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The Impact of Surface Water Seepage on Seismicity and Rockbursting in Mines

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Abstract: Retrospective analysis of data obtained from long-term monitoring of technogenic seismicity and rockbursts at the Apatitovy Tsirk and the Rasvumchorr Plateau deposits (Russia) showed that there is a significant (by 50% or more) increase in the number of geodynamic events during spring snowmelt periods. An upswing of seismic activity within this rock massif occurs when following conditions are true: water reserve in the snow cover on the deposit area is more than 3×10^8 m^3; snowmelt period exceeds 40 days; increase in water ingress rates continues for over 5 days and total water inflow volume exceeds the previous daily measurements by at least a factor of 2. Seismic activity of the massif starts to intensify after the snowmelt develops momentum. Major induced earthquakes occurred in the years when these conditions were met (for example, in 2005 there was a magnitude 2.3 earthquake; in 2009, M = 1.6 earthquake), and more than 1000 seismic events were recorded during the snowmelt period. It has been established that when mining reaches the depths of more than 500 m, seismic events during infiltration of atmospheric precipitation begin to occur from a depth of 100–200 m and are recorded to depths of about 900 m. A possible controlling factor of the seismic activation is the reactivation of tectonic faults, which occurs under conditions of the critically stressed state of the massif, due to a decrease in their normal compression during infiltration. Retrospective analysis of the factors contributing to a strong rockburst (K = 10–11) in 1990 at a bauxite mine in the South Urals shows that prior to this disaster there was an inrush of the Ai River waters into the mine workings through a large tectonic disturbance, which has not been previously taken into account when analyzing the mechanism of this geodynamic event. The intrusion of water into the fault located in the field of regional stresses and subsequent partial relief of its fault plane from normal stresses could have triggered the rockburst with fault-slip mechanism. The study of the relationship between amount of precipitation and the degree of water encroachment into the field, on the one hand, and seismicity, on the other hand, is needed to draw up recommendations on improving geodynamic and environmental safety of mining regions in order to ensure their sustainable development.

Keywords: rock mass watering; rockburst; seismic activity; mining-induced earthquakes; critical stress state; water inflow

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1. Introduction

It is vitally important to be aware of possible geodynamic consequences of human activity, including manifestations of strong rockbursts [1,2], induced seismicity [3,4] and geodynamic activity [5,6], as this promotes better planning of sustainable development of industrial regions and ensures environmental integrity. The long-term existence of the rockburst problem indicates its complexity and multifactoriality. Different researchers continue studies in the field of integrated rockburst hazard provision [7,8], trigger mechanisms and development of appropriate classifications [9,10]; seismological studies [11,12] and monitoring [13,14]; and studies of influencing factors [15,16] and rock behavior in zones of critical stress [17].

One of the factors that change the geomechanical state of the rock mass and affect the geodynamic events is its watering. For example, wetting of the rock mass is used as a preventative measure against rockbursts [18]. Water is considered as a lubricant that contributes to the activation of faults [19,20]. Hydraulic fracturing of rocks and fluid injection into boreholes are associated with seismicity [21,22]. The occurrence of seismicity during the flooding of the Champion Reef mine in India [23] and coal quarries in Russia in the 1990s [24] was explained by the reactivation of tectonic faults when their normal compression was reduced under the influence of hydrostatic pressure. Seismic activations during mine flooding in the deposits of South Africa [25] and Europe [26] are similarly explained.

The influence of atmospheric precipitation and surface water bodies on seismicity occurrence has been repeatedly discussed in seismology. Therefore, specialists are aware of the connection between the filling of water reservoirs and the occurrence of seismicity [27,28]. The authors of [29,30] have studied the connection between rains and weak earthquakes. However, the issue of changes in the geodynamic activity of the rock massif during its watering in running mining enterprises remains insufficiently studied.

The apatite–nepheline and rare-metal ore deposits in the Khibiny and Lovozero rock massifs, respectively, are some of the most rockburst-hazardous in Russia. They were exposed to the strongest rockbursts with magnitude $M_L = 5.1$ and mining-induced earthquakes with magnitude $M = 4.2$. Seismic events registered in the central part of the Khibiny rock massif are explained by the redistribution of stresses in the rock mass under the influence of large-scale mining operations, not only during ore extraction, but also during dumping and formation of tailings [31,32]. The relationship between the intensity of precipitation and rockburst hazard was also registered in [33]. The Urals is another area of strong rockburst occurrences with energy up to 10^{11} J. In 1990, a rockburst occurred and caused destruction to an area of about 45 hectares at the mine, which was located within 0.5–1 km from the large river Ai and was hydrogeologically connected with it.

Mining enterprises operating in difficult geomechanical conditions have to establish and trace connections between the rock mass watering and rockburst occurrence for monitoring and justification of measures to ensure geodynamic safety. The authors studied the relationship between rockbursts and rock mass watering based on the geodynamic monitoring data analysis and also on the framework of a geodynamic model of the upper part of the Earth's crust in a critically stressed state.

2. Study Site

2.1. The Apatite–Nepheline Deposits, Kola Peninsula

The apatite–nepheline deposits have been mined since the 1930s. Fifty years later, the situation with the occurrence of tectonic rockbursts has become more complicated. On April 16, 1989, a mining-induced earthquake of magnitude 4.2 occurred in the Kirovsky mine during a bulk blast; this event remains the strongest to date. The strongest rockburst ($M_L = 5.1$) at the Umbozero mine took place on August 17, 1999. The depth of the hypocenter was measured to be 300 m [34].

The Rasvumchorr mine develops the Apatitovy Tsirk deposit, and the Tsentralny open pit mine develops the Rasvumchorr Plateau deposit. Currently, the deposits are located in a zone of active mutual influence: the underground mine workings are on the walls of the open pit and underneath the open pit; the open pit dumps are located on the surface above the underground workings. Mining pressure is observed in the junction zone of the underground mine and the open pit more often than on the opposite flanks of the mine fields. The tectonic stress field is characterized by the sublatitudinal orientation of the maximum compression σ_{max} in the subhorizontal plane and the vertical orientation of the minimum compression σ_{min}. The ratio $\sigma_{max}/\sigma_{min}$ is estimated as 2.5.

Seismological monitoring is carried out by an automated control system for rock mass conditions, registering seismic events with energy from 100 J and hypocenter location accuracy up to several meters.

The underground Rasvumchorr mine controls the junction area of the Tsentralny open pit, the ore pass area and the northwest wall of the pit. Figure 1 shows the epicenters of seismic events with energy class K $\geq$ 6.

