



Seismic Activity in the Focus of the Ulegorsk Earthquakes, Sakhalin Island, Related to Intensive Development of Coal Deposits

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Abstract—Induced seismicity is an increase in seismic activity caused by human engineering. Examples of such activity include mineral exploration, large water reservoir construction, and exploitation of underground oil and gas storage. The authors studied the seismicity in the Ulegorsky district of the Sakhalin region, where the Solntsevskoye brown coal field is located, which is the most promising on the island. Its area is over 100 km², and productive strata of the Verkhneduiskaya formation with a thickness of up to 600 m contain 12 coal seams, eight of which are working. Active mining of brown coal is carried out at the Solntsevsky coal mine, and blasting operations are performed on a large scale, which therefore does not exclude the relation between seismic processes and anthropogenic seismicity. Earthquake recurrence curves for two decades beginning from 2000 to the present were constructed in this work to compare the characteristics of the seismic regime in the study area. The difference in the slope angle of the recurrence graph during the period of 2011–2020 (the period of the most active development of the Solntsevsky coal mine) relative to the previous decade is quite significant. Maps of the spatiotemporal distribution of seismic event epicenters in the vicinity of Solntsevsky coal mine were constructed, and contraction of zones of seismic event concentration to the mining areas, first of all to the Solntsevsky coal mine, was found. Such a combination allows us to note an increase in seismicity in the region during the past few years and a change in its character from natural to mixed natural and technogenic. The focal mechanisms of the largest earthquakes occurring in the Ulegorsky district were constructed in order to confirm the change in the nature of the seismicity and reasons for earthquake occurrence in the study area. The mechanisms of seismic events of 2020 were classified as strike-slip faults, which is not characteristic of most earthquakes in the territory of Sakhalin Island. The authors made an attempt to determine the regularities of the parameters of the produced blasts and earthquakes through dynamic parameters of the seismic event foci by studying the frequency content of earthquakes and blasts in order to determine a corner frequency from the focal velocity spectrum.

Keywords: Earthquakes, induced seismicity, anthropogenic impact, earthquake focal mechanism, coal fields.

1. Introduction

Induced seismicity, which is defined as an earthquake in any way associated with engineering, is believed to be a manifestation of anthropogenic impacts on the earth's crust. Many works (Adushkin, 2016, 2018; Adushkin & Turuntaev, 2015; Emanov et al., 2014, 2017, 2018, 2019, 2020a; Kochyaryan et al., 2019; Nikolaev, 1994) have confirmed the existence of induced seismicity near mining areas and the absence of an unambiguous relation to the faults (Novikov et al., 2013).

Basically, such earthquakes are weak, but the magnitudes of individual events can reach significant values. The earthquakes associated with the rock extraction in quarries belong to the category of rather rare manifestations of anthropogenic seismicity. Nevertheless, the largest seismic event initiated by mining works was associated just with open-pit coal mining. This earthquake with a magnitude of $M_L = 6.1$ occurred on June 18, 2013, in Kuzbass in the immediate vicinity of the Bachatsky coal mine. Ground motion intensity within the earthquake epicentral zone was 7 points (Emanov et al., 2014, 2017, 2020b).

It is known (Kochyaryan et al., 2019) that the main factors associated with earthquake initiation are the regular impact of industrial blasts on the rock mass with a total charge weight of hundreds of tonnes and a change in the relief due to open mine works, including actual open-pit mines in the form of

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indentations in the relief and dumps in the form of artificial mounded hills. It should be noted that the dumps, which are artificially created soil massifs, have a strong local impact on the earth's crust. The response seismic activation with respect to the shallow depths of the foci (first few kilometers) and confinement to the region can be interpreted as induced seismicity. In fact, we are dealing with the aftereffect of the reaction of the earth's interior to the anthropogenic impact in the form of the rock mass movement.

At the same time, the main part of small seismic events is usually confined directly to the place of mining operations and occurs at the time when major blasts are carried out in coal mines or 1–3 h later (Yakovlev et al., 2013). Another criterion is the depth of anthropogenic earthquakes. Small earthquakes are found to be concentrated under the central part of the open-pit mine, and the largest ones are close to its sides, while the depth of the foci is 3–4 km (Emanov et al., 2014). Thus, coal mining creates a strong anthropogenic impact on the earth's crust, thereby initiating a large-scale process of the development of induced seismicity (Adushkin & Turuntaev, 2015; Emanov et al., 2009).

The mineral reserves of Sakhalin Island are diverse and quite large for certain types. There are more than 50 types of mineral raw materials on Sakhalin, of which the extraction of oil, gas, and hard and brown coal is of prime importance. The active development of the listed minerals is accompanied by a significant impact on the island territory, which has high seismogenic potential. However, while there are separate studies on the anthropogenic impact of the development of oil and gas fields (Kovachev et al., 2018; Nikolaev, 1995; Tikhonov, 2010), the impact of coal field development on the seismicity of production areas remains an unexplored direction for Sakhalin. The motivation for such studies is not only the absence of similar works, but also a significant increase in resource extraction activity. This paper considers the seismicity of the area where coal is mined in order to both identify generally accepted indicators of the anthropogenic response (Dahm et al., 2013) and, if possible, determine new features of the seismic process under the conditions of a sharp

increase in the level of impact on the geological environment.

