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SEISMIC PRODUCTIVITY OF BLASTS: A CASE-STUDY OF THE KHIBINY MASSIF

The authors study the property of production-scale blasts to induce seismic events classified as micro shocks, rock bursts and earthquakes caused by sudden slips along faults. The study area is the production performance zone of Apatit's Kirovsk Branch. It is situated in the south-east of the Khibiny Massif on the Kola Peninsula and is subjected to continuous autonomous seismicity monitoring. The subject of the research is the production blasts and seismic events recorded by the seismic monitoring station of Apatit's Kirovsk Branch between January 1996 and June 2019. Blasting-induced seismic events were identified using the nearest neighbor method and the seismicity-dependent proximity function of the space—time—magnitude (energy), calculated with respect to the blasts. The threshold of the proximity function to assume a seismic event as the blast-induced event was selected using the model-independent method of seismic catalog randomization. It is shown that the number of blasting-induced seismic events—blasting productivity—obeys an exponential distribution irrespective of magnitudes or occurrence depths of the studied events. The obtained result conforms with the earlier determined productivity law for natural earthquakes on a global and regional scale, as well as for mining-induced seismicity in the Khibiny Massif. Accordingly, the productivity distribution is governed by the properties of a medium and is independent of the source mechanism of a triggering event (explosion, seismicity).

Keywords: *production blasts, triggers, seismic events, productivity, exponential distribution, Khibiny Massif.*

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Introduction

Mining-induced seismicity in high-stress rock masses results in disastrous seismic events such as overlying rock collapse, rock bursts and manmade earthquakes. Such events are associated with great noise and various phenomena. Operating underground mines subjected to high confining pressure experience discontinuities in the adjacent rock mass in the form of spalling, extensile fracturing, micro shocks and rock bursts [1].

Blasting increases energy of seismic processes and, consequently, alters the seismic behavior in an area [2], particularly, in the areas of low seismicity. Regarding the East European Platform or Baltic Shield, for instance, the seismic energy of blasts exceeds the energy of tectonic earthquakes by a few orders of magnitude [3].

The effect generated by blasting on seismicity can be of two kinds: long-term impact due to softening of faults as a consequence of blasting [4] and short-term impact in the form of increased seismicity for a certain time and in a certain vicinity of the hypocenter [5–9]. The latter effect is similar to the main shock–aftershocks pattern, with explosion to play the role of the main shock [6, 7], and attenuation of seismicity with time proceeds in accordance with the Omori–Utsu law [10, 11]. As with aftershocks of tectonic earthquakes, blasting-induced seismic events constitute an individual threat. Apatite ore mining technologies including regular and high-scale mass blasts govern seismicity in the form of aftershock sequences [1]. For this reason, some mines attempt to try to reduce seismic risk and suspend actual mining operations in a close-spaced vicinity of seismic hypocenters, including in the post-blasting period [10, 11]. For example, at Apatit's Kirovsk Branch, after large-scale explosions, detection procedure of premonitory sings and indicators of strong seismic events is launched, and in case of their detection, the first hazard level is announced [1]. People and machines are immediately evacuated from the hazardous zone until the threat is removed. Accordingly, seismic emission analysis of high-stress rock mass, or seismic hazard assessment should consider explosions as potential triggers.

In the hazard analysis of blasting-induced shocks as with aftershocks of tectonic earthquakes, the critical characteristic is productivity, or the expected number of the induced events with magnitude higher than a preset value. This value is one of the parameters which govern both magnitude of the strongest repeated shock [12] and duration of the hazardous period [13].

The present paper authors have earlier found that productivity of tectonic earthquakes features an exponential distribution on a global and regional scale [13]. The result is analogues for the mining-induced seismicity in the Khibiny Massif [14].

This research aims to show that the blasting-induced seismic events also feature an exponential distribution. This allows a statement that productivity is governed by the properties of a medium and is independent of the trigger mechanism (explosion, seismic event).

The Khibiny Alkaline Massif in the center of the Kola Peninsula represents a large and high-stress alkaline Paleozoic intrusion composed of various tectonic structures [15]. The Khibiny Massif holds apatite–nepheline ore bodies which are developed by Apatit's Kirovsk Branch and North-Western Phosphorus Company by underground and surface mines.

Source data

We studied the data on different-scale blasts carried out in headings and excavations in Kirovsk and Rasvumchorr mines of Apatit's Kirovsk Branch in 1996–2019, as well as catalogs of seismic events with energy $E \geq 10^4$ J recorded by the seismic monitoring network of Apatit's Kirovsk Branch in the same period. The network is composed of 50 three-component seismic sensors arranged in Kirovsk and Rasvumchorr mines and performing recording at sampling frequency of 1000 Hz. The monitoring network identifies hypocenters of seismic events with an energy from $E = 10^3$ J within an accuracy of 25 m in the high precision region and to 100 m in the confident recording region.