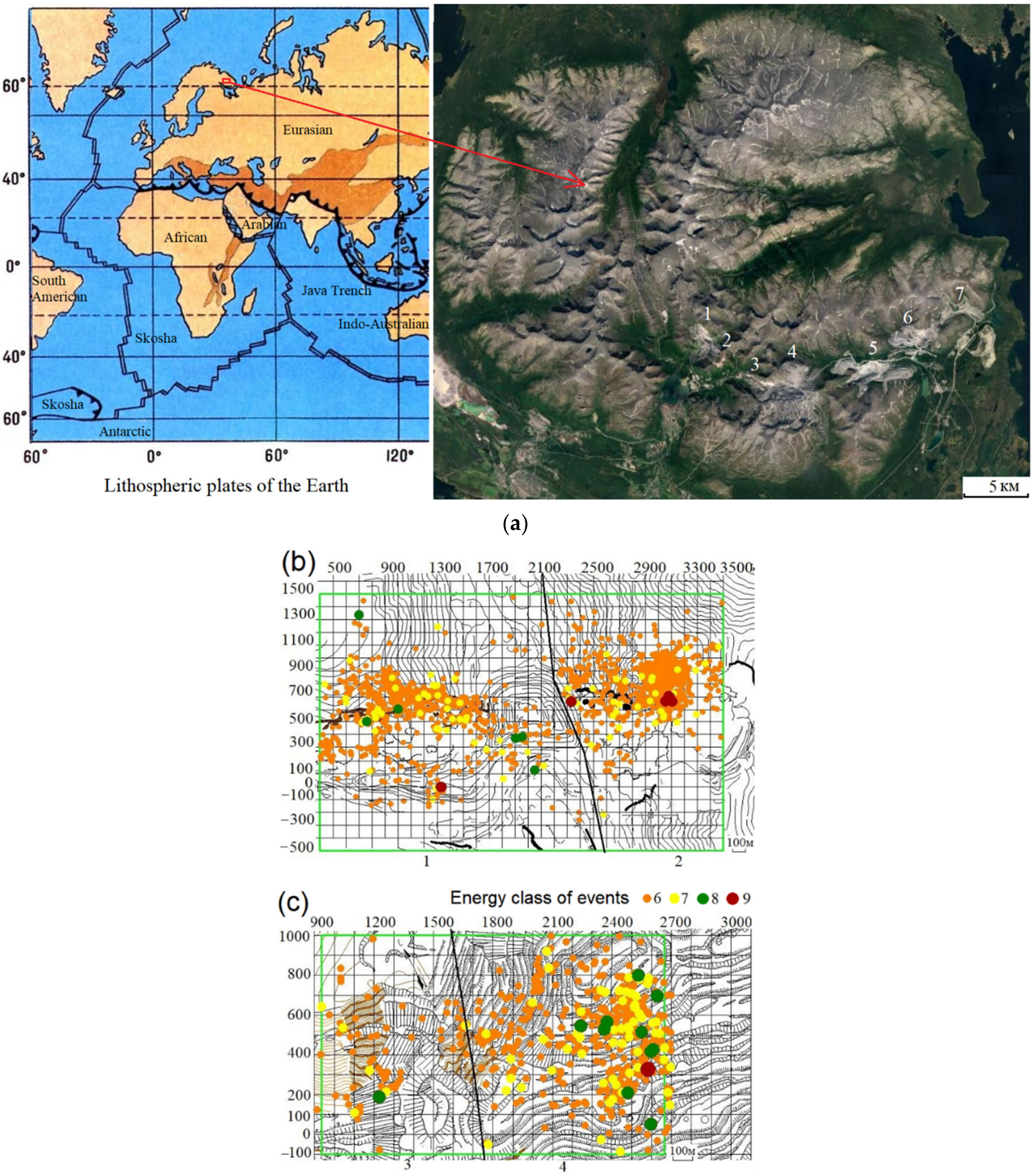


Figure 1. Distribution of epicenters of seismic events (2002–2018). (**a**) Lithospheric plates of the Earth (**left**) [35], the Khibiny rock massif (on **right**). Seismicity at the Kirovsky mine (**b**). Seismicity at the Rasvumchorr mine and Tsentralny open pit (**c**); vertical line divides the deposits. 1—Kukisvumchorr deposit; 2—Yukspor deposit; 3—Apatitovy Tsirk deposit; 4—Plateau Rasvumchorr deposit; 5—Koashva deposit; 6—Niorpakhk deposit; 7—Oleniy Ruchey deposit.

Since 1987, within the Kirovsky mine zone of seismological monitoring, 2500 such events were registered; since 2004 at the Rasvumchorr mine, 480 events; in the Tsentralny open pit (with an error in determining the hypocenter of more than 100 m), 300 events. Most of the events are concentrated in the area of mining operations and in the zone of influence of the underlying rock console, as well as in the zone of the junction of the underground Rasvumchorr mine and the Tsentralny open pit.

The rock mass of the junction zone and ore pass area of the Tsentralny open pit is characterized by the presence of radial faults, among which there are steeply dipping lamprophyre dikes, as well as faults in the form of spreusteinized zones that form a block structure of the rock mass. In the eastern part of the ore body, a diabase dike occurs in one of the radial faults, with which the Draznyashchee Echo Gorge and Glavny Fault [36] are connected. It is a sublatitudinal spreusteinization zone, 1 to 10 m thick, where strong seismic events (energy class $K \geq 6$) are recorded periodically in the spring and autumn periods.

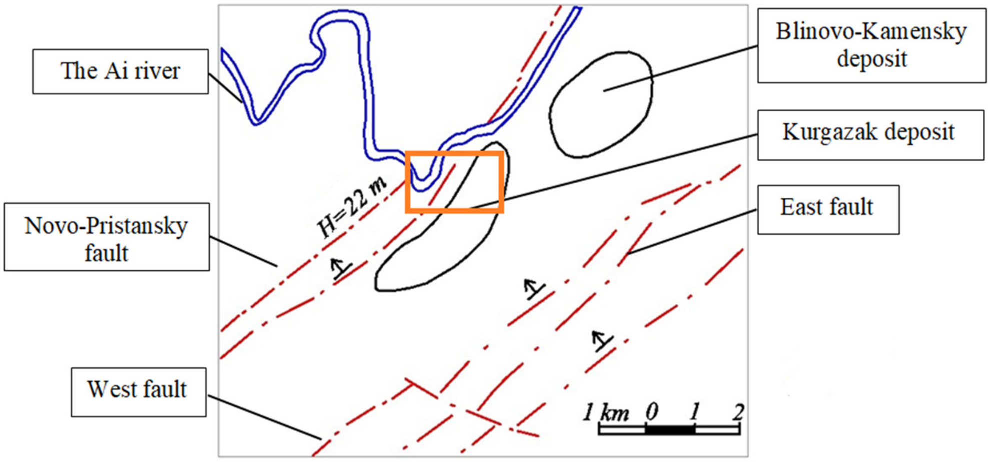
The underground mine and open pit are flooded due to fractured and fractured-vein waters of the Palaeozoic aquifer complex and seepage of atmospheric precipitation through the failure zone, as well as due to groundwater rising during intensive snowmelt and prolonged rainfall.

