# Influence of Watering of Khibiny Mountains on the Earthquake-Size Distribution

**Svetlana Zhukova, Alexander Motorin, and Sergey Baranov**

**Abstract** According to the long-term earthquake statistic and the data of monitoring of water inflows carried out at the apatite-nepheline deposits of the Khibiny massif, the authors have revealed a statistically significant decrease in the *b*-values of the Gutenberg-Richter law during the period of high watering (May–October) compared with the period of low watering (November–April). A sharp increase in seismicity (*a*-value of the Gutenberg-Richter law) with the beginning of the watering increase in the deposits of the Khibiny massif caused by the melting of snow accumulated over the winter is demonstrated. A decrease in the strength of rocks and the dilatancy of cracks due to the influence of additional pore pressure can serve as an explanation for the dependence of the seismic regime on the change in the level of watering of the rocks.

**Keywords** Khibiny massif · Watering · Mining-induced seismicity · Earthquake-size distribution

S. Zhukova · A. Motorin · S. Baranov (✉)
Kola Branch of Geophysical Survey, Russian Academy of Sciences, 14 Fersmana, Apatity 184209, Russia
e-mail: bars.vl@gmail.com
URL: http://www.krsc.ru/

S. Zhukova
e-mail: svetlana.zhukowa@yandex.ru
URL: http://www.goikolasc.ru/

S. Zhukova
Mining Institute of Kola Science Center, Russian Academy of Sciences, 24 Fersmana, Apatity 184209, Russia

A. Motorin
Kirovsk Branch of JSC Apatit, Leningradskaya 1, Kirovsk 184250, Russia

 
A. Kosterov et al. (eds.), *Problems of Geocosmos—2022*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-031-40728-4_12

## 1 Introduction

To date, numerous experimental and field data on the problem of the influence of watering of rocks on the parameters of the seismic regime for natural and mining-induced seismicity are available. A vivid illustration of the manifestation of this effect is the well-known experiment on the injection of water into a seismically active fault under the solid bed in a deep gold mine [4]. As a result of this experiment, it was demonstrated that the stick-slip motion was initiated by a water pressure of about 20 MPa, and led to a significant redistribution of stresses. Later, direct evidence of the influence of fluids on the activation of faults during the increase in seismicity in reservoir areas [23, 24, 28] and fluid injection into wells [31] was obtained.

To date, the physical mechanisms of the influence of fluids on the destruction of geologic material in the context of induced seismicity are well understood, however, a number of relevant aspects remain insufficiently clarified (see, for example, [5, 20]. For instance, the problem typical for the real case [22]. When the geological environment is simultaneously affected by natural and technogenic factors of different nature, duration and intensity, what will the reaction of the environment to a particular impact be? This question remains poorly explored. In this regard, the problem of identifying the correlation between the watering of the massif and the seismicity that occurs during the extraction of minerals in tectonically loaded rocks is not fully understood presently and this paper is dedicated to it.

The influence of the hydrogeological factor on the geomechanical state of a rock massif has been identified earlier in many studies, for example, in [8], where a causation was established between prolonged rains and weak earthquakes in Bavaria during observations of the 1775-meter Hochstaufen mountain in the Alps. Thanks to the dense network of meteorological and seismic stations installed in this area, it was possible to reveal that seismic activity increased by 20 times during prolonged rains. Subsequent analysis showed that precipitation is the dominant trigger of earthquakes in this region [7]. The correlation of the number of earthquakes in the upper part of the crystalline crust with the intensity of snow melt and precipitation has been observed in western Norway [16], where the precipitation-caused seasonal increase in the pore pressure of the fluid in the fractured crystalline rock and changes in the water load caused an increase in local seismicity. In [9], statistical analysis revealed that changes in pore fluid pressure may have caused at least 19% of the analyzed earthquake swarms in Northwest Bohemia.

The change in the pore fluid pressure affects the earthquake triggering; the porosity and moisture saturation of the rocks play a significant role. For instance, the presence of geological structures with high permeability concentrates the flows of atmospheric and groundwater and causes changes in pore pressure, which in turn provokes the displacement of the blocks of the massif relative to each other. At the same time, seismicity levels also correlate with changes in groundwater reserves in the hydrological basin [19, 23, 28]. A recent laboratory study has shown a correlation between pore pressure in a saturated rock and acoustic emission due to fluid-induced fracturing of the rock [10].