During the seismic data processing, we calculated energy of explosions and seismic events similarly. Then, the energy was converted to the magnitude using Rautian's formula [16]: $\lg E(\mathrm{J}) = 1.8M + 4$.

Since 1998 the catalog of seismic events is assumed as representative starting from the magnitude $M_s = 0$, which corresponds to the energy $E_s = 10^4$ J.

Identification of blasting-induced seismic events

The further analysis assumes that each blast can induce a few seismic events but each event can only be initiated by one specific explosion. In this case, productivity of an explosion is taken to be as the number of events induced by this blast–trigger. The count included induced events η_{ij} with magnitude higher than a certain threshold. The relationship between the blasts and seismic events was determined by the nearest neighbor analysis [17] and using the natural modification of the proximity function [18] on the space–time–magnitude scale:

$$\eta_{ij} = \begin{cases} t_{ij}(r_{ij})^{d_f} 10^{-bm_i}, & t_{ij} > 0, \\ +\infty, & t_{ij} \leq 0, \end{cases} \quad (1)$$

where $t_{ij} = t_j - t_i$ is the time span between a j-th event and an i-th blast, which is positive if the j-th event occurs after the i-th blast and is otherwise negative; $r_{ij} \geq 0$ is the distance between the hypocenters of the blast and event; m_i is the magnitude of the i-th blast; b is the Gutenberg–Richter parameter assessed from the catalog of seismic events; d_f is the fractal dimensionality of distribution of hypocenters of the events, determined using the cell count method.

For each seismic event from the catalog, the nearest blast is identified by the minimum of the proximity function from all preceding blasts. If the target value of the proximity function exceeds the preset threshold η_0, the link is broken, and the event is assumed to have no an 'ancestor' (i.e. it is uninitiated by blasting). Alternatively, the connection is preserved and the event is assumed as blast-induced.

There exist various techniques to find the threshold η_0 [13, 17, 19] by declustering of catalogs of tectonic earthquakes. The present authors use the model-independent method [13], preferable in case of induced seismicity. The method consists in decomposing the distribution of distances to the nearest blast, $F_{\mathrm{real}}(\eta)$, in the real catalog into two parts:

$$F_{\mathrm{real}}(\eta) = (1 - \kappa)F_{\mathrm{clustered}}(\eta) + \kappa F_{\mathrm{random}}(\eta), \quad (2)$$

where $F_{\mathrm{random}}(\eta)$ reproduces the distribution of distances from the blasts for individual (non-clustered) seismic events from a randomized catalog (the hypocenter and magnitude are taken from the catalog for each time of event at a random fashion); $F_{\mathrm{clustered}}(\eta)$ is the distribution for clustered (blast-induced) events; the weight κ is found from the best coincidence of the densities $\kappa p_{\mathrm{random}}(\eta)$ and $p_{\mathrm{real}}(\eta)$. Curves *1* and *2* in **Figs. 1a and 1b** depict the clustered and random components, respectively.

The threshold η_0 is evaluated as η such that the fraction of clustered events with the nearest neighbors $\eta > \eta_0$ (error order I) is equal to the fraction of non-clustered events with the nearest neighbors $\eta \leq \eta_0$ (error order II) (**Fig. 1**):

$$1 - F_{\mathrm{clustered}}(\eta_0) = 1 - [F_{\mathrm{real}}(\eta_0) - \kappa F_{\mathrm{random}}(\eta_0)]/(1 - \kappa) = F_{\mathrm{random}}(\eta_0). \quad (3)$$

