Seismic activity in the focus of the Uglegorsk earthquakes, Sakhalin Island in relevance to intensive development of coal deposits

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Research Article

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Abstract

Induced seismicity is an increase in seismic activity caused by the human engineering. An example of such activity is the mineral exploration, large water reservoirs construction, exploitation of underground oil and gas storages, etc. The authors studied the seismicity in the Uglegorsky district of Sakhalin region, where the Solntsevskoye brown coal field is located, which is the most promising in the island. Its area is over 100 sq. km, and productive strata of the Verkhneduiskaya formation with a thickness of up to 600 m contains 12 coal seams, 8 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, that, as a result, does not exclude the relation of the seismic process to technogenic seismicity. The earthquake recurrence curves for two decades beginning from 2000 to the present were constructed in the work to compare the characteristics of the seismic regime in the studied area. The difference in the slope angle of recurrence graph during the period of 2011-2020 (the period of the most active development of the Solntsevsky coal mine) from the previous decade is quite significant. The maps of spatiotemporal distribution of seismic events epicenters in the vicinity of Solntsevsky coal mine are constructed. The contraction of zones of seismic events concentration to the mining areas, first of all to the Solntsevsky coal mine, have been found. Such a combination allows us to talk about an increase in seismicity of the region during the last years and change in its character from the natural to a mixed natural and technogenic. The focal mechanisms of the largest earthquakes occurred in the Uglegorsky district have been constructed in order to prove the change in seismicity character and reasons for the earthquake occurrence in the studied area. The mechanisms of seismic events of 2020 are classified as strike-slip faults, that is not character for the most earthquakes on 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 events foci by means of studying the frequency content of earthquakes and blasts in order to determine a corner frequency from the focal velocity spectrum.

Introduction

Induced seismicity, which is the earthquakes in any way associated with engineering, is believed to be one of the manifestations of anthropogenic impact on the earth's crust. Many works [Nikolaev, 1994; Adushkin, Turuntaev, 2015; Adushkin, 2016; 2018; Kochyaryan et al., 2019] proved the existence of induced seismicity near the mining companies and the absence of an unambiguous relation to the faults [Novikov et al., 2013].

Basically, such earthquakes are weak, but magnitude 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 technogenic seismicity. Nevertheless, the largest seismic event, initiated by the mining works, is associated just with the open pit coal mining. This earthquake with a magnitude of ML = 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].

It is known [Kochyaryan et al., 2019], that the main factors associated with the 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 workings, including the actual open pit mines in the form of 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 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 technogenic impact in the form of the rock masses movement.

At the same time, the main part of small seismic events is usually confined directly to the place of mining operations and falls on the time when major blasts are carried out in coal mines, or in 1–3 hours after them [Yakovlev, 2013]. Another criterion is the depth of technogenic earthquakes. The 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, the coal mining creates a strong technogenic impact on the earth's crust and, as a result, it starts a large-scale process of the development of induced seismicity [Emanov et al., 2009; Adushkin, 2015].

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, 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 a high seismogenic potential. But if for the development of oil and gas fields there are separate studies on technogenic impact [Nikolaev, 1995; Tikhonov, 2010; Kovachev et al., 2018], the impact of the coal fields 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 proposed to consider the seismicity of the area where coal is mined in order to identify both generally accepted indicators of the technogenic response [Dahm et al, 2013] and, if possible, to determine new features of the seismic process under the conditions of a sharp increase in the level of impact on the geological environment.

Study Object

The territory of Sakhalin is located in the zone of earthquakes of 8–9 points 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 the 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 itself 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 M > 5.9 (Fig. 1): Lesogorsk-Uglegorsk earthquake in 1924 (Mw = 6.8; 8–9 points) [Soloviev et al., 1967] and the Uglegorsk-Ain one in 2000 (Mw = 7.1; 9 points) [Poplavskaya et al., 2006].