A similar situation is observed in the Khibiny Mountains, where large deposits of apatite-nepheline ores have been developed for about a century. For example, in [14, 29] n there was revealed a pattern of seasonal increase in the number of earthquakes and the seismic energy released during the period of snowmelt and precipitation. The seismicity of the Khibiny massif deposits is determined by the high level of horizontal tectonic stress [13], the presence of fragile high-strength rocks and fault structures filled mainly with oxidized loose rocks [17], as well as the volume of annually extracted rock mass. For instance, in 2019, only the total volume of extracted apatite-nepheline ore amounted to 38 million tons [18].

This paper is devoted to the study of the influence of watering of rock on the distribution of magnitudes of seismic events recorded at the developed deposits in the Khibiny massif.

## 2 Materials and Method

The study uses a catalogue of seismic events recorded by the seismic monitoring network of Kirovsk branch of “Apatit” JSC [11] for the period from 2002 to 2020 (Fig. 1). Currently, the network consists of 65 three-component seismometers located at the Kirovsky Mine and Rasvumchorr Mine, with an input sampling rate of 1000 Hz. The network is capable of determining the hypocenters of seismic events with a magnitude of $M \geq -0.5$ (energy $E \geq 10^3$ J) with an accuracy of up to 25 m in the area of increased accuracy and up to 100 m in the area of confident registration. For 2002–2020 the catalogue is complete starting from zero magnitude ($M_c = 0$).

Data on water inflows at the deposits of the Khibiny massif were provided by the geological service of the Kirovsk branch “Apatit” JSC. Water inflow measurements were carried out at underground mines once a day in water collecting header located on production levels. Flooding of mines and boreholes of horizons occurs due to the infiltration of atmospheric precipitation. Measurements of the volumes of water inflows in the quarry were carried out in ore discharges in special drainage grooves twice a day.

Analysis of data on the distribution of water inflow volumes by month showed that the maximum is observed during the period of snow melt (in June) and heavy rains. Minimal water inflow due to the lack of replenishment of natural groundwater resources is observed in winter with the duration of the drainless period about 4–5 months (from November to April).

To compare variations in watering and seismicity, we estimated the parameters of the Gutenberg-Richter law [6]

$$\lg N = a - bM, \tag{1}$$

where $N$ is the number of seismic events with magnitude $M \geq M_c$ (the magnitude of completeness); $b$-value is the slope of frequency-magnitude plot; $a$-value describes seismic activity.

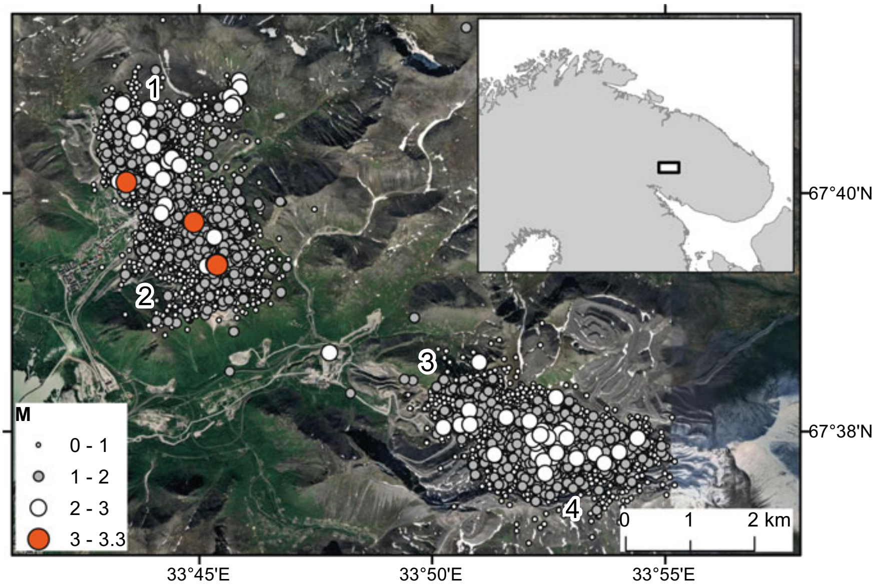


**Fig. 1** Epicenters of seismic events with $0 \leq M \leq 3.3$ recorded the developed deposits of the Khibiny massif for 2002–2020 against terrain relief map. Mineral deposits: (1) Kukisvumchorr, (2) Yukspor (mined by Kirovsk mine); (3) Apatite Circus (Rasvumchorr mine); (4) Rasvumchorr Plateau (until 2014 Central mine; currently Vostochnyi mine). The box in the inset indicates location of the study region

The estimation of $b$-value was performed using the maximum likelihood method according to the Aki's formula adapted for discrete magnitudes [15, 26]:

$$b = \frac{\log_{10} e}{E[M] - M_c + \frac{\Delta M}{2}}, \tag{2}$$

where $M_c$ is the magnitude of completeness, $E[M]$ is the average magnitude of the sample for $M \geq M_c$, $\Delta M$ is the binning magnitude width of the catalogue. The error distribution of $b$-value and the standard deviation $\sigma$ were calculated using the bootstrap technique. The $a$-value was estimated using the estimated $b$-value with formula (1).

