechanical conditions in the Khibiny mining technical system is a convincing evidence of the above said.

Prediction and preventive measures of the mining-induced seismicity are based on the strategic and tactical measures. The strategic measures involve studying of tectonics and stress state of the mining technical system geological environment, small-scale numerical modeling of stress strain state of mining technical systems geomechanical space and organization of complex geodynamical monitoring of mining technical systems geomechanical space. The tactical measures involve large-scale numerical modeling of problem parts of geological environment in the mining technical system, instrumental control for rocks properties and state in the mining workings, and determination of optimal sequences of mining operations development and rational methods of rock

mass stress state decrease, as well as a choice of rational methods of mining workings supporting.

There is no doubt, that there is necessity for active development of a monitoring system with following analysis of maximum number of parameters of seismic emission. Also it is necessary to improve prediction models concerning occurrence and development of natural and mining-induced dynamic rock pressure within mine fields during large-scale mining operations in the high stressed rockburst hazardous rock massifs.

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