2. Study Object

The territory of Sakhalin is located in the zone of earthquakes of 8–9 Modified Mercalli Intensity units (MMI) with a recurrence probability of 10% over a period of 50 years according to the maps of general seismic zoning (enacted in 2015) (ed. by Rogozhin, 2015). The hypocenters are located mainly at depths of 5–35 km and associated with the zones of regional faults: West Sakhalin, Central Sakhalin and Hokkaido-Sakhalin. The West Sakhalin fault strikes along the western coast of the island for a distance of more than 600 km and manifests in the form of a system of interlinked normal and reverse faults, accompanied by the faults of the northwestern and northeastern strikes and the systems of conjugated linear anticlines and synclines (Fig. 1). Latitudinal and diagonal normal and reverse faults divide the fault into many sectors. The width of a zone of the near-fault dislocations is up to 20 km. The deep location of the fault is determined by its spatial connection with the magma belt striking along the Sakhalin coast from the village of Ust'-Agnevo in the north to Cape Lamanon in the south (Dymovich et al., 2017). The West Sakhalin fault and the related bed forms are one of the main waveguides in the depths of middle and southern Sakhalin. They create the necessary conditions for the propagation of the deformation front due to the minimum stress dissipation (Saprygin, 2017). Seismic activity of the West Sakhalin fault is rather high. Several earthquakes were observed in its zone with magnitude $M > 5.9$ (Fig. 1): the Lesogorsk-Ulegorsk earthquake in 1924 ($M = 6.8$; 8–9 MMI) (Soloviev et al., 1967) and the Ulegorsk-Ain earthquake in 2000 (moment magnitude $M_w = 7.0$; 9 MMI) (Poplavskaya et al., 2006).

Several crustal earthquakes of $M > 4.5$ with a macroseismic effect have occurred in the study area over the 20 years since the Ulegorsk-Ain earthquake in 2000; for example, the earthquake on February 8, 2003, with local magnitude $M_L = 5.1$ (Fokina et al., 2009). However, a seismic event with $M_L = 4.8$ on September 13, 2020, which occurred in the area of