2.2. A Bauxite Mine, Southern Ural

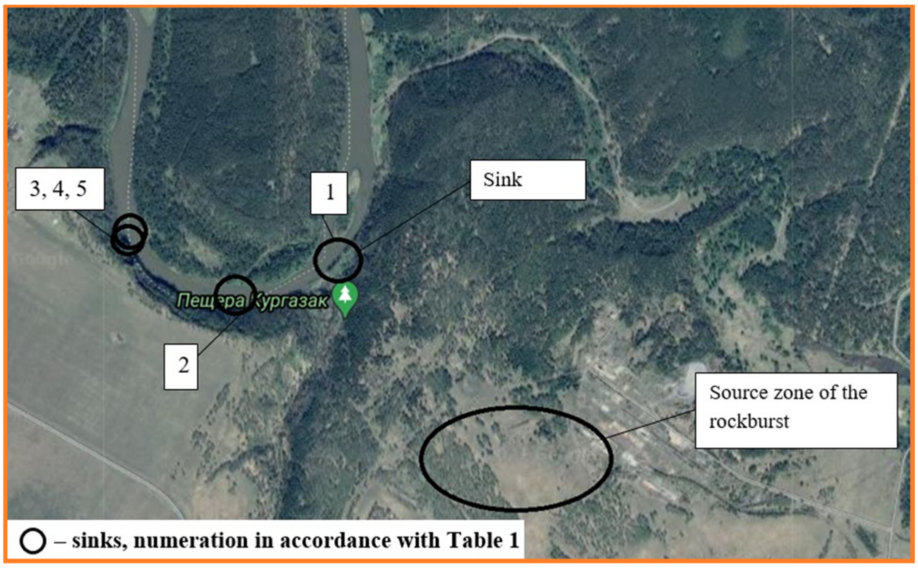
Underground development of the Novo-Pristanskaya group bauxite deposits began in 1952. In 1969, the Blinovo-Kamensky mine was put into operation with a production of up to 650,000 tons of ore per year; and in 1979, the Kurgazak mine was put into operation with a production of up to 450,000 tons [37]. The Kurgazak mine developed the Kurgazak bauxite deposit, presented by an ore body of plate form with a thickness of 2.5 m and in some places up to 4 m, occurring at 225–550 m. The ore body was up to 6 km long and up to 1.2 km wide, extending NE–SW with a dip of angle from 0 to 15 degrees; the host rocks were limestone. Soil limestones with a thickness of 20 m lie on clay limestones and marls with a thickness of 10–20 m, which, in turn, lie on heavily faulted clayey–sandy rocks. The depth of mining works was 340 m by 1990. The ore body was produced using the chamber-and-pillar mining method without backfill; the roof in the mined space was supported by numerous pillars ranging in size from 1.5×1.5 to 5×5 m [38].

On 28 May 1990, the mine experienced two consecutive strong rockbursts with energies of $10^{10–11}$ J, which destroyed pillars on an area of about 0.45 km^2 in the central part of the mine field. There were also soil heaving and fractures, and roof collapses in some sections of the workings. On the surface, this rockburst was noted as a strong shock; cracks appeared on the ground surface; a brick wall that protected the ventilation shaft from dust collapsed, and the plaster in an administration building cracked. The mechanism of this rockburst [38] is associated with the compression of the rock mass by horizontal forces, which led to the breaking of the soil and the destruction of the pillars. The author of [34], based on the calculation of the load on the pillars, has concluded that the rockburst was a chain reaction of pillar destruction, provoked by the crushing of the weakest of them. However, the phenomenon of the destruction of pillars by the movement of the ore body bed from bottom to top has remained unexplained.

The authors studied the stress state of the rock mass in the area of the deposit by tectonophysical methods after the rockburst of 1990. According to geomorphological features, the whole studied region is experiencing intensive recent uplift, which is explained by an excess of horizontal compression over vertical compression. The meanders of rivers deeply incised into the bedrock, for example, 150–200 m for the Ai River, and the location of its terraces at a height of 40 m above the water's edge demonstrate the elevation of the territory. A comparison of the topographic maps of different publication years shows a tendency of riverbed straightening for 109 years. Zones of tectonic faults are expressed in the modern relief by lowered areas, steep ledges and zones of karst development. For the area of the mine field, a subhorizontal location of the axis of maximum compression in the NW–SE direction has been defined (Figure 2a).



(**a**)



(**b**)

Figure 2. Study site of the Kurgazak mine: (**a**) Tectonic map; (**b**) space image of the region studied; 1–5: karst sinkholes according to the table in Section 4.1.

The mine field is bounded to the northwest by a large branch of the Novo-Pristansky fault of northeastern strike. To the southeast of the mine field occurs a zone of tectonic faults up to 1.5 km wide, also of northeastern strike, represented by the west and east thrust faults and their apophyses. Both the Novo-Pristansky fault and the west and east thrust faults have a southeastern dip, forming a tectonic plate including the deposit, with its dip to the southeast. The mentioned branch of the Novo-Pristansky fault is exposed by mine workings in different parts of the deposit. The amplitude of this fault ranges from 12 m in the northeast of the mine field to 22 m in the southwest. The smaller faults are also produced by mine workings: northeast strike faults with northwest and southeast dipping of fault planes and steeply dipping northwest shear faults (Figure 2a).

Mining operations at the mine were carried out in rather difficult hydrogeological conditions, which were associated with the presence of karst and the hydraulic connection of the mining area with the Ai River. Karst sinkholes appeared from time to time in the Ai riverbed, and an increase in water inflow in the mine Kurgazak has been registered (Figure 2b).

3. Theory and Methods

3.1. Tectonophysics Conditions of Faults' Reactivation

Rockbursts of "fault slip", "slip burst" and "tectonic rockburst" types, according to the Russian classification, are accompanied by movements of the walls of tectonic faults, i.e., their reactivation [39–41]. The effect of fault reactivation under the influence of mining operations is explained by the favorable location of the fault in the stress field. Usually, the direction of movement is determined by a local mining-induced stress field formed as a result of mining activities and connected with the forming stress concentration zones. However, for strong rockbursts, as well as for induced earthquakes in other engineering activities, the correspondence is noted of the direction of movement along the reactivated faults to the regional stress field, i.e., the stress field of the undisturbed rock massif [42].

Strong rockbursts at the Karnasurt mine of the Lovozersky GOK and the Kirovsky mine of JSC Apatit were accompanied by displacement of the walls of large faults by up to 16 cm in the directions corresponding to the regional stress field. Focal zones of strong rockbursts had dimensions of up to 1 km and a hypocenter depth of 300–400 m [34,43].

It is obvious that the danger of dynamic fault reactivation depends on the values of tangential stresses in its fault plane, which depends on the orientation of the fault plane relative to the stress field. In this connection, the authors propose the use of the index $\hat{\tau} = \tau_n/\tau_{\max}$.

This index reflects the relative magnitude of tangential stresses acting at an arbitrarily oriented site (fault plane) and thus characterizes the possibility of shear displacement along the fault. The highest tangential stresses are achieved on the fault planes located close to the areas of maximum tangential stresses $\tau_{\max}$. The sites (fault planes) where tangential stresses are equal to zero are located perpendicular to any of the main stress axes. A relative value of the tangential stresses on the sites, given by the normal to the fault plane $\overline{n}$, can be estimated by the following formula [44]:

$$\hat{\tau} = \tau_n/\tau_{\max} = 2n_1n_3/x_2, \text{x} \tag{1}$$

where τ_n is the value of tangential stresses on the plane of the fault plane with the normal $\overline{n}$, n_1 and n_3 are the cosines of the angles between the normal $\overline{n}$ and axes of principal stresses σ_1 and σ_3, and x_2 is the cosine of the angle between the axis σ_2 and a line in the plane of the fault plane perpendicular to the vector of displacement $\hat{\tau}_n$. Thus, the position of the fault plane relative to the sites $\tau_{\max}$ can be evaluated in the range from 0 to 1 in terms of index $\hat{\tau}$.