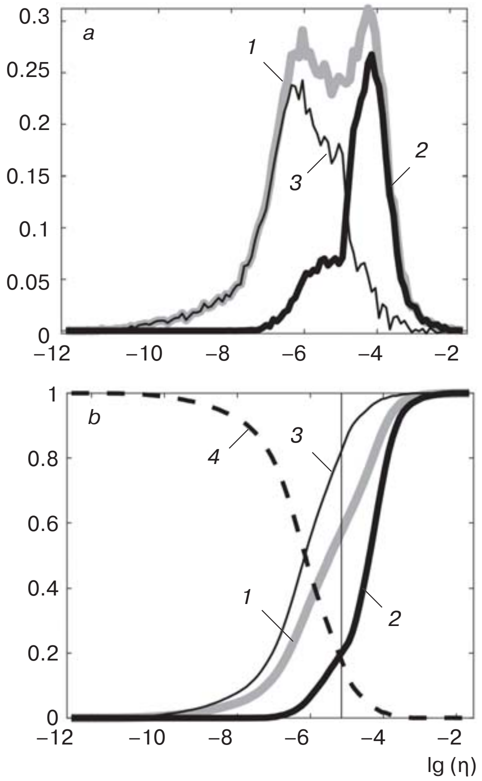

Fig. 1. Determination of threshold η_0 for proximity function η (1) at $M \geq 0$:
(a) probability distribution of proximity function (1) for the nearest neighbors in real catalog $p_{real}(\eta)$ (curve *1*) and its decomposition into two components (formula (3)): κp_{random}(curve *2*) and (1–κ) $p_{clustered} = p_{real} - \kappa p_{random}$ (curve *3*). Description of randomized catalog generation is given in the text;
(b) determination of threshold η_0: distribution functions F_{real} (curve *1*), F_{random} (curve *2*), $F_{clustered}$ (curve *3*) and component $1-F_{clustered}$ (curve *4*). Threshold η_0 is the intersection of F_{random} and $1-F_{clustered}$ (vertical straight line).

Figure 1 illustrates this approach in terms of the source data and proximity function (1). The empirical probability distribution of (h) (**Fig. 1a**) has two maximums, which is indicative of good discriminability of the blast-induced and independent seismic events. The events spaced from the nearest explosions at the distances smaller than the value h_0 are assumed as the blast-induced events, the other events are directly unrelated with blasting.

Calculation results

In the test catalog, over the period from Jan 1996 to Jun 2019, 2181 blasts with magnitude $M_t \geq 2$ ($E \geq 4´10^7$ J) were identified as triggers. They were associated with 5793 induced seismic events having magnitudes $M \geq M_t - \Delta M$, where $\Delta M = 2$ is a relative threshold. The representative magnitude in the catalog is $M_s = 0$, thus, the use of the relative threshold above is correct. The distribution of the induced events together with the exponential distribution and Poisson's distribution at the same parameter $\Lambda_2 = 5793/2181 = 2.7$ is shown in **Fig. 2.** From the comparison of the empirical and theoretical distributions, the productivity complies with the exponential distribution having density:

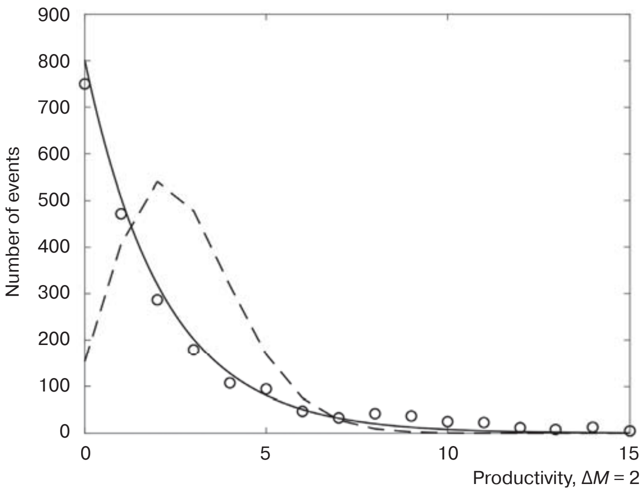

Fig. 2. Distribution of seismic events with $M \geq M$t – ΔM, $\Delta M = 2$ initiated by blasts with Mt ≥ 2 (circles). Solid curve is the exponential distribution approximation. Dashed curve is Poisson's distribution.

Parameters of proximity function (1), threshold η and average earthquake productivity ΛΔM at $\Delta M = 2$ for blast–trigger magnitude Mt ≥ 2

Time span	*b*	*df*	κ	$10^{-6}\eta_0$	Λ_2
Jan 1996–Jun 2019	1.25	1.50	0.4	5.62	2.7

$$f(x) = \frac{1}{\Lambda_{\Delta M}} e^{-x/\Lambda_{\Delta M}}, \quad (5)$$

where $\Lambda_{\Delta M}$ is a distribution parameter equal to the average number of induced events with magnitude $M \geq M_t - \Delta M$. The same distribution was earlier obtained by the authors for the tectonic earthquakes on a global and regional scale [13], as well as for the induced seismicity in Khibiny [14]. It is worthy of mentioning a common though erroneous assumption [20–22] that productivity of earthquakes obeys Poisson's distribution.

The major difference between the exponential distribution and Poisson's distribution is the maximum at zero: this means that it is most likely that blasting-induced events are zero while Poisson's distribution at average >1 has a distinct non-zero mode and a maximum nearby the average. The parameters of proximity function (1) obtained by the authors are given in the **table**.