## 3 Results

Figure 2 shows monthly variations in watering (water inflow value, $m^3$/day) and seismicity (parameters $a$, $b$ of the Gutenberg-Richter law at the fields of the Khibiny massif for 2002–2020). The period of increased watering of the Khibiny massif

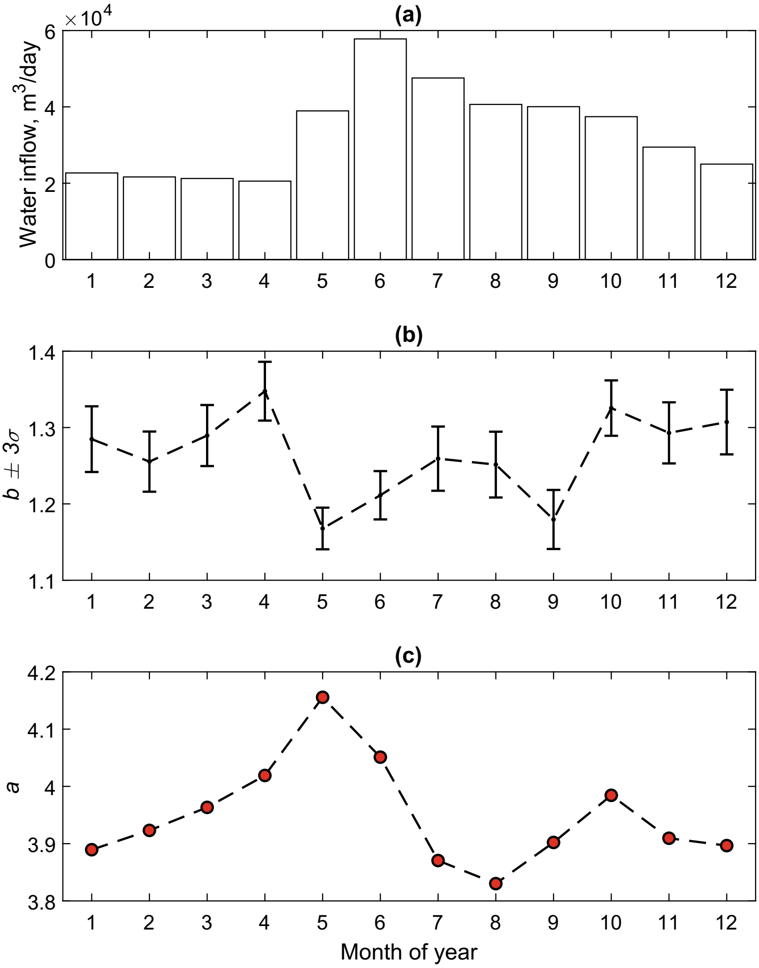


**Fig. 2** Monthly variations in watering and seismicity at the deposits of the Khibiny massif for 2002–2020. **a**—average water inflow ($m^3$/day); **b**—$b$-values (error bars denote the values of a triple standard error $\pm 3\sigma$); **c**—$a$-values

falls on May–October (Fig. 2a), while from November to April the watering is low. The increase in watering in May and June is caused by a sharp melting of snow accumulated over the winter. From July to October this increased level of watering of the massif is maintained by rains. From about October, the air temperature in Khibiny becomes negative and the watering of the massif starts to decrease.

Comparing the temporal variations in watering and seismicity (Fig. 2b, c), it can be stated that with an increase in the water inflow values there is a significant (more than 3 standard errors $\sigma$) decrease in the $b$-value (Fig. 2b). And this reduced value of $b$ persists throughout the period of increased watering until September inclusive.

Then, starting from October, the value of $b$ increases to the level observed during the period of low watering at the beginning of the year. Further, the watering decreases slightly, but the increased level persists until September. And in the same period, the $b$-values are smaller compared to January–April. In November, there comes a period of low watering and the $b$-value reaches the level of January–April. Thus, the $b$-value significantly decreases (increases) with rock watering increase (decrease). Almost the same behavior of $b$-value was observed, for example, in the Three Gorges Reservoir area (Western China) [28] and Koyna–Warna region (Western India) [23].