3.2. Reactivation of Faults during the Pore Pressure Measurement

In this paper, the authors rely on the theoretical statements presented in Gupta and Rastogi's work on the effect of water reservoirs on the seismic regime [27]. An increase in the pore water pressure P in the rock mass (due to a rise in the water level in the reservoir) decreases the normal compression σ_n of the walls of tectonic faults by the value P, while the tangential stress τ_n in their fault planes remains at the same level. A decrease in normal compression of fault planes with remaining values of tangential stresses leads to a decrease in shear strength by fault plane from τ to τ^* (Formulas (2) and (3) [27]) that promotes fault wing movement.

$$\tau = \sigma_n \times tg\varphi + C \tag{2}$$

$$\tau^* = (\sigma_n - P) \times tg\varphi + C \tag{3}$$

For open pits and mines, reactivation of faults is additionally promoted by the presence of significant-sized mined-out spaces, where the walls of faults can move during tectonic rockbursts since the presence of decompacted areas in the rock mass reduces its adhesion C. The authors assume that the seepage of precipitation in the mine fields increases the hydrostatic pressure in the zones of fault planes and that reactivation is experienced primarily by those of them that are favorably located in the field of active stresses. Satisfaction of equality 2 or 3 for a particular fault plane represents the achievement of the critically stressed state in this plane, after which the dynamic displacement by the fault is possible.

"A rockburst is a brittle fracture of a critically stressed pillar or an edge part of the formation"—from this definition by [40] follows the idea of the source of a rockburst as a zone in which the critically stressed state of rock mass has been reached at the moment of fracture. In practice, the sizes of the rockburst sources are estimated by the results of the examination of faults in mine workings. Strong tectonic rockbursts with reactivation of faults at the Khibiny apatite deposits and in the Urals had focal areas of several hundred thousand square meters and linear dimensions of more than 1 km [7,38]. For example, during a rockburst on 17 August 1999, at the Umbozero mine (Khibiny) with magnitude ML = 5.1, the destruction area was more than 650,000 m^2, and the linear size of the focal zone reached 1–1.5 km. Cracks appeared on the ground surface. The rockburst at Kurgazak mine on 28 May 1990, with magnitude M = 4 resulted in a destruction area of about 450,000 m^2, but the linear size of focal zone reached 1–1.2 km. The depth of the hypocenter was estimated to be 300–350 m. Cracks appeared on the ground surface. If it is assumed that the focus of the rockburst was a zone of critically stressed rock mass state, then with its linear dimension L = 1–1.5 km and hypocenter depth H = 0.3 km, one can obtain $L/2 > H$; i.e., the zone of critically stressed state occupied some space from the Earth surface to depth. The outcrop of cracks to the surface demonstrates that the fracture zone reached the Earth's surface. In the case of the rockburst at the Umbozero mine, the Alluaiv Creek drained into the mine workings through the formed cracks.

According to Professor I.M. Petukhov, the zones of the critically stressed state of the upper part of the Earth's crust are formed under the influence of horizontal compression forces, and their thickness depends on the interaction of the Earth's crust blocks [40]. The facts given above about the ratio of the size of tectonic rockbursts' centers L and the depth of their hypocenters H indirectly prove this effect in the deposit under study. Of course, the authors consider such a critically stressed state of the rock mass, taking into account the scale factor. The zone of the critically stressed state of the rock mass is characterized by structural hierarchy and discreteness of stress distribution. Local areas with the critical state are interspersed with relatively unloaded ones, but they collectively form a zone of critical state of a larger rank. Dynamic events at water infiltration are the result of successive disturbances of equilibrium in the rock mass sections, which are in the critically stressed state due to the above-described event of the hydraulic thrust of tectonic disturbances.

4. In Situ Studies

4.1. Monitoring of Water Inflows

The Rasvumchorr mine's workings and boreholes are watered due to seepage of precipitation coming in through the caving funnel and, partially, due to groundwater levels rising during intensive snowmelt and prolonged rains. Starting from the +470 m level, ore mining is carried out in difficult hydrogeological conditions, i.e., in the zone of constant water saturation. At the junction zone of the underground Rasvumchorr mine and the Tsentralny open pit, watering of the rocks occurs due to surface water; in this connection, it is customary to use daily data on measurements of the mine water inflow in the ore passes of the Tsentralny pit located directly in the junction area.

Figure 3 shows the distribution of water inflow by seasons (spring–summer–autumn) for the monitoring period 2004–2018. The division by seasonal periods is carried out as follows: the spring period is established from the beginning of the decrease in the snow cover height and increase in water inflow until the end of snowmelt (zero snow level); the summer period runs from the end of snowmelt until September 1; the autumn period lasts from September 1 until the beginning of frost (average daily temperature is negative) and reduction in water inflow (to constant low values).

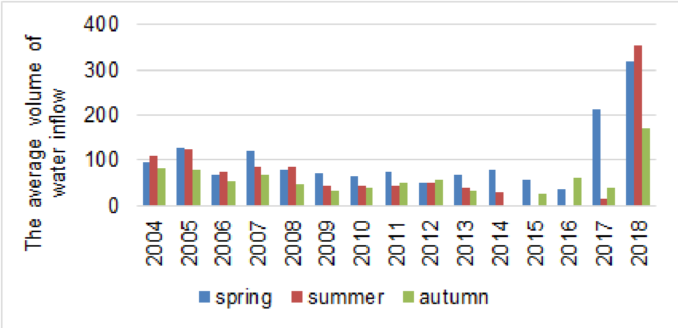


Figure 3. Average daily water inflow (m^3/day). The measurements were performed in the junction area of the Rasvumchorr underground mine and the Tsentralny open pit. There are no data on water inflow measurements during the summer period of 2015–2016.

It is noticed that the values of water inflows are higher in the spring period than in the autumn period, although it is more short-term. The pie chart shows the ratio of total water inflow in the spring and autumn periods according to the data for 2004–2018 (Figure 4).

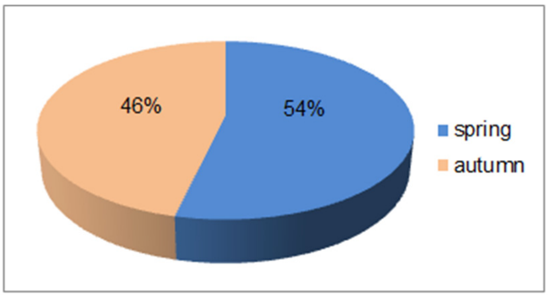


Figure 4. Ratio of the level of mine water inflow in spring–autumn period.

Annual water inflow indices are not uniform and depend on the amount of snowfall, liquid precipitation and positive air temperature (abundant snowmelt). The change in the maximum height of snow cover in May according to the Avalanche Safety Department of Apatit JSC is shown in Figure 5.

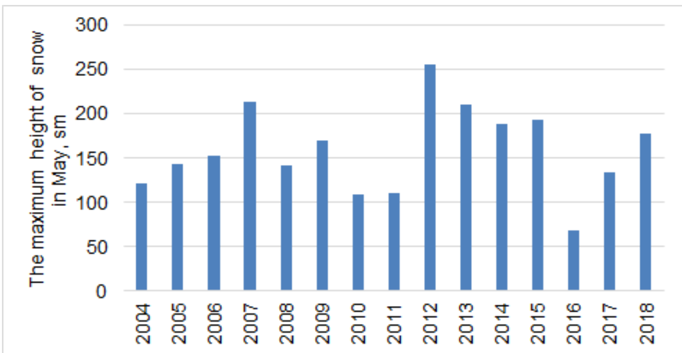


Figure 5. Maximum height of the snow cover per day in May.