Several crustal earthquakes of M > 4.5 with a macroseismic effect occurred in the studied area over the 20 years that had passed since the Uglegorsk-Ain earthquake in 2000, for example, the earthquake on February 8, 2003, with MLH = 5.1 [Fokina et al., 2009]. However, a seismic event with ML = 4.8 on September 13, 2020, which occurred in the area of active development of coal fields, had the greatest resonance [Semenova et al., 2020].

The coal bearing of the Uglegorsky district is associated with the Paleogene and Neogene sediments. Eight fields are confined to sediments of the Neogene age, including the large developed fields 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 20th century during the existence of the Japanese Karafuto gouvernership in southern Sakhalin, when 15 mines were opened in 11 settlements on the territory of the modern Uglegorsky district [Masafumi, 2017]. Most of them were closed in the middle of the 20th century, and only four mines were working by the end of the 20th century, when the coal industry of Sakhalin were in a deep crisis of the 90s. Two of them («Tel’novskaya» and «Boshnyakovo») were closed in 1995 and 1998 respectively [Vakulenko, 2015], and the last two mines («Uglegorskaya» and «Udarnovskaya») were officially closed already in the 21st century (2005 and 2017), although the coal mining at the «Udarnovskaya» mine was actually suspended in 2009 [Dorokhina, 2018]. The revival began in the early second decade of the 21st century, when significant changes took place in technology, 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 Uglegorsky district [Ugol’, 2011]. Solntevskoye brown coal field in the Uglegorsky district of the Sakhalin region was discovered in 1980s and immediately recognized as the most promising on the island. Its area is more over 100 sq. km. Productive strata of the Verhneduiskaya formation with a thickness of up to 600 m contains 12 coal seams, of which 8 are working. However, its potential could not be revealed for a long time. 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 reequipment (Fig. 2) [Ugol’, 2019]. Already in 2012, the miners of the 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 the EMCO to obtain record levels of extraction and shipment of 11 million tonnes of coal [Ugol', 2021], that is 78% of total coal production in the Sakhalin region. Thus, a radical restructuring of the extraction technologies during last 20 years is evident. Resume these changes in general figures, it can be noted once again that until the middle of the 90s, the main coal production in Sakhalin in general, and in the Uglegorsky district in particular, was carried out by the underground technique (mines), but already in 2000 the share of open pit coal mining were 80% [Kovalchuk, 2002], by 2010–94% [Streltsov, 2010], and 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 = 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.

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, 2019] to study the change in the seismicity of the area, under the conditions of the intensification of open pit mining, in square of 48.4°-49.4° N and 141.7°-142.4° E, which includes both tectonic 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 the catalog declustering was carried out using the algorithm [Gardner, Knopoff, 1974] to exclude the influence of the aftershock sequences of 2000 and 2020 earthquakes on the recurrence graphs and the maps of epicenter positions for assessing the seismicity.

The result of dynamics of change in seismicity of the specified area during 20 years, after declustering, is presented in Figure 3.

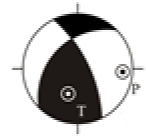
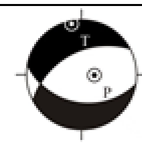
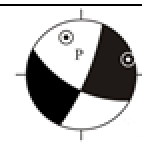
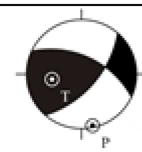
It is worthy of note the increase in the seismicity of the area in 2012-2013, which coincides with the beginning of active development of the Solntsevsky Coal Mine and, accordingly, a significant increase in the volume of overburden operations at the open pit during this period. The recurrence graphs 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 studied area (Figure 4). The difference in a slope angle of the recurrence graph in the period of 2011-2020 is quite significant. The increase of a slope angle means more low energy earthquakes in the total number of events. According to [Yakovlev, 2013; Emanov et al., 2020], such b-values (about 1.0) are typical for anthropogenic activations in the areas with induced seismicity. For comparison, the graph on the left (Figure 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 (Figure 5).

As it can be seen, location of the epicenters of seismic events during 2000-2010 (on the left in the figure) is confined mainly to the fault structures, that testify to activity of the Krasnopol'evskiy fault, which is a 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 (on the right in the figure) is occurred in the second decade of the 21st century, while the fault remains active. Such a combination allows us to talk about an increase in seismicity of the region during the last years and change in its character from the natural to a mixed natural and technogenic.