Seismic activity, characterized by the $a$-value of the Gutenberg-Richter law, increases from February to May, in May there is a sharp increase to the maximum value, then a decline until August, an increase until October and again a decline until January (Fig. 2c). Probably, an increase in the watering of the massif in May, caused by the melting of snow that fell during the winter, affects the growth of seismic activity and leads to a discharge of tectonic stresses accumulated during the period of low watering. After that, the activity decreases, and the massif goes into a state of high watering, which is observed until October. The first half of the time interval from October to May, the period of low watering, (November–January) corresponds to the lowest seismic activity of the massif. It can be assumed that during this period there is an accumulation of tectonic stresses in the rock massif.

To illustrate these processes more clearly, we removed aftershocks from the catalogue using the nearest neighbor method [27]. The application of this method to the mining-induced seismicity of Khibiny Mountains is considered in detail in [1]. Variations in the parameters characterizing background seismicity and watering are shown in Fig. 3. In May, there is a significant (more than $3\sigma$) decrease in the $b$-value (Fig. 3b) and a sharp increase in seismic activity characterized by the $a$-value (Fig. 3c), which indicates the unloading of accumulated stresses caused by a sharp increase in water inflow. The maximum background seismic activity occurs in June and coincides with the maximum of watering. Since July, the water inflow starts to gradually decrease, which is revealed by a gradual increase of the $b$-value. A sharp decrease in background seismic activity ($a$-value, Fig. 3c) in July indicates that the stress accumulated during the low watering has been dropped or redistributed to other parts of the massif. A low level of background seismic activity persists until February, then there is some increase.

In order to more clearly demonstrate the effect of watering on seismicity, we estimated $b$-values during the periods of high (May–October) and low (November–April) watering of the Khibiny massif for all earthquakes (Fig. 4) and for background seismicity (Fig. 5). In both cases, the $b$-values for high watering are significantly less (more than $3\sigma$) than those for low watering (Table 1).

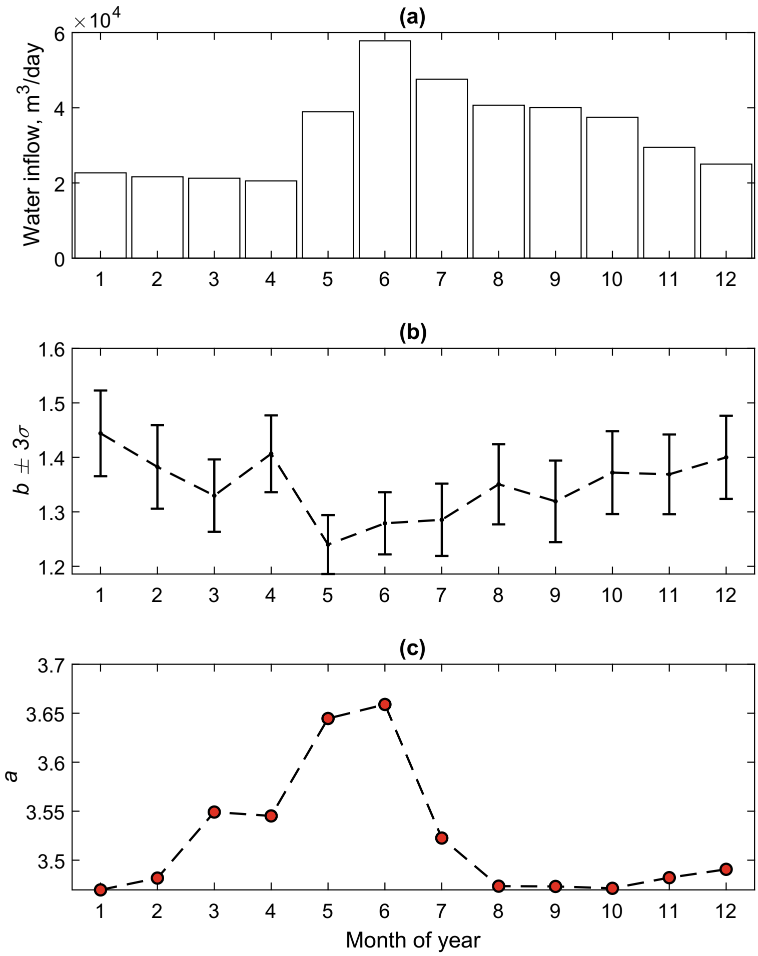


**Fig. 3** Monthly variations in watering and background seismicity at the deposits for the Khibiny massif for 2002–2020: **a**—average water inflow ($m^3$/day); **b**—$b$-values (error bars denote the values of a triple standard error $\pm 3\sigma$); **c**—$a$-values

## 4 Discussion of the Results

The main result of the study is the revealed dependence of the parameters of the mining-induced seismicity of the Khibiny deposits ($a$ and $b$-values) on the change in the level of watering of the medium. As in [19], no explicit delay in the response of seismicity to changes in the water cut of the rock was observed. The monthly variations of the $b$ and $a$-values appear correlated, without evident temporal delay, with monthly water inflow changes. However, we assume that such a delay can be revealed in variations for smaller period (see, e.g. [23, 28]).