In the Khibiny deposits, where there is a large snow accumulation in the caving zones and open pits, artificial fracturing is of considerable importance when the underground workings are watered by atmospheric waters. Shifting of large rock masses is accompanied by the formation of large cracks of the console part of the rock massif at a distance up to 100–150 m from the caving edge. Meltwater easily penetrates into the cracks.

At the Kurgazak mine, a seasonal increase in groundwater inflow was also noted. The correlation of inflows with infiltration losses of rivers was noted earlier during the development of deposits in karst rock massifs, and this was considered as direct evidence of the hydraulic connection of the river with underground mine workings [45]. The most expressive occurrences of such a connection were the formation of deep karst sinkholes directly in the Ai riverbed during floods and a sharp increase in mine water inflow. Some examples are given in Table 1.

Table 1. Characteristics of karst sinkholes in the Ai riverbed.

Discovery Date	Type of a Sinkhole	Note	Schematic Symbol, Figure 2
Spring of 1980	6 × 7 m in plan, depth 2 m	Backfilled in June of 1980	1
15 July 1984	By river width—10 m; by river length—14 m; depth—21 m.	Backfilled by 1 September 1984	2
21 June 1985	By river width—10 m; by river length—8 m; depth—6 m.	Backfilled on 2 August 1985	3
29 August 1985	By river width—5 m; by river length—4 m; depth—20 m.	Backfilled in autumn of 1985	4
Spring of 1990	Was formed on the site of sink 2	Existed to the moment of a rockburst on 28 May 1990	5

The mechanism of increase in river water inflows into bauxite mines along tectonic faults is considered in [45]. Karst cavities along the fault planes of tectonic faults are usually filled with loose clastic, sandy–clayey material. When the deposit is drained and the groundwater level is lowered, the filtration flow gradient increases, which triggers suffosion processes in karst cavities. The loose fine-grained material is directly washed out of karst cavities when tectonic faults are undercut by mine workings. This process develops from the bottom upwards and gradually reaches the Earth's surface. As a result, karst sinkholes are formed, including those in the riverbed. In addition, zones of tectonic faults, as zones of high disturbance, are themselves groundwater reservoirs. Thus, a mine working of block 18, level—10 m, in the near-contact zone of fault 2 (Section 5.2 stripped a source of water with a flow rate of 1500–2000 m^3/hour. Mining operations were stopped and a barrier pillar of 4 m was left along the fault.

From these observation results, the authors conclude that tectonic faults, which are conductors of river water into the mine workings, have well-washed fault planes, which ensures the transfer of hydraulic pressure along them when they are filled with water.

4.2. Monitoring of Seismic Events

The seismic monitoring in the Khibiny deposits has found that in late May–early June and in September–early October, the seismic activity annually increases in the form of an increased number of events and released seismic energy (Figure 6). In recent years, the greatest number of geodynamic events, accompanied by shaking of the Earth's surface, crumbling of wall benches and damage to ore passes of the Tsentralny open pit, and violations of the working contour integrity of the underground Rasvumchorr mine, were registered in the spring and autumn.

The Kurgazak mine did not have a seismic station, and dynamic rock pressure was recorded by external signs. Shooting and dynamic failures at the roof of the stopping chambers were noted mainly in the northeastern part of the mine. Shocks from the soil of the stopping chambers, including in the central part of the mine field, were also noted. Four to five days before the rockburst of 28 May 1990, there was intense spalling in the pillars and shooting.

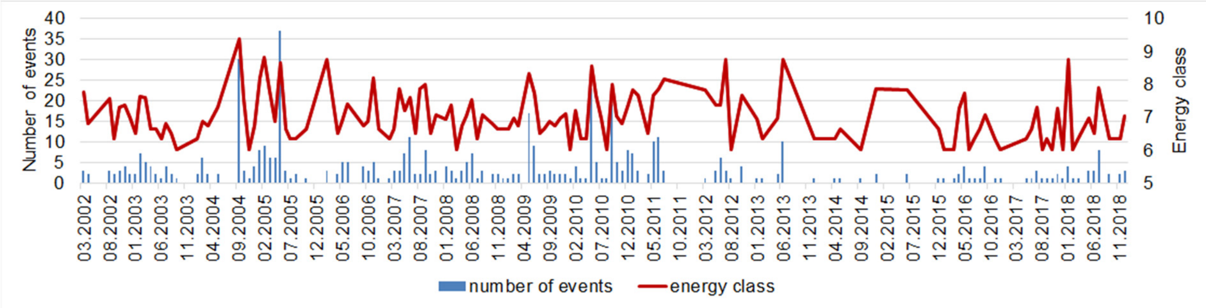


Figure 6. Monthly distribution of seismic events of energy class K $\geq$ 6 in the control zone of the Rasvumchorr mine and the junction zone with the Tsentralny open pit.

5. Results and Discussion

5.1. Regularity of the Increase in Seismic Activity of the Rock Mass Whilst under the Impact of Surface Seepage during Snowmelt or Heavy Precipitation in the Khibiny Deposits

The tectonic stress field in the area of the Khibiny deposits is characterized by sublatitudinal subhorizontal orientation of the maximum compression axis and submeridional orientation of the minimum compression axis. The fracture faults are represented by smoothly curving, steeply dipping faults of northeastern and northwestern orientation. Their fault planes can be traced along the dip usually for tens and hundreds of meters and are often filled with secondary minerals. In the active stress field, such fault planes gravitate toward the τ_{max} sites and their index $\hat{\tau}$ is close to 1.

Modern seismological and geomechanical monitoring at mining enterprises allows revealing regularities of the influence of watering on the rock mass rockburst hazard. According to the data obtained, seismic activity increases annually in the spring season. At the Rasvumchorr Plateau deposit, seismicity activates earlier than that at the adjacent Apatitovy Tsirk deposit. This can be explained by the fact that the Rasvumchorr Plateau is a mined open pit, and therefore more cracks and tectonic faults, which are watered out during snowmelt, are exposed in this area. As a consequence, in the critically stressed state, faults are reactivated and seismic activity increases.

Detailed analysis of meteorological, hydrological and seismic data for the spring monitoring period from 2004 to 2018 has shown that the annual distribution of solid precipitation (snow) and water inflow is uneven and that the beginning of the snowmelt season varies from April to June. For example, in 2015 and 2018, it was early May; in 2016, it was late April, and in 2017, it was early June (Table 2). So on 7 May 2015, the height of snow cover was ≈193 cm; on 26 April 2016, it was ≈91 cm; the growth of water inflows was recorded in a few days, and in 2017, due to the cold spring, it shifted to June.

Table 2. Dynamics of annual snow melting.

Year	Day/Month	*h* (cm)	Δ*h* (cm)	Start Date W (m^3/Hour)
2015	7 May	193	−5	9 May
2016	26 April	91	−1	29 April
2017	7 June	120	−1	10 June
2018	6 May	177	−6	12 May

Since the water inflow growth is affected by the rate of snow melting and total watering of the rock massif, the authors have introduced the parameter of changes in the snow cover height per day, Δh (cm): $\Delta h = h_i - h_{i+1}$, where h_i is the snow height of the previous day. The Δh parameter shows to what extent the snow height has changed in one direction or another. Positive values indicate, for example, that there may have been blizzard transport of previously fallen snow in the measurement area. Figure 7 shows the results for 2015–2016.