It is necessary to pay attention to the seismic dislocations of the largest earthquakes of first (earthquake of 2000) and second (earthquake of 2020) decades in order to confirm the change in character of seismicity and the reasons of earthquake occurrence in the studied 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 (Mw=4.5) has realized under the conditions of horizontal sublatitudinal extension and near-horizontal submeridional compression and is classified as strike-slip fault [Semenova et al., 2020]. Considering that the West Sakhalin fault manifests itself 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 studied area. Configuration of the aftershocks of 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 has affected this earthquake occurrence. In this case, it is possible to draw a parallel with the strongest technogenic 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 seismic event of the same 2020, 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 studied 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 obtained solution, 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.

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)
			T		*P*		*NP*1			*NP*2				
			PL	*Az*	*PL*	*Az*	PL	*Az*	*PL*	*Az*	PL	*Az*		
1	2000-08-04 21:13	M=7.0	46	201	16	94	225	45	154	334	72	48	Reverse fault	
2	2020-01-03 20:46	M=3.9	5	349	69	92	100	44	-60	242	53	-115	Normal fault	
3	2020-09-13 13:42	M=4.8	9	72	24	338	23	80	–24	118	66	–169	Strike-slip fault	
4	2020-09-13 14:09	M=4.5	41	260	3	168	41	65	33	295	60	150	Strike-slip fault	

We will further consider the features of seismic processes in the studied area during the last decade taking into account the effect of industrial blasting on the geological environment, that is carried out on the Solntsevsky coal mine when overburden working. SB GS RAS monitors and records such blasts using the equipment of the «Uglegorsk» seismic station, which is located in the immediate vicinity of the Solntsevsky coal mine territory. The «Uglegorsk» station is equipped with the modern digital equipment by the Güralp Systems: a Güralp CMG-6T 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 general case and are described in detail [Morozov, 2008; Asming et al., 2010]. 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, presence of a surface wave are usually considered as the criteria for separating the blasts and earthquakes. In addition to 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 with lower-frequency radiation compared to earthquakes. Other authors aimed the analysis of local seismic events spectrograms recorded in the areas with technogenic influence on the geological medium not only at identifying the blasts, but also at discriminating technogenic and tectonic seismic events. In particular, the recording spectra of technogenic earthquakes are noted to be usually in the 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 to determine the regularities of the parameters of the produced blasts and earthquakes by the dynamic parameters of the seismic events foci is taken below. The frequency composition of earthquakes and blasts (during the period from 2015 to 2020) was studied in order to determine the corner frequency (Fc) from the focal velocity spectrum (Figure 6).

It is known [Dobrynina, 2009] that the study of the earthquake focal parameters (including corner frequency) allows 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 calculation of the corner frequency was performed for 100 randomly selected blasts. According to the calculation results, it was found that corner frequency values in the case of blasts are in the range of 1.0-3.0 Hz.

Table 2. Correlation between magnitude, corner frequency and distance from a seismic station for the earthquakes during the period of 2015-2020.

№	Year	Month	Day	Hour	Minute	Latitude, °	Longitude, °	Depth, km	magnitude	Corner frequency (Fc), 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, that was constructed according to these data (Figure 7, left), generally correspond to the works [Sycheva, 2017; Dobrynina, 2009]. At the same time, it is obvious that several seismic events have the values of corner frequency anomalous for earthquakes (they are highlighted in color 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 (no. 42 and no. 43 events in the table).

Figure 7 is fully consistent with the distribution of the aftershock cloud of the seismic event of September 13, 2020, when considering the position of these “anomalous” earthquakes epicenters. In addition, these events being 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, no. 35 event, the mechanism of which has been constructed above and corresponds to the idea about the nature of seismicity manifestations in this area), and the seismic events of potentially technogenic character, possibly having a strike-slip character of the mechanisms. It is necessary to create a local seismic network in the studied area in order to confirm this assumption.