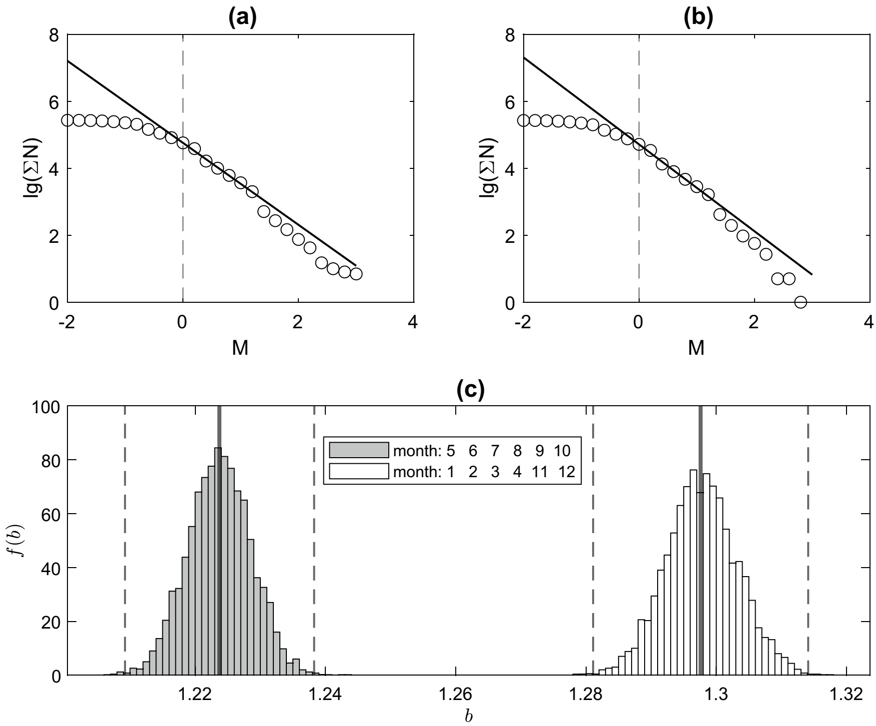


**Fig. 4** Earthquake-size distributions (**a**, **b**) and error distributions of $b$-value estimations (c) calculated for all earthquakes for periods of high (May–October) and low (November–April) watering of the Khibiny massif during 2002–2020. **a**, **b**—Frequency-magnitude plots for the periods of high (**a**) and low (**b**) watering: circles denote actual data; each dashed vertical line is the magnitude of completeness $M_c = 0$; each solid line is the approximation with the expression (1) for $b = 1.22$ (high watering), $b = 1.30$ (low watering). **c**—error distributions for estimation of the $b$-values for the periods of high and low watering: bars are empirical probability density function of error; vertical solid lines are estimations of $b$-values; dotted lines are $b \pm 3\sigma$, where $\sigma$ is a standard error (for high watering $3\sigma = 0.014$, for the low one $3\sigma = 0.017$)

It is necessary to explain how water penetrates into the solid rock mass, which is characterized by reduced water saturation. The feature of the deposits of the Khibiny massif, in addition to the high level of horizontal tectonic stresses and fragile high-strength rocks, is the presence of fault structures filled mainly with oxidized loose rocks [17]. Such loose rocks during the period of snowmelt and rain become actually moisture-saturated aggregate, thanks to which there is an unimpeded displacement of massive blocks relative to each other, since the value of the cohesion of rocks at the block-fault boundary actually becomes close to (and in some cases equal to) zero. This kind of displacement leads to the release of significant seismic energy. Attenuation surfaces in the rock massif, represented by zones of oxidation of rocks, zones of cracking and other inhomogeneities of the environment, significantly reduce the strength characteristics of the rock, which creates conditions for realization of