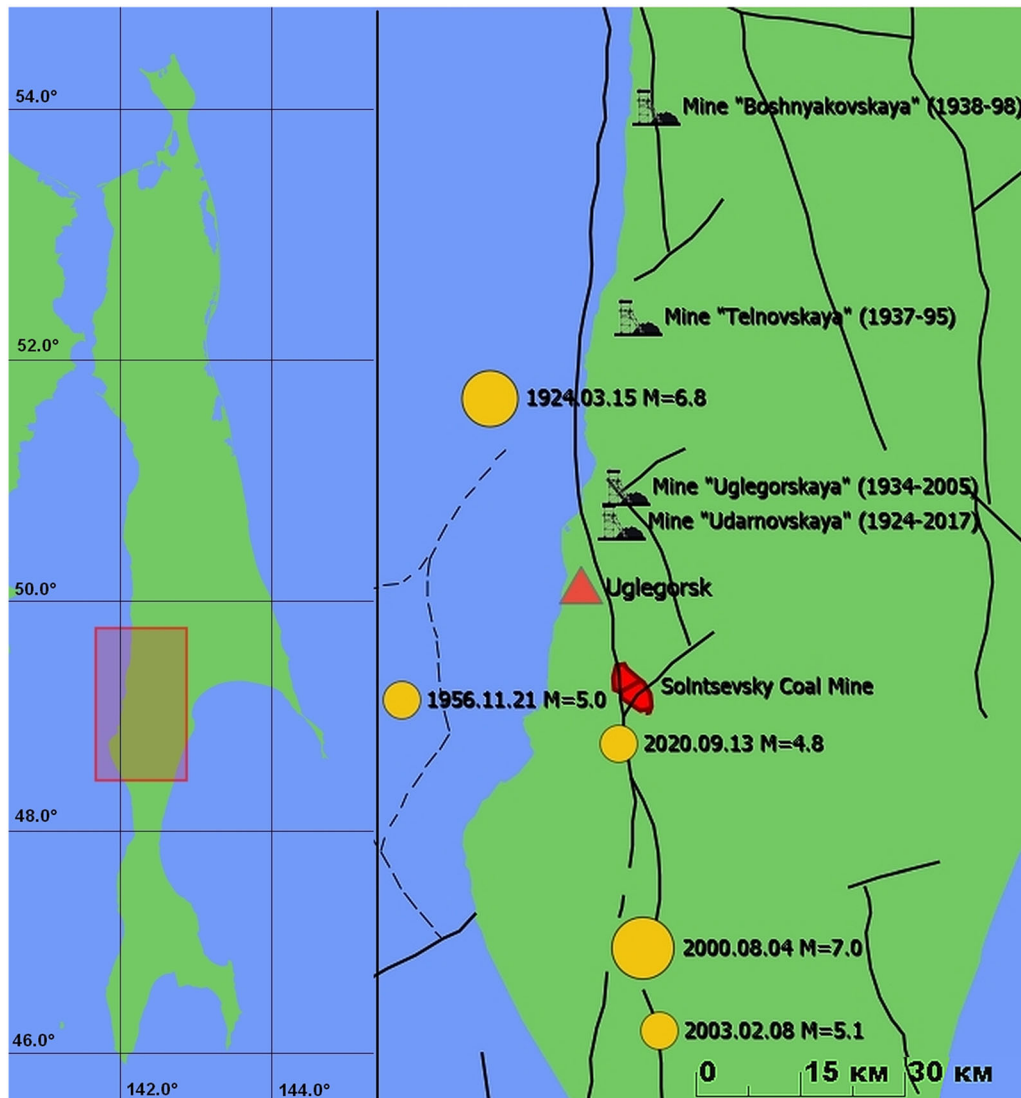


Figure 1

The study area location. On the left: the study area on the map of Sakhalin Island; on the right: tectonic faults (Dymovich et al., 2017). The coal mining areas are highlighted in red and marked with icons, the strongest seismic events in the study area are marked with yellow circles, the Uglegorsk seismic station is marked with a triangle

active development of coal fields, had the greatest resonance (Semenova et al., 2020).

The coal-bearing area of the Uglegorsky district is associated with Paleogene and Neogene sediments. Eight fields are confined to sediments of the Neogene age, including the large developed fields of Boshnyakovskoye, Lesogorskoye, Shakhterskoye (Uglegorskoye), Solntsevskoye and others (Fig. 1). As a rule, all deposits have a complex geological

structure, with steep dip angles, complicated by tectonic faults (Sakhalin region mineral resources, 2013). The study and development of coal resources in the Uglegorsky district of the Sakhalin region began as early as 1860 (Vakulenko, 2004). The coal resources of Sakhalin were most intensively developed in the twentieth century during the Japanese Karafuto governorship in southern Sakhalin, when 15 mines were opened in 11 settlements on the territory

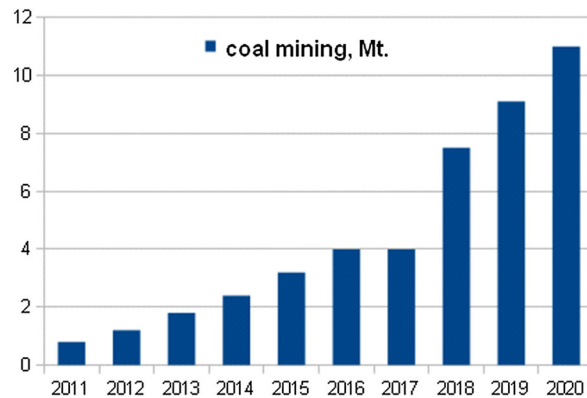


Figure 2

Dynamics of change in the extraction volumes at the Solntsevskoye coal field during the last 10 years

of the modern Ulegorsky district (Masafumi, 2017). Most of them were closed in the middle of the twentieth century, and by the end of the twentieth century, only four mines were still in operation, as the coal industry of Sakhalin was in a deep crisis during the 1990s. Two of them, Tel'novskaya and Boshnyakovo, were closed in 1995 and 1998, respectively (Vakulenko, 2015), and the last two mines, Ulegorskaya and Udarnovskaya, were officially closed in 2005 and 2017, respectively, although coal mining at the Udarnovskaya mine was actually suspended in 2009 (Dorokhina, 2018). The revival began in the early second decade of the twenty-first century, when significant changes in technology took place, with the transfer of coal mining from mines to open pits. Nowadays, the largest coal mining enterprise in the Sakhalin region, which has a full cycle for the extraction and shipment of solid fuel, is East Mining Company Limited (EMCO Ltd), with the affiliated companies Solntsevsky Coal Mine LLC and Coal Sea Port of Shakhtersk LLC, located in Ulegorsky district (Ugol', 2011). The Solntsevskoye brown coal field in the Ulegorsky district of the Sakhalin Region was discovered in the 1980s and had been recognized as the most promising on the island. Its area is over 100 km². Productive strata of the Verhneduiskaya formation, with a thickness of up to 600 m, contain 12 coal seams, eight of which are in operation. However, its potential could not be realized for many years. For example, only 4.4 million tonnes of coal were extracted in total during 1987–2003. The

situation began to change in 2011, when the new owners of the Solntsevsky coal mine launched a large-scale program of the enterprises re-equipment (Fig. 2) (Ugol', 2019). Already in 2012, the miners of EMCO Ltd, which owns the Solntsevsky open-pit mine, managed to increase coal production to 1.2 million tonnes in 2012 and to 1.8 million tonnes in 2013 (Ugol', 2014). Realization of new projects in 2020 allowed EMCO to obtain record levels of extraction and shipment of 11 million tonnes of coal (Ugol', 2021), which is 78% of total coal production in the Sakhalin region. Thus, a radical restructuring of the extraction technologies over the past 20 years is evident. Summarizing these changes in general figures, it can be noted once again that until the middle of the 1990s, the main coal production in Sakhalin in general, and in the Ulegorsky district in particular, was carried out by underground techniques (mines), but already in 2000, the share of open-pit coal mining was 80% (Kovalchuk, 2002), by 2010 it was 94% (Streltsov, 2010), and it has been 100% since 2017, after the closure of the last mine in Sakhalin.