Conclusion

This work considers the series of classic indicators for identifying the technogenic component in seismicity character, each of which indicates the changes in a seismic regime in the area of hydrocarbons 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 technogenic trigger earthquakes. There is a number of criteria for similar earthquakes [Adushkin, 2016]. For example, long-term and intense technogenic impact on the earth's crust in a form of mining operations with large volumes of extracting and displaced rock is required. Besides, the massif, where an earthquake has occurred (with high magnitude for technogenic earthquakes) should be characterized by high stress state level without any relevance to the impact of external technogenic sources.

The presence of additional signs of technogenic seismicity (change in the nature of the recurrence curves slope, migration of earthquake epicenters, etc.) allows to speak about a transition from natural seismicity to mixed natural and technogenic seismicity in the Uglegorsk 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 technogenic 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 «Uglegorsk» seismic station.

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Competing Interests

Authors declare no competing interests.

Figures

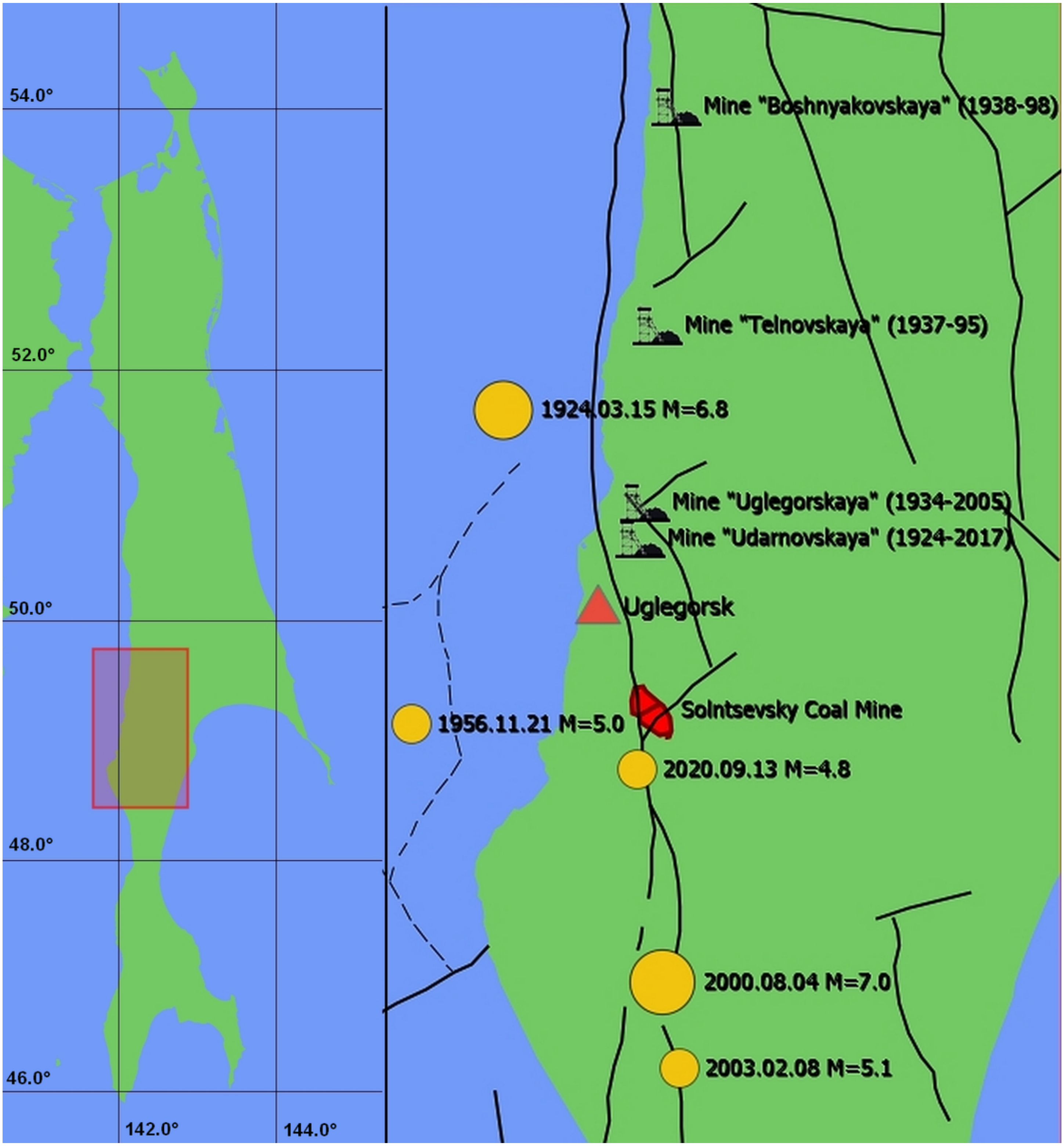

Figure 1

The studied area location. On the left: the studied 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 studied area are marked with yellow circles, the «Uglegorsk» seismic station is marked with a triangle