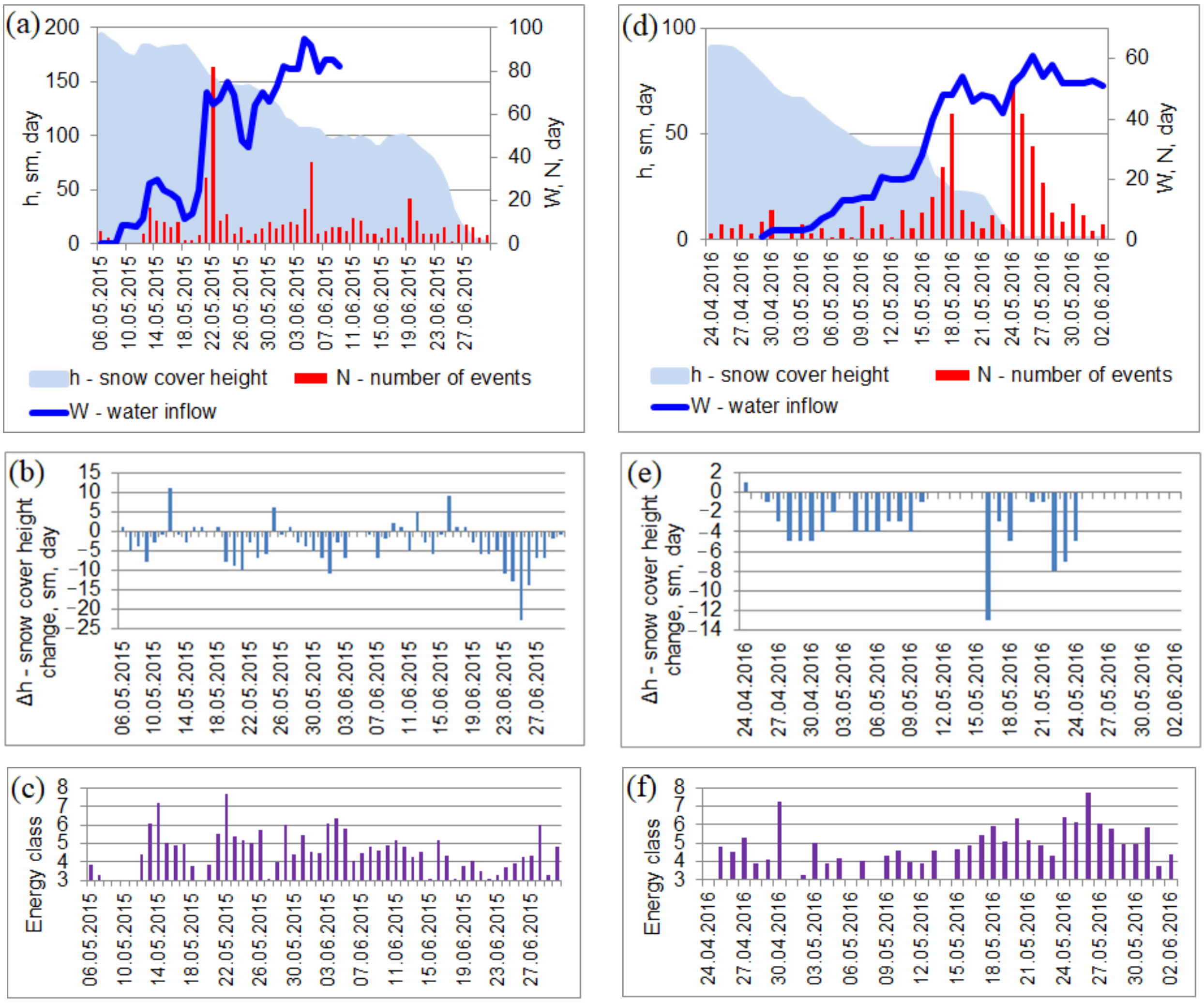


Figure 7. Influence of snow cover height and water inflow on seismicity changes. (**a**,**d**) the relationship of seismicity, water inflow, snow cover height; (**b**,**e**) snow cover height change; (**c**,**f**) energy class of seismic events change; (**a**–**c**) 2015 year; (**d**–**f**) 2016 year accordingly.

The above data show the increase in seismic activity (50% and more) both after a prolonged decrease in the snow cover height and after extreme changes in the snow cover height. Both coincide with a jump-like growth of water inflow. Positive air temperature leads to the formation of free water in the snow cover (when the snow reaches the melting temperature, i.e., 0° Celsius) and the beginning of its infiltration into the cracks on the surface of the rock mass. It is seen that the increase in the water ingress rates continued for over 5 days and the total water inflow volume exceeded the previous daily measurements by a factor of 2 (Figure 7a,d).

Figure 8 shows the results of a comparative analysis of seismic and meteorological monitoring data for the snowmelt period. Calculation of the water supply in the snow cover for the area of the Tsentralny open pit and the dumps was performed according to the formula Z = 10*hd*, where *h* is the average height of the snow cover (cm) and *d* is the snow density (g/cm^3). Taking into account the area of the open pit and dumps, the water reserve is equal to Z × S (m^3) (Figure 8b does not show the water reserve in the snow cover after 2015 due to the lack of data). The values of the water reserve in the snow cover show how much moisture is supplied for infiltration to the entire catchment area during the melting of the snowfall of the whole season, taking into account the liquid precipitation recorded in the spring period.

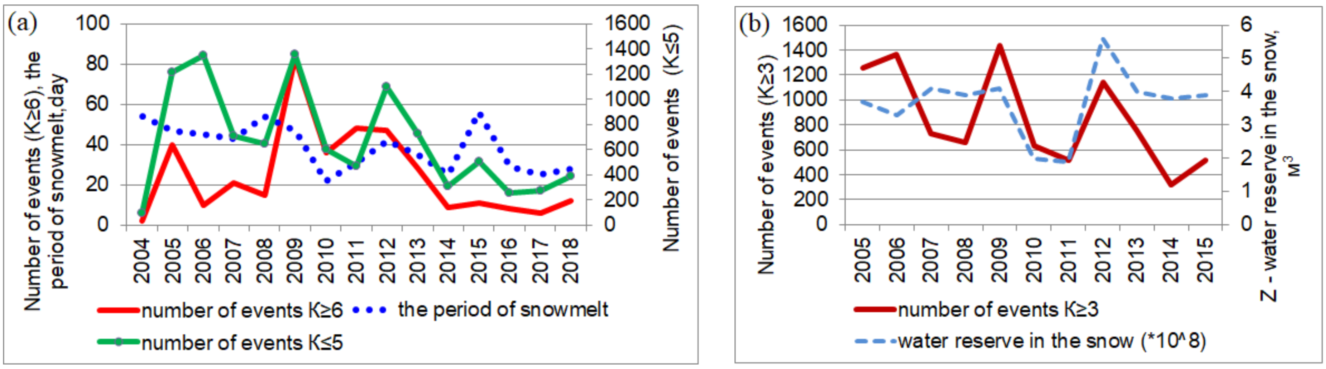


Figure 8. Comparison of seismic and meteorological monitoring data: changes in seismicity from snowmelt period (**a**), changes in seismicity from water reserve in snow cover (**b**).