In the context of the foregoing, strong earthquakes associated with movements along faults located in coal mining areas are of particular interest, such as the earthquake with $M_L = 4.8$ that occurred on September 13, 2020 (Semenova et al., 2020) in the immediate vicinity of the Solntsevsky coal mine. The features of this seismic event occurrence will be considered in the sections below.

3. Research Methods and Results

The earthquake catalog of the Sakhalin Branch of Geophysical Survey of the Russian Academy of Sciences (SB GS RAS) from 2000 to 2020 was used (for example, Fokina et al., 2021) to study the change in the seismicity of the area, under the conditions of the intensification of open-pit mining, in a square of 48.4° – 49.4° N and 141.7° – 142.4° E, which includes both tectonically active structures and the territories of closed mines and areas of intensively developed open coal deposits (first of all, the Solntsevsky coal mine).

The ZMAP software suite (Wiemer, 2001) was used to analyze the catalog, by means of which catalog declustering was carried out using the algorithm of Gardner & Knopoff (1974) to exclude the influence of the aftershock sequences of the 2000 and 2020 earthquakes on the recurrence graphs and the maps of epicentral positions for assessing the seismicity.

The results of seismicity change dynamics for the specified area during 20 years, after declustering, are presented in Fig. 3.

It is worth noting the increase in the seismicity of the area in 2012–2013, which coincides with the beginning of active development of the Solntsevsky

Coal Mine and, accordingly, a significant increase in the volume of overburden operations at the open pit during this period. The recurrence graphs were plotted for the first and second decade (during the period of active development of the Solntsevsky coal mine) in order to compare the characteristics of the seismic regime in the study area (Fig. 4). The difference in slope angle of the recurrence graph in the period of 2011–2020 is quite significant. The increase in slope angle means more low-energy earthquakes among the total number of events. According to Emanov et al. (2020) and Yakovlev et al. (2013), such b-values (about 1.0) are typical for anthropogenic activations in areas with induced seismicity. For comparison, the graph on the left (Fig. 4) shows the b-value inherent in natural seismicity.

Studying the change in the spatial distribution of earthquake epicenters in the period of 2000–2010 and 2011–2020 is also of interest (Fig. 5).

As can be seen, the location of the epicenters of seismic events during 2000–2010 (on the left in the figure) is confined mainly to the fault structures, confirming the activity of the Krasnopol'evskiy fault, which is part of the West Sakhalin deep fault, during this period (Prytkov & Vasilenko, 2006). Contraction of the seismic events concentration zones to the mining areas, first of all to the Solntsevsky coal mine

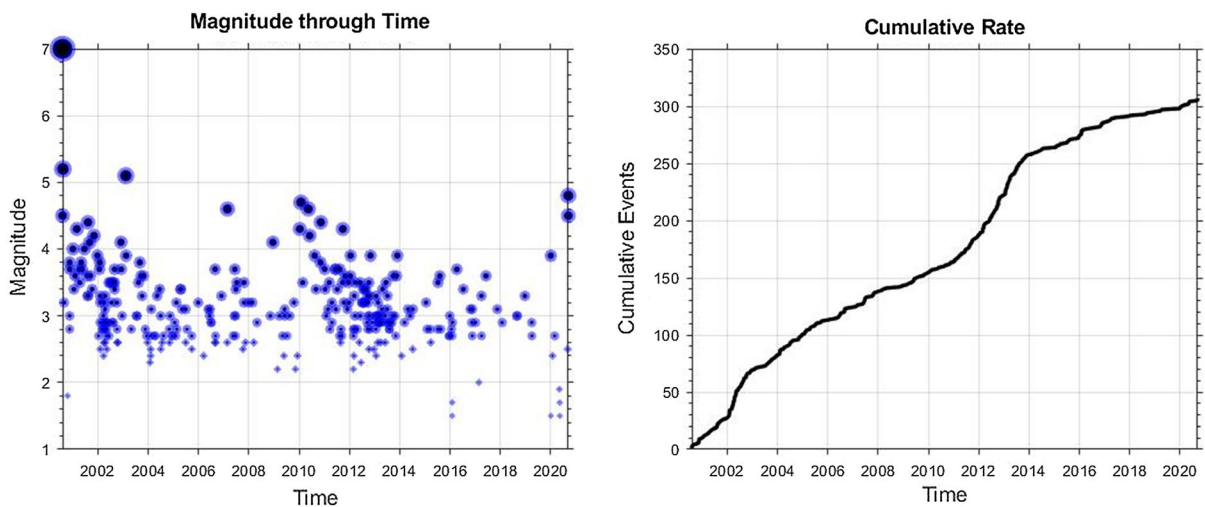


Figure 3

Dynamics of change in seismicity of the study area in 2000–2020. Distribution of the earthquake magnitudes (M_L) by years (left) and cumulative graph (right)