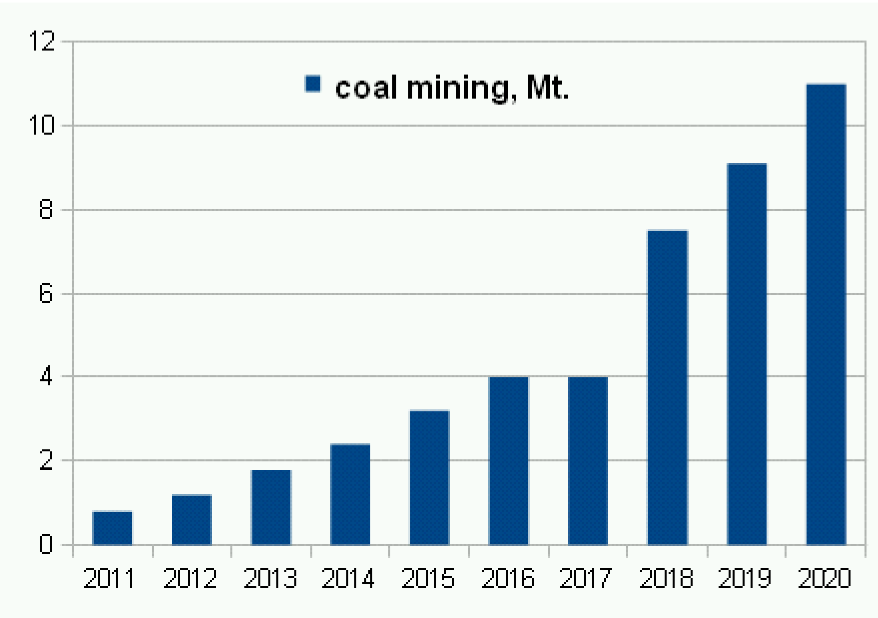

Figure 2

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

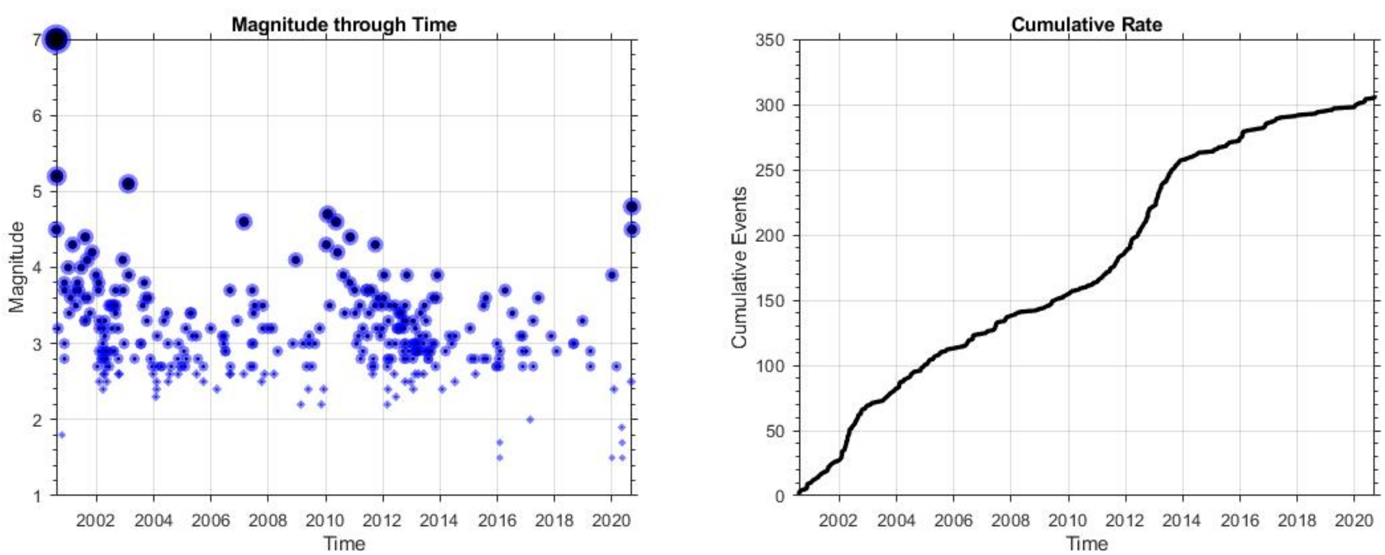

Figure 3