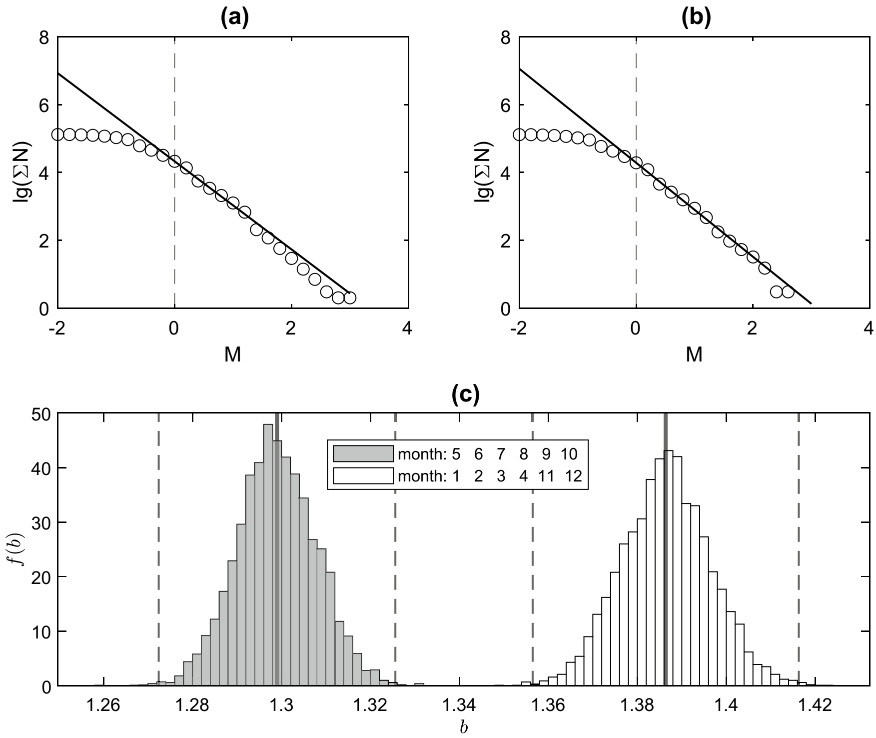


**Fig. 5** Earthquake-size distributions (**a**, **b**) and error distributions of $b$-value estimations (c) calculated for background earthquakes for the periods of high (May–October) and low (November–April) watering of the Khibiny massif during 2002–2020. **a**, **b**—Frequency-magnitude plots for the periods of high (**a**) and low (**b**) watering: circles denote actual data; each dashed vertical line is the magnitude of completeness $M_c = 0$; each solid line is the approximation with the expression (1) for $b$ = 1.30 (high watering), $b = 1.39$ (low watering). **c**—error distributions for estimation of the $b$-values for the periods of high and low watering: bars are empirical probability density function of error; vertical solid lines are estimations of $b$ values; dotted lines are $b \pm 3\sigma$, where $\sigma$ is a standard error (for high watering $3\sigma = 0.027$, for the low one $3\sigma = 0.030$)

mining-induced earthquakes [3]. The reason for this is the increase in pore pressure caused by an increase in the watering of the medium, since the higher the pore pressure, the lower the shear strength of the rocks [25]. In addition, mining operations have changed the relief of the surface part of the mountain range and revealed many tectonic disturbances, which contributes to the unimpeded penetration of atmospheric waters deep into the rock massif [14]. In this regard, the physical and mechanical properties of the rocks of the massif change and the probability of movement of blocks through geological structures increases, which is expressed in an increase in seismic activity, characterized by the $a$-value of the Gutenberg-Richter law.

The physical mechanism of this phenomenon can be described using the Coulomb failure criterion (see, for example, [21])

**Table 1** Estimation of $b$-values and standard errors ($\sigma$) calculated for high and low watering using data on all and background seismicity of Khibiny Mountains deposits for 200–2020 ($N(M \geq M_c)$ is the number of earthquakes with $M \geq Mc$)

| Watering | All earthquakes | | Background earthquakes | |
|---|---|---|---|---|
| | $N(M \geq M_c)$ | $b \pm 3\sigma$ | $N(M \geq M_c)$ | $b \pm 3\sigma$ |
| Low watering (November–April) | 51769 | $1.30 \pm 0.017$ | 19161 | $1.39 \pm 0.030$ |
| High watering (May–October) | 57370 | $1.22 \pm 0.014$ | 21211 | $1.30 \pm 0.027$ |

$$\sigma_f = \tau_\beta - \mu(\sigma_\beta - p), \tag{3}$$

where $\sigma_f$ is the critical stress at which the fracture occurs (Coulomb strength); $\tau_\beta$ is the tangential stress in the direction of motion on the fracture plane; $\sigma_\beta$ is the normal stress; $p$ is the pore pressure of the liquid; $\mu$ is the friction coefficient. During periods of increased watering at the block-fault boundaries, there is a decrease in the friction coefficient and an increase in pore pressure, which, according to the Coulomb criterion (3), leads to a decrease in Coulomb strength and increases the probability of movement.