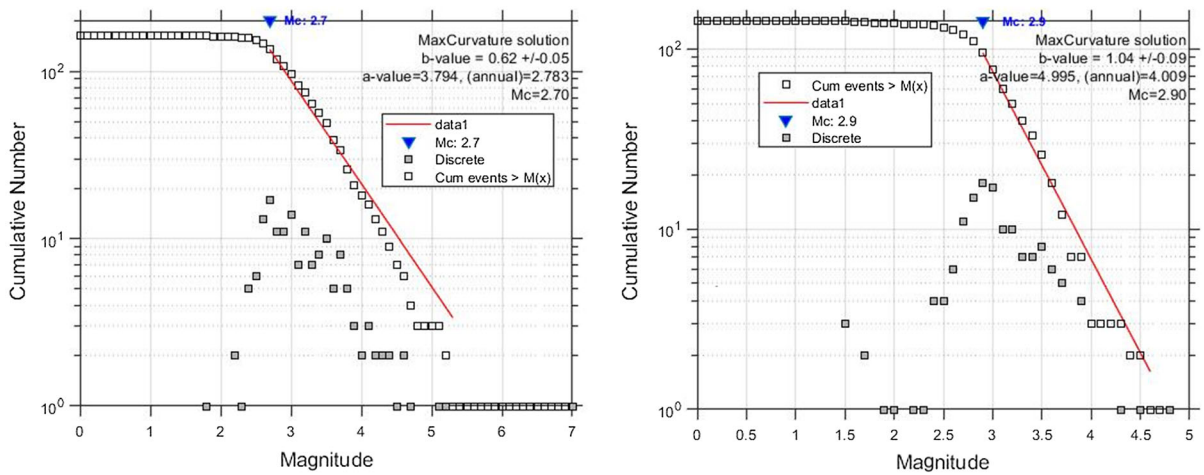


Figure 4
Graphs of earthquake distribution by magnitude (M_L) during 2000–2010 (left) and 2011–2020 (right)

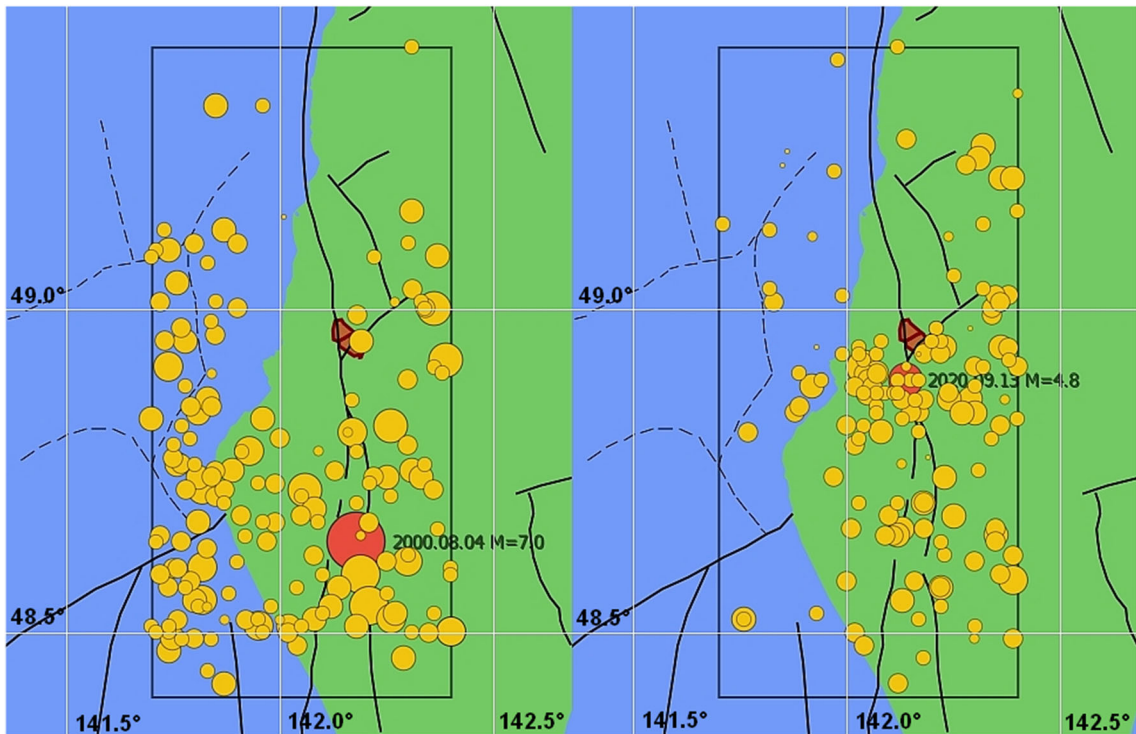






Figure 5
Earthquake epicenters (yellow circles) during 2000–2010 (left) and 2011–2020 (right). Sectors of the Solntsevsky coal mine are marked with a red polygon, and the strongest earthquakes of each decade are highlighted in red. The size of the circles corresponds to magnitudes (M_L) from 1.5 to 7.0

(on the right in the figure) occurred in the second decade of the twenty-first century, while the fault

remains active. Such a combination allows us to note the increase in the seismicity of the region during the

Table 1
Parameters of the earthquake focal mechanisms

No.	Date/time	Magnitude	Principal stress axes				Nodal planes				Seismic dislocation type	Focal mechanism stereogram (lower hemisphere)		
			<i>T</i>		<i>P</i>		<i>NP1</i>		<i>NP2</i>					
			PL	Az	PL	Az	PL	Az	PL	Az				
1	2000-08-04 21:13	$M_w = 7.0$	46	201	16	94	225	45	154	334	72	48	Reverse fault	
2	2020-01-03 20:46	$M_L = 3.9$	5	349	69	92	100	44	-60	242	53	-115	Normal fault	
3	2020-09-13 13:42	$M_L = 4.8$	9	72	24	338	23	80	-24	118	66	-169	Strike-slip fault	
4	2020-09-13 14:09	$M_L = 4.5$	41	260	3	168	41	65	33	295	60	150	Strike-slip fault	

last few years and the change in its character from natural to a mixed natural and technogenic.