Statistical analysis of the data shows that the cyclicity of geodynamic events in the studied area felt on the Earth's surface is 3–4 years. This may be contributed to by both prolonged snow melting (the period exceeds 40 days on average) and water reserve in the snow cover of more than 3×10^8 m^3 (Table 3), which may be explained by peculiarities of the hydrogeological situation at the Apatitovy Tsirk and Rasvumchorr Plateau deposits. Unexpected effects of the major mining operation impact on the ground geodynamic regime are earth movements, rockbursts and induced earthquakes in surface mining operations—rare phenomena in mining practice. Examples are the events that occurred in 1995, 1998, 1999, 2003, 2004, 2005 and 2009 at the Rasvumchorr Plateau deposit, which were felt by residents of nearby cities.

Table 3. Seismic and meteorological monitoring data.

Year	The Period of Snowmelt (Day)	Initial Height of Snow Cover for the Snowmelt Period (cm)	Average Water Inflow during the Snowmelt Period (m^3/hour)	Total Released Energy of Events (J)	Water Reserve in the Snow ($\times 10^8$) (M^3)	Number of Events K $\geq$ 6	Number of Events K $\geq$ 3
2004	54	121	1737	2.0×10^7	-	2	97
2005	47	143	1504	4.7×10^8	3.7	40	1258
2006	45	152	985	2.4×10^7	3.3	10	1361
2007	43	214	1889	7.4×10^7	4.1	21	729
2008	54	141	717	8.0×10^7	3.9	15	657
2009	47	170	722	6.8×10^8	4.1	83	1438
2010	22	109	315	4.2×10^7	2	36	635
2011	31	110	339	2.4×10^8	1.9	48	520
2012	42	254	701	5.7×10^8	5.6	47	1143
2013	35	210	864	6.8×10^8	4	28	755
2014	25	186	630	1.9×10^7	3.8	9	318
2015	56	193	551	1.5×10^8	3.9	11	517
2016	29	91	196	2.6×10^7	-	8	262
2017	25	121	2303	1.2×10^7	-	6	278
2018	28	177	3991	2.9×10^7	-	12	404

Note: average water inflow for the snowmelt period—from the beginning of water inflow growth to the end of snowmelt—period of increased watering (m^3/hour).

In 2012 and 2013, tremors were registered in the open pit, felt in the underground workings of the Rasvumchorr mine. Most of the events of energy class K $\geq$ 6 in 2012 were registered on May 18 and 19. The bulk blast produced in the Tsentralny open pit on May 18 contributed to the relaxation of stresses in the rock mass, resulting in a decrease in the overall energy level of the events.

Thus, a pattern can be traced, according to which during snowmelt or heavy precipitation the seismic activity in the rock mass increases. Some examples of seismic events and the nature of their occurrences during snowmelt are presented in detail in Table 4.

Table 4. Characteristics of seismic events, Rasvumchorr Plateau, 2005–2018.

Energy Class of the Main Event/Altitude Mark	Snow Melting Period	Energy Class of Foreshock/Aftershock Events	Height Range of Foreshocks/Aftershocks (m)	Description
		Earthquake of 25 May 2005		
K = 8/altitude mark 445 m	1 May–17 June	K = 4 − 6/K = 4 − 8	200–700/150–850	A series of shocks was felt in the area of ore passes and in the administrative buildings. In the open pit, crumbling of rock was observed in the spreusteinization zone.
		Earthquake of 25 May 2009		
K = 10/altitude mark—not determined (beyond the registration zone)	8 May–24 June	K = 4 − 7/K = 4 − 7	100–860/100–900	The main event as well as a series of foreshocks and aftershocks were felt in underground workings; in buildings of the Rasvumchorr, Tsentralny and Kirovsky mines; and in Kirovsk town. Rock falling off the walls and dust rising near the epicenter of the pit were noted at the mine. The events were triggered by a fault movement.
		Shock of 18 May 2012		
K = 8/altitude mark—not determined (beyond the in the control zone)	16 May–27 June	K = 4 − 5/K = 4 − 7	340–600/100–700	Shocks were felt in the junction zone of the underground Rasvumchorr mine and the Tsentralny open pit, as well as shocks to the Earth's surface in the open pit.
		Shock of 2 June 2013		
K = 8/altitude mark 436 m	16 May–20 June	K = 4 − 6/K = 4 − 7	100–600/100–700	Activation of seismic activity was registered in the junction area and in the ore pass area. Workers at the Rasvumchorr mine felt tremors on June 2. No damage was found.

Gupta and Rastogi explained the development of slips along the faults in the vicinity of dams by relief of normal stress due to pore pressure acting as a wedge [27]. It is assumed that a similar mechanism is also realized when mines are flooded [23–25]. Recent studies reveal new details in the seismicity evolvement process in the dam area, such as seismicity migration [46–48] and fault activation at a distance of over one kilometer from the hydraulic fracturing location [5]. Some features of the fault activation process in response to cyclic and single-stage water injection are not yet entirely clear [49]. Table 4 shows that seismic events began to occur from a depth of 100–150 m, which can prove the hypothesis of a critically stressed state of the upper part of the Earth's crust in the area of the deposit. The zone of the critically stressed state of the Earth's crust near the surface in the area of the deposit under development could have been formed under the influence of interacting blocks of the Earth's crust in the tectonic stress field [50].

Thus, the mining area of the Khibiny rock massif can be considered as a part of the Earth's crust, within which the critically stressed state has been reached from the surface to a certain depth. In this case, both the geomechanical impact from mining operations and the seepage of precipitation cause an immediate redistribution of stresses in the rock mass, which leads to seismicity and strong tectonic rockbursts.

An upswing of seismic activity during the snowmelt period within this rock massif occurred when a range of conditions was met:

– Water reserve in the snow cover was more than 3×10^8 m^3;
– The snowmelt period exceeded 40 days;
– Increase in water ingress rates continued for over 5 days and the total water inflow volume exceeded the previous daily measurements by a factor of 2.
– Some additional data is placed in Supplementary Materials.

5.2. A Possible Origin of the Strong Rockburst, Southern Ural

The rockburst at Kurgazak mine, one of the strongest rockbursts in the Russian mines, proceeded in several stages. The first rockburst occurred at 6.30 a.m. and was felt on the surface as a 5-point earthquake on the MSK-64 scale. At 8.40 a.m., there was a second shock, also felt on the surface, which caused the brick wall to collapse and cracks to appear in the mine building. In addition, according to eyewitnesses, 4 h later there were vibrations in the mine building and its rocking was noted again [51]. There are estimates that the hypocenter of this event was several kilometers deep [38]. According to the survey of the rockburst focal zone, fresh traces of displacement were noted on the surfaces of the shear fault planes. The dimensions of the focal zone along the strike reached 1.2 km with fractures reaching the surface, which can be regarded as evidence of the critically stressed state of the upper part of the Earth's crust at the time of the rockburst. During the repeated analysis of the mine documentation, the authors have found data showing that in the Ai riverbed, on the eve of the rockburst in 1990, another karst failure was found in the place where such failures had been formed repeatedly before (Figure 9). This previously unaccounted-for fact allows for further understanding of the mechanism of this rockburst.

At the present time, there are several ideas about the tectonophysical conditions of occurrences of strong rockbursts which have reactivations in large faults of mine fields and have depths of hypocenters below an area of mining operations. Available factual data on the conditions of rockburst occurrence in the Kurgazak mine allow the proposal of the following tectonophysical model of this event (Figure 9).