The $b$-value of the Gutenberg-Richter law determines the proportion of strong and weak seismic events. With a decrease (increase) of $b$, the proportion of strong events increases (decreases). The observed decrease in the values of the $b$ during the period of high watering corresponds to the enlargement of earthquake sources, which can be explained by the effect of dilatancy of cracks under the influence of additional pore pressure [2]. This effect is observed for water-saturated rocks with low Poisson ratios (less than 0.23). According to [11, 30], the main seismic activity in the fields of the Khibiny massif is concentrated in the enclosing rocks, which have a Poisson ratio of 0.2 [12].

The effect of pore pressure growth on acoustic emission and the values of $b$ was also observed in laboratory experiments on initiating rock fracture by fluids. After increasing the pore pressure, the value of $b$ decreases significantly, while the acoustic emission increases [10]. This behavior, which corresponds to the scenario of coalescence and growth of cracks, is known as the formation of an avalanche-unstable fracture.

## 5 Conclusion

The paper considered the influence of the rock watering on the seismic regime of the deposits of the Khibiny massif. According to the data of long-term observations a statistically significant decrease in the slope of earthquake-size distribution ($b$-value) and an increase in seismic activity ($a$-value) during the period of high watering in the rocks of the deposits were established. This phenomena can be explained by a decrease in the strength of rocks and the dilatancy of cracks due to the additional pore pressure. The dependence of the parameters of the Gutenberg-Richter law on the level of watering should be taken into account when assessing the rockburst hazard during mining operations at the deposits of the Khibiny massif.

**Financing** The research was supported by the Russian Science Foundation, Project No. 22-27-20125.

## References

1. Baranov, S.V., Zhukova, S.A., Korchak, P.A., Shebalin, P.N.: Productivity of mining-induced seismicity. Izvestiya, Physics of the Solid Earth **56**(3), 326–336 (2020). https://doi.org/10.1134/S1069351320030015
2. Costain, J.K.: Groundwater recharge as the trigger of naturally occurring intraplate earthquakes. Geological Society, London, Special Publications **432**(1), 91–118 (2017). https://doi.org/10.1144/SP432.9
3. Fedotova, I., Kozyrev, A., Yunga, S.: Mine-induced seismicity in the central part Kola Peninsula in Russia, contribution of rock mechanics to the new century. In: Proceedings of the ISRM International Symposium: Third Asian Rock Mechanics Symposium, Kyoto, Japan, Nov (2004)
4. Fluid injection for rockburst control in deep mining, *U.S. Rock Mechanics/Geomechanics Symposium*, vol. All Days (1992). ARMA-92-0111
5. Gibowicz, S.J., Lasocki, S.: Seismicity induced by mining: Ten years later. Advances in Geophysics, 44, 39–181. (2001). https://doi.org/10.1016/S0065-2687(00)80007-2
6. Gutenberg, B., Richter, C.F.: Frequency of earthquakes in California. Bulletin of the Seismological Society of America **34**(4), 185–188 (1944). https://doi.org/10.1785/BSSA0340040185
7. Hainzl, S., Ben-Zion, Y., Cattania, C., Wassermann, J.: Testing atmospheric and tidal earthquake triggering at Mt. Hochstaufen, Germany. Journal of Geophysical Research: Solid Earth **118**(10), 5442–5452 (2013). https://doi.org/10.1002/jgrb.50387
8. Hainzl, S., Kraft, T., Wassermann, J., Igel, H., Schmedes, E.: Evidence for rainfall-triggered earthquake activity. Geophysical Research Letters **33**(19) L19303 (2006). https://doi.org/10.1029/2006GL027642
9. Heinicke, J., Woith, H., Alexandrakis, C., Buske, S., Telesca, L.: Can hydroseismicity explain recurring earthquake swarms in NW-Bohemia? Geophysical Journal International **212**(1), 211–228 (2017). https://doi.org/10.1093/gji/ggx412
10. Kartseva, T., Smirnov, V., Patonin, A., Sergeev, D., Shikhova, N., Ponomarev, A., Stroganova, S., Mikhailov, V.: Initiation of rock fracture by fluids of different viscosities. Izvestiya, Physics of the Solid Earth **58**(4), 576–590 (2022). https://doi.org/10.1134/S106935132204005X
11. Korchak, P., Zhukova, S., Menshikov, P.: Formation and development of the monitoring system for seismic processes in the production area of JSC "Apatit". Gornyi Journal (10), 42–46 (2014)
12. Kozyrev, A., Semenova, I., Zemtsovskiy, A.: The variants of advanced unloading zone creation on the deep levels of the kukisvumchorr deposit. Mining informational and analytical bulletin (4), 231–245 (2016). In Russian.
13. Kozyrev, A., Semenova, I., Zemtsovskiy, A.: Investigation of geomechanical features of the rock mass in mining of two contiguous deposits under tectonic stresses. Procedia Engineering **191**, 324–331 (2017). https://doi.org/10.1016/j.proeng.2017.05.188. ISRM European Rock Mechanics Symposium EUROCK 2017