It is important to examine the seismic dislocations of the largest earthquakes of the first (earthquake of 2000) and second (earthquake of 2020) decades in order to confirm the change in the character of seismicity and the reasons for earthquake occurrence in the study area. The focal mechanism of the earthquake in 2000 and its strongest aftershocks are identified in Poplavskaya et al. (2011) as reverse faults (or normal faults), which is typical for most earthquakes occurring on Sakhalin Island. A movement in the focus of the earthquake of September 13, 2020, and its largest aftershock ($M_w = 4.5$) was realized under conditions of horizontal sublatitudinal extension and near-horizontal submeridional compression and is classified as a strike-slip fault (Semenova et al., 2020). Considering that the West Sakhalin fault manifests as a system of interlinked normal and reverse faults, the type of seismic dislocations of the earthquakes of September, 2020, is clearly unusual for the study area. The configuration of the aftershocks of the earthquake on September 13, 2020, with their sublatitudinal orientation, indicates

the influence of mining operations (movement of the rocks when overburden works) as a possible trigger effect, which affected this earthquake occurrence. In this case, it is possible to draw a parallel with the strongest anthropogenic earthquakes on the Kola Peninsula, where the strike-slip character of displacements in earthquake foci was found to be caused by high tectonic stresses acting in the massifs, the presence of tectonic disturbances and voids formed during the preparation and extraction of ore deposits (Lovchikov, 2011). The authors computed the mechanism of the 2020 seismic event, which occurred on the 3rd of January (20:46), with $M = 3.9$, by means of the FOCMEC computation module integrated in the SEISAN complex of seismic programs (Ottemöller et al., 2011), in order to obtain an additional information about the earthquake character in the study area. A total of 19 arrival signs of the P-wave first swings, registered on the vertical component of the seismic vibration recording, were used. According to the solution obtained, the type of seismic dislocation was a normal fault, which generally corresponds to the normal fault with a reverse component seismicity of the area (Dymovich et al., 2017).

The mechanisms of all earthquakes are computed at the IMGG FEB RAS and presented in Table 1.

We will further consider the features of seismic processes in the study area during the last decade taking into account the effect of industrial blasting on the geological environment, as carried out on the Solntsevsky coal mine when overburden working. SB GS RAS monitors and records such blasts using the equipment of the Ulegorsk seismic station, which is located in the immediate vicinity of the Solntsevsky coal mine territory. The Ulegorsk station is equipped with modern digital equipment by Güralp Systems: a Güralp CMG-6 T broadband seismometer and a CMG-5TD accelerometer (Mishatkin et al., 2011). Over 100 blasts at the mine are recorded annually. The methods used by SB GS RAS for identifying and determining the blasts do not pose any difficulties in the general case and have been described in detail (Asming et al., 2010; Morozov, 2008). The ratio of the amplitudes of P- and S-waves (P/S), the ratio of Pg- and Sg-waves (Pg/Sg), record form, first arrival signs, and presence of a surface wave are usually considered as the criteria for separating the blasts and earthquakes. In addition to the above criteria, many studies show that the spectral and temporal analysis of seismograms of the records of blasts and earthquakes is the most informative (Dobrynina & German, 2016). It was found that the studied blasts are characterized by lower-frequency radiation compared to earthquakes. Other authors has

analyzed spectrograms of local seismic events recorded in the areas with anthropogenic influence on the geological medium not only to identify the blasts, but also to discriminate anthropogenic and tectonic seismic events. In particular, the recorded spectra for anthropogenic earthquakes are usually found to be in a frequency band up to 7 Hz, and the frequency of the maximum spectral density is 2–3 Hz, which is usually lower than that of tectonic earthquakes (Andruschenko et al., 2012).

In this regard, an attempt is made below to determine the regularities of the parameters of the produced blasts and earthquakes by the dynamic parameters of the seismic event foci. The frequency composition of earthquakes and blasts (during the period from 2015 to 2020) was studied in order to determine the corner frequency (F_c) from the focal velocity spectrum (Fig. 6).

It is known (Dobrynina, 2009) that the study of earthquake focal parameters (including corner frequency) allows us to better understand the nature of the processes of accumulation and discharge of tectonic stresses in seismically active regions. Correlation was obtained between the focal parameters and local magnitude. The results are presented in Table 2. Separate calculations of the corner frequency were performed for 100 randomly selected blasts. According to the calculation results, the corner frequency values in the case of blasts are in the range of 1.0–3.0 Hz.