The productivity distribution is exponential in different ranges of magnitudes of blasts–triggers (**Figs. 3a and 3b**). The distribution parameter Λ_2 diminishes with increasing M_t (**Fig. 3a**). When M_t = 1.5–2.4 $\Lambda_{1.5}$ is the same (these curves are nearly parallel in **Fig. 3b**), whereas when $M_t \geq 2.4$ $\Lambda_{1.5}$ decreases as the blast–trigger magnitude grows. That is the difference from the productivity of earthquakes when $\Lambda\Delta_M$ is independent of the magnitudes of the triggering events [13]. The matter is that magnitudes of explosions and earthquakes are inequivalent owing to different mechanisms of energy release. A blast has no shear component.

The productivity distribution remains exponential as the threshold magnitude ΔM changes from 2 to 1 (**Fig. 3c**). As

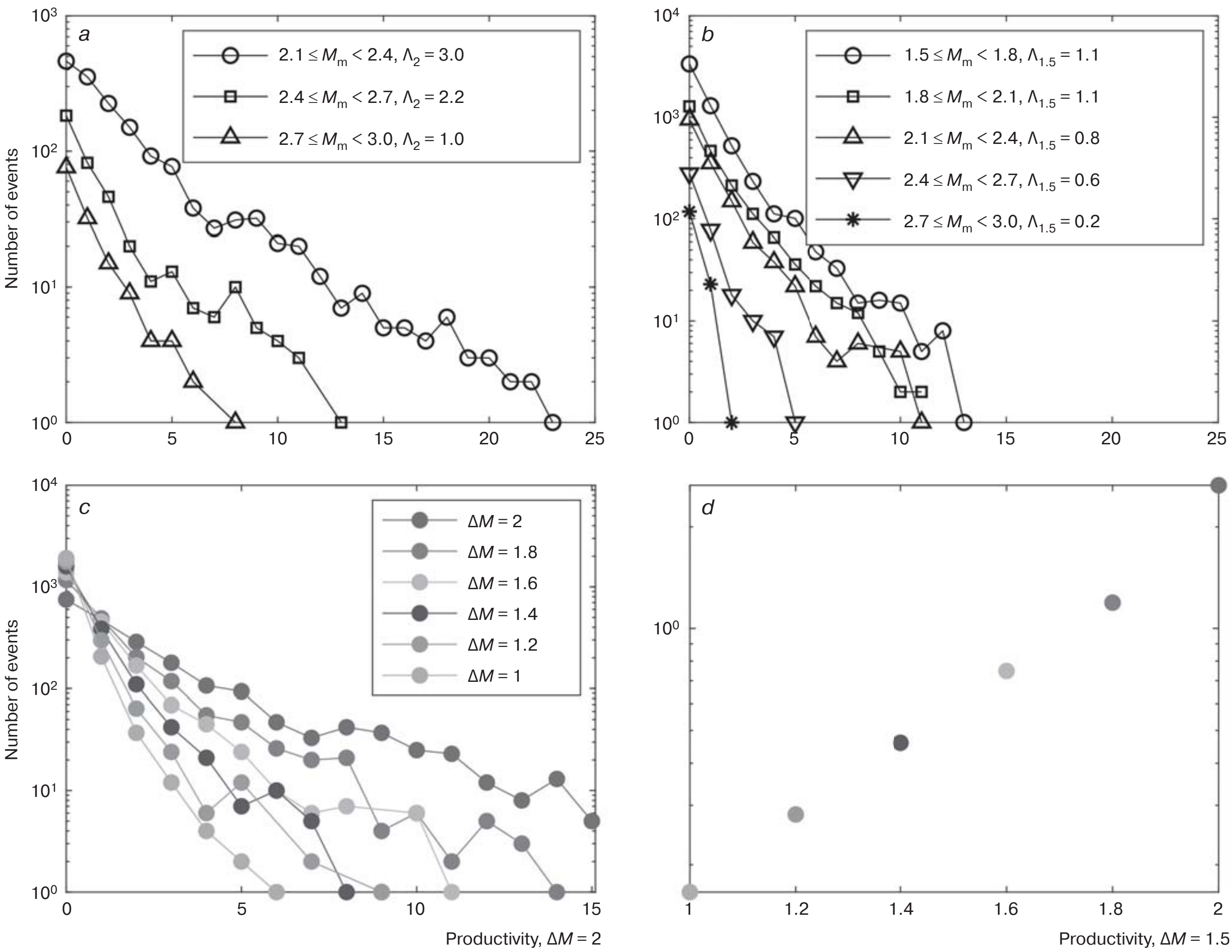

Fig. 3. Magnitude–productivity relationship for blasts:
(*a*), (*b*) productivities at different magnitudes *M*t of blasts–triggers at $\Delta M = 2$ and $M = 1.5$, respectively; (*c*) distribution of induced events having $M \ge M$t – ΔM when $\Delta M = 1, 1.2, ..., 2$, induced by blasts–triggers with *M*t ≥ 2; (*d*) number of induced seismic events as function of ΔM