14. Kozyrev, A., Zhukova, S., A.S., B.: Influence of water content on seismic activity of rocks mass in apatite mining in Khibiny. Gornyi Journal (1), 31–36 (2021). https://doi.org/10.17580/gzh.2021.01.06
15. Marzocchi, W., Sandri, L.: A review and new insights on the estimation of the *b*-value and its uncertainty. Annals of Geophysics **46** (2003). https://doi.org/10.4401/ag-3472
16. Maystrenko, Y.P., Bronner, M., Olesen, O., Saloranta, T.M., Slagstad, T.: Atmospheric precipitation and anomalous upper mantle in relation to intraplate seismicity in Norway. Tectonics **39**(9), e2020TC006070 (2020). https://doi.org/10.1029/2020TC006070
17. Onokhin, F.: Particularities of the structures of the Khibiny massif and apatite-nepheline deposits. Nauka (1975). In Russian
18. Phosphate segment upstream. https://ar2019.phosagro.com/strategic-report/operational-review/phosphate-segment-upstream?ysclid=l9qtw1t0ao568532121. Last accessed 2022/11/10
19. Pintori, F., Serpelloni, E., Longuevergne, L., Garcia, A., Faenza, L., D'Alberto, L., Gualandi, A., Belardinelli, M.E.: Mechanical response of shallow crust to groundwater storage variations: Inferences from deformation and seismic observations in the Eastern Southern Alps, Italy. Journal of Geophysical Research: Solid Earth **126**(2), e2020JB020586 (2021). https://doi.org/10.1029/2020JB020586
20. Renner, J., Steeb, H.: Modeling of Fluid Transport in Geothermal Research, pp. 1–55. Springer Berlin Heidelberg, Berlin, Heidelberg (2020). https://doi.org/10.1007/978-3-642-27793-1_81-2
21. Scholz, C.H.: The Mechanics of Earthquakes and Faulting, 3 edn. Cambridge University Press (2019). https://doi.org/10.1017/9781316681473
22. Smirnov, V., Ponomarev, A.: Physics of transient regimes. Russian Academy of Sciences (2020). In Russian.
23. Smirnov, V., Potanina, M., Kartseva, T., Ponomarev, A., Patonin, A., Mikhailov, V., Sergeev, D.: Seasonal variations in the b-value of the reservoir-triggered seismicity in the koyna–warna region, western india. Izvestiya, Physics of the Solid Earth **58**(3), 364–378 (2022). https://doi.org/10.1134/S1069351322030077
24. Talwani, P.: On the nature of reservoir-induced seismicity. Pure and applied geophysics **150**(3), 473–492 (1997). https://doi.org/10.1007/s000240050089
25. Terzaghi, K., Peck, R.B., Mesri, G.: Soil mechanics in engineering practice. John Wiley & Sons (1996)
26. Utsu, T.: A statistical significance test of the difference in b-value between two earthquake groups. Journal of Physics of the Earth **14**(2), 37–40 (1966). https://doi.org/10.4294/jpe1952.14.37
27. Zaliapin, I., Ben-Zion, Y.: A global classification and characterization of earthquake clusters. Geophysical Journal International **207**(1), 608–634 (2016). https://doi.org/10.1093/gji/ggw300
28. Zhang, L., Liao, W., Chen, Z., Li, J., Yao, Y., Tong, G., Zhao, Y., Zhou, Z.: Variations in seismic parameters for the earthquakes during loading and unloading periods in the three gorges reservoir area. Scientific Reports **12**(1), 11211 (2022). https://doi.org/10.1038/s41598-022-15362-9
29. Zhukova, S.: The relationship of hydrogeological situation and activization of seismic activity on apatite circus deposit and Rasvumchorr deposit. Mining informational and analytical bulletin (scientific and technical journal) (1), 319–329 (2015). In Russian.
30. Zhukova, S., Zhuravleva, O., Onuprienko, V., Streshnev, A.: Seismic behavior of rock mass in mining rockburst-hazardous deposits in the khibiny massif. Mining informational and analytical bulletin (7), 5–17 (2022). https://doi.org/10.25018/0236_1493_2022_7_0_5. In Russian.
31. Zoback, M.D., Harjes, H.P.: Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany. Journal of Geophysical Research: Solid Earth **102**(B8), 18,477–18,491 (1997). https://doi.org/10.1029/96JB02814