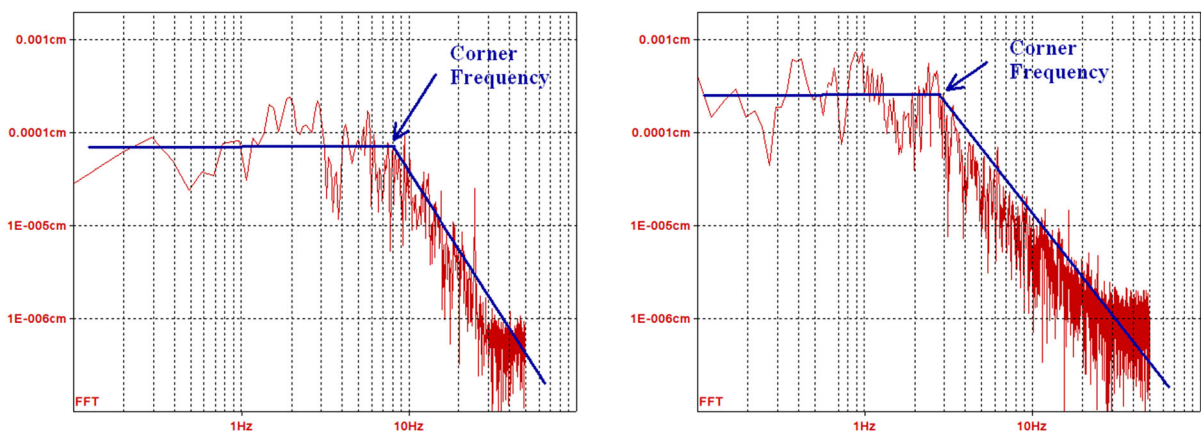


Figure 6

Example of corner frequency value determination for the velocity spectrum by the data of the Ulegorsk seismic station for earthquakes (left) and blasts (right)

Table 2

Correlation between magnitude, corner frequency and distance from a seismic station for the earthquakes during the period of 2015–2020

No.	Year	Month	Day	Hour	Minute	Latitude (°)	Longitude (°)	Depth (km)	Magnitude (M_L)	Corner frequency (F_c), Hz	Distance to seismic station (km)
1	2015	Jan	18	8	51	48.65	142.11	10	3.2	2.5	37.7
2	2015	Feb	1	2	21	49.02	141.99	15	2.8	5	9.8
3	2015	Mar	19	13	5	49.21	141.97	10	2.8	5.5	15.9
4	2015	Mar	28	3	23	48.95	142.08	10	2.6	3	11.2
5	2015	Jul	5	17	18	48.81	142.17	7	2.8	5.5	26.1
6	2015	Jul	10	15	56	48.57	142.22	5	3.5	8	47.6
7	2015	Aug	6	4	40	48.55	142.13	11	3.6	3.5	46.7
8	2015	Aug	20	11	31	49.4	142.12	9	2.8	6.5	29.1
9	2015	Dec	17	16	34	48.8	142.03	10	2.7	5	24.5
10	2015	Dec	21	7	27	48.92	142.04	10	2.7	5.5	14
11	2015	Dec	28	10	15	48.66	142.18	10	3	7	38.7
12	2016	Jan	22	9	38	48.93	142.07	10	2.8	6	12.8
13	2016	Jan	31	3	16	48.94	142.03	10	2.7	5.5	12.6
14	2016	Feb	1	21	55	48.97	142.29	12	1.7	6	26.6
15	2016	Feb	2	9	27	48.93	142.17	8	1.5	6	17.3
16	2016	Feb	5	9	41	48.97	142.21	10	2.9	5.5	18.5
17	2016	Apr	8	12	36	48.65	142.35	8	3.7	5.5	49
18	2016	Jul	11	8	35	49.01	142.36	12	3.4	3	33.2
19	2016	Oct	22	8	56	48.64	142.35	10	3.1	6	49.6
20	2016	Nov	11	2	55	48.84	142.07	10	2.9	6	20.7
21	2016	Nov	18	8	57	48.53	141.93	10	2.7	6	50.2
22	2016	Nov	19	2	57	48.62	142.39	10	3.1	6	53.9
23	2017	Jan	4	16	59	48.87	142.04	10	2.9	8	18.3
24	2017	Feb	24	1	31	49.33	142.4	10	2	3.5	43.3
25	2017	Apr	1	17	38	49.01	141.83	11	3.3	6	26.9
26	2017	Apr	2	20	55	49.15	142.4	6	2.7	9	37.7
27	2017	Jun	6	23	50	48.94	142.23	14	3.6	6	21.8
28	2017	Nov	16	21	52	48.65	142.09	10	3.1	6	37.5
29	2018	Jan	27	17	19	48.46	142.18	8	2.9	7	55.5
30	2018	Aug	27	17	58	48.59	142.36	12	3	5.5	53.8
31	2018	Sep	3	2	34	48.58	142.16	13	3	8	44.8
32	2018	Dec	22	23	51	48.66	142.35	12	3.3	7	48.3
33	2019	Apr	1	17	54	48.91	142.32	3	2.9	10.5	31.8
34	2019	Apr	3	8	39	48.7	142.12	8	2.7	7	33.6
35	2020	Jan	3	20	46	48.88	141.92	6	3.9	5.5	23.7
36	2020	Jan	4	11	47	48.94	141.93	10	1.5	9.5	19.3
37	2020	Jan	27	17	41	48.49	142.3	5	2.4	9	57.7
38	2020	May	6	2	17	49.24	141.86	5	1.9	10.5	27
39	2020	May	11	23	15	48.77	142.19	5	1.7	10.5	30.2
40	2020	May	12	18	41	49.22	141.85	5	1.5	10.5	27.1
41	2020	Sep	5	14	10	48.83	142.4	11	2.5	10.5	43
42	2020	Sep	13	13	42	48.89	142.14	8	4.8	2.5	18.3
43	2020	Sep	13	14	9	48.91	142.04	6	4.5	3	14.9