expected, the average values of $\Lambda\Delta_M$ decrease subject to *b*, which is the distribution of magnitudes of seismic events (**Fig. 3d**). Accordingly, the exponential distribution of productivity can be assumed as a general property of seismic events in the Khibiny Massif irrespective of strength and source mechanism (explosion, seismicity).

It can be supposed that by analogy with productivity of tectonic [13] and induced seismicity [14], productivity of blasts depends on the occurrence depth (altitude) of the sources. **Figure 4** demonstrates the blasting productivity distribution at different altitudes of blasts–triggers. The calculations reveal variation in Λ_2 with varying height from –500 to 1000 m starting from the Kronstadt Sea Gauge. The shape of an exponential graph is preserved at various occurrence depths of the triggering events, characterized by various values of lithostatic pressure and horizontal stresses, as well as by different intensity of mining and cleavage cracking in overlying rocks [23].

Discussion and outcomes

The main result of the accomplished research is the found exponential distribution of blasting-induced seismic events –blasting productivity. The shape of the exponential function is independent of the magnitudes and source depths of the blasts, as well as of the magnitudes of the induced events. The same distribution was earlier obtained for the productivity of tectonic earthquakes on a global and regional scale [13], and for the mining-induced seismic events in the Khibiny Massif [14]. Thus, the distribution of the triggered events is governed by the properties of the medium and is independent of the mechanism of the trigger (explosion, seismic event).

In case when the blast–trigger magnitude $M_t \ge 2$ ($E \ge 4´10^7$ J), the average number of the induced events with magnitudes $M \ge M_t - \Delta M(\Delta M = 2)$ is 2.7 (See the **table**). From calculations for the seismic events–triggers by analogy with [13, 14], their productivity is 7.3, i.e. 2.7 times higher; at $M_t \ge 1.5$, $\Delta M = 1.5$ productivity of seismic events also exceeds productivity of blasts by 2.7 times.

The question then arises as to why blasting initiates less seismicity than seismic events of the same magnitude. Partly, because of the different mechanisms of blasts and seismic events, which leads to the inequivalence of their magnitudes. On the other hands, for a seismic event–trigger with $M \ge 2$ to

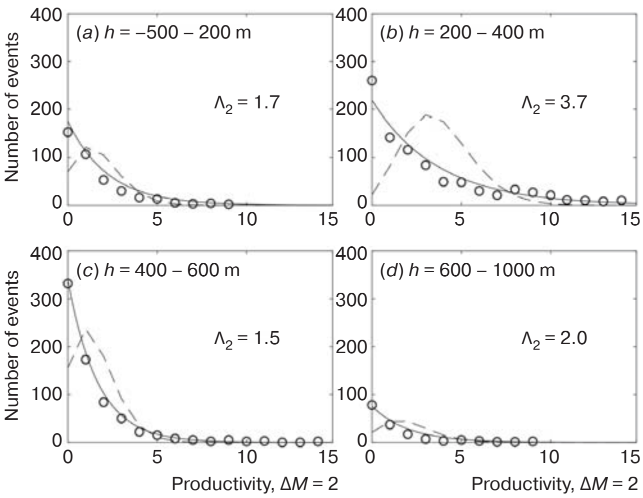

Fig. 4. Blasting productivity in different ranges of altitude in the Khibiny Massif. Distributions of induced seismic events with $M \geq M$t – ΔM, $\Delta M = 2$, initiated by blasts–triggers with Mt ≥ 2 (circles) at different altitudes h.
Solid curve is the exponential distribution approximation with Λ_2. Dashed curve is Poisson's distribution.

be initiated, it is required that stresses concentrate in a certain region, then relax and cause repeated events. Blasting is performed on a regular basis, and stress relaxation takes place at a lower level of stresses. As with explosion, a seismic event drives up repeated events which would occur any way though a little bit later. In the latter case, the repeated events will be more in number, and probability of a higher energy shock is accordingly higher [13, 24]. This property of repeated events is an additional reason for the destressing blasting in stress concentration areas to reduce probability of strong seismic events.

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