The stress state of the mine field area is characterized by the following orientation of the principal stress axes: the maximum compression axis σ_{max} is oriented along the azimuth 115° in an almost horizontal plane; the minimum compression axis σ_{min} is oriented along the azimuth 205° also in an almost horizontal plane; axis σ_2 is almost vertical. The mine field crosses a major fault with an amplitude of 22 m, which has an azimuth and dip angle of 130° and 60°, respectively. For this fault, $\hat{\tau} = \tau_n/\tau_{\max} = 0.8$. As can be seen, the fault is located favorably in the field of regional stresses for the occurrence of reverse fault movement. The hanging wing of this fault in the field of regional stresses tends to shift upward into the area of the mined-out space (Figure 9).

A characteristic feature of the deposit development was regular water breakthroughs from the Ai River into the mine workings. From the sinkholes, sometimes more than 20 m deep in the riverbed, water flowed through tectonic faults into the mine, located hundreds of meters away from the river (Table 1). On the eve of the rockburst, another sinkhole was formed in the Ai riverbed at the place where it was crossed by a large fault.

Figure 9 shows that karst sinkholes had repeatedly been formed earlier, and the water from these faults had entered into the mine for weeks. On this basis, it is possible to assume that the fault planes had already been well washed out beforehand and represented macrochannels. The water inflow into these macrochannels from the surface resulted in hydraulic pressure of up to several megapascals at the depth of mining operations and below, which provided a reduction in the normal pressure of the reverse fault and the subsequent series of dynamic shifts. After the first movement (a rockburst), conditions may have been created to establish a hydraulic connection with the deeper levels of the rock mass, which caused the second and subsequent sudden movements. The hypocenters of these seismic events were below the mining area. The main movement occurred along the reverse fault, but, apparently, the shears transverse to the deposit strike were also reactivated, as evidenced by the presence of fresh traces of displacements on their fault planes.

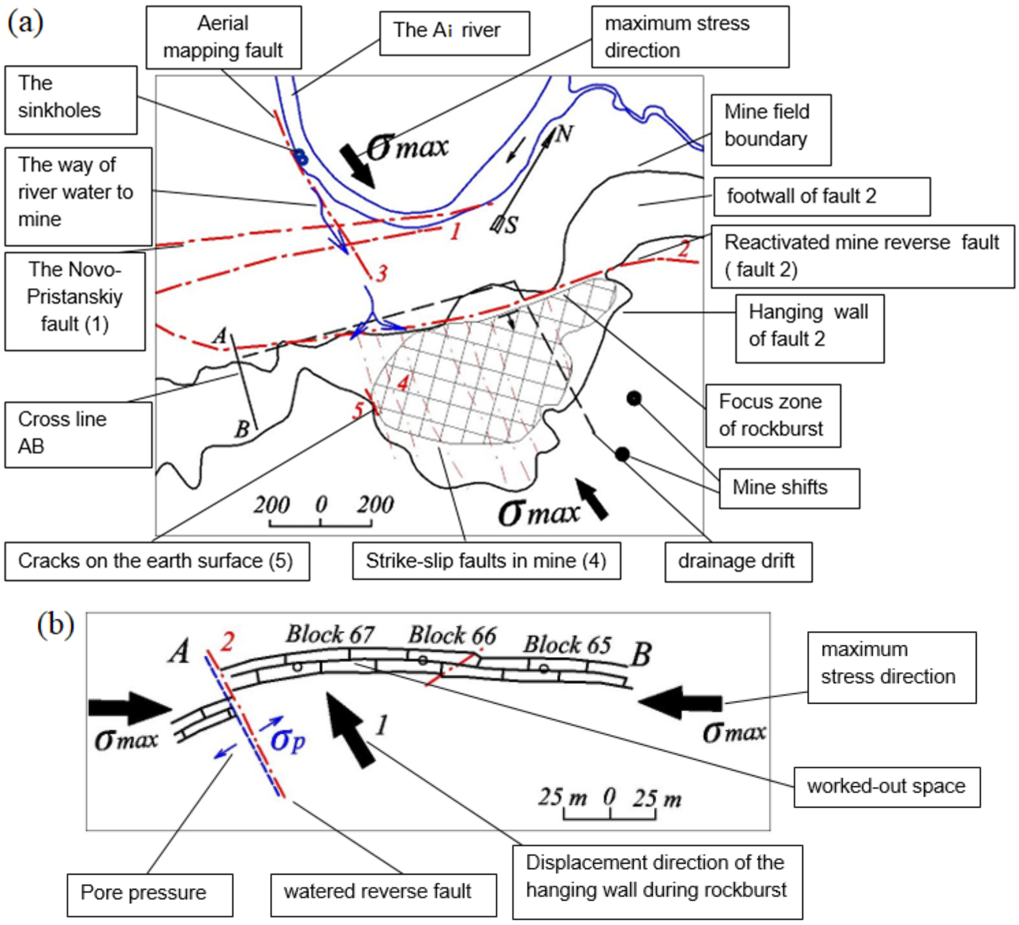


Figure 9. Tectonophysical diagram of the 28 May 1990, rockburst: Factual scheme of the bauxite deposit region (**a**); cross section along AB line (**b**) (according to (**a**)).

Thus, prior to this strong rockburst, there was an inrush of the Ai River waters into the mine workings along a large tectonic fault, which was not previously taken into account when analyzing the mechanism of this geodynamic event. The mechanism of this rockburst could be related to the reactivation of a large tectonic fault in the conditions of the critically stressed state of the rock mass with a decrease in the normal pressure of the fault plane during the water breakthrough from the surface reservoir.

6. Conclusions

Throughout the fifteen-year period of seismic monitoring at the Khibiny's Apatitovy Tsirk and Rasvumchorr Plateau fields, a seasonal trend of seismicity increase (by over 50%) during the spring snowmelt was recorded. An upswing of seismic activity during the snowmelt period within this rock massif occurred when a range of conditions was met:

− Water reserve in the snow cover was more than 3×108 m^3;
− The snowmelt period exceeded 40 days;
− Increase in water ingress rates continued for over 5 days and the total water inflow volume exceeded the previous daily measurements by a factor of 2.

Despite the fact that mining is at depths of more than 500 m, seismic events during infiltration of water began to occur from a depth of 100–200 m and are recorded to depths of 900 m. The dimensions of the strong rockburst focal zones are several hundred meters vertically, which indicates that the rock massif in the area of these deposits is in a critically stressed state practically from the Earth's surface to depths below the current mining levels. A possible controlling factor of the rock massif seismic activation during the period of intense snowmelt and precipitation is the reactivation of tectonic faults, which occurs under conditions of the critically stressed state of the massif, due to a decrease in their normal compression during infiltration.

Prior to a strong rockburst (K = 10–11) in the Southern Urals in May 1990, there was an inrush of the Ai River waters into the mine workings along a large tectonic fault, which was not previously taken into account when analyzing the mechanism of this geodynamic event. The intrusion of water into the fault located in the field of regional stresses and subsequent partial destressing of its fault plane from normal stresses could have triggered the rockburst with a fault-slip mechanism. With a depth of the rockburst hypocenter of about 300 m, the size of the source zone reached 1.2 km, which can be regarded as evidence of the critically stressed state of the massif at the time of the rockburst.

It is necessary to take into account the revealed mechanisms, i.e., the influence of natural factors on rockburst hazards, when preparing mining plans and conducting geomechanical monitoring.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142215414/s1.

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