The values obtained and the trend graph of frequency dependence on magnitude (blue line in Fig. 7a) that was constructed according to these data (Fig. 7a) generally correspond to the works of Dobrynina (2009) and Sycheva (2017). At the same time, it is obvious that several seismic events are clearly below the trend line. They can be defined as “anomalous” earthquakes (they are highlighted in red

on the graph, and numbers from the table are specified for them). The same list includes the earthquake of September 13, 2020, as well as its main aftershock (events 42 and 43 in the table).

Figure 7b is fully consistent with the distribution of the aftershock cloud of the seismic event of September 13, 2020, when considering the epicentral positions of these “anomalous” earthquakes. In

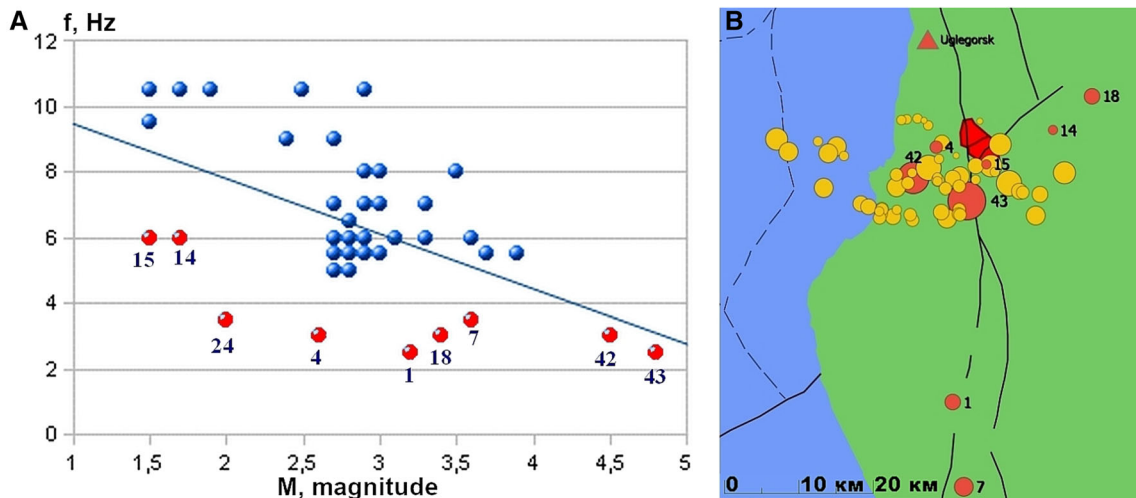


Figure 7

a Graph of corner frequency (Y axis) dependence on event magnitude (X axis). **b** Distribution of epicenters of the “anomalous” earthquakes of 2015–2020 (red circles) and position of the aftershock cloud of the September 13, 2020, earthquake (yellow circles). The size of the circles corresponds to magnitudes (M_L) from 0.2 to 4.8

addition, these events, while at the same time confined to the fault structures, are also located in the immediate vicinity of the Solntsevsky coal mine.

Thus, the method for assessing the nature of a seismic event through the study of corner frequency dependence on magnitude makes it possible to distinguish both the seismic events of tectonic character (for example, event no. 35, the mechanism of which was constructed above and corresponds to the idea about the nature of seismicity manifestations in this area) and the seismic events of potentially anthropogenic character, possibly having mechanisms with a strike-slip character. It is necessary to create a local seismic network in the study area in order to confirm this assumption.

4. Conclusion

This work considers a series of classic indicators for identifying the anthropogenic components in seismicity, each of which indicates the changes in a seismic regime in the area of hydrocarbon mining during the last decade. In this regard, the earthquake of September 13, 2020, can be attributed to a special type of strong natural and anthropogenic trigger earthquakes. There are a number of criteria for

similar earthquakes (Adushkin, 2016). For example, long-term and intense anthropogenic impact on the earth’s crust in the form of mining operations with large volumes of extraction and displaced rock is required. In addition, the massif where an earthquake has occurred (with high magnitude for anthropogenic earthquakes) should be characterized by a high-stress state without any relevance to the impact of external anthropogenic sources.

The presence of additional signs of anthropogenic seismicity (change in the nature of the recurrence curve slopes, migration of earthquake epicenters, etc.) allows us to note a transition from natural seismicity to mixed natural and anthropogenic seismicity in the Ulegorsk district of Sakhalin.

Thus, it would be appropriate to arrange a special program to study the nature of seismic processes in the depths of the region in detail and identify signs of an increase in mixed natural and anthropogenic seismic activity. This program could include, in particular, the creation of a seismic local network around the territory of the Solntsevsky coal mine, as well as an integrated geophysical polygon based on the Ulegorsk seismic station.

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