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

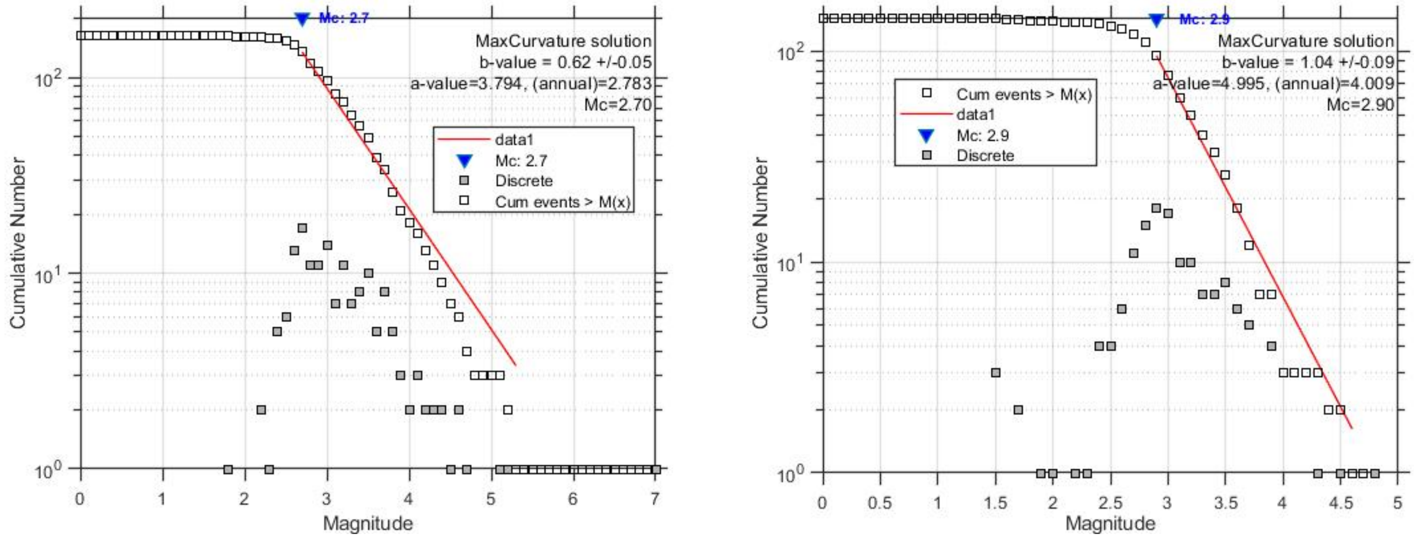

Figure 4

Graphs of earthquake distribution by magnitude during 2000-2010 (left) and 2011-2020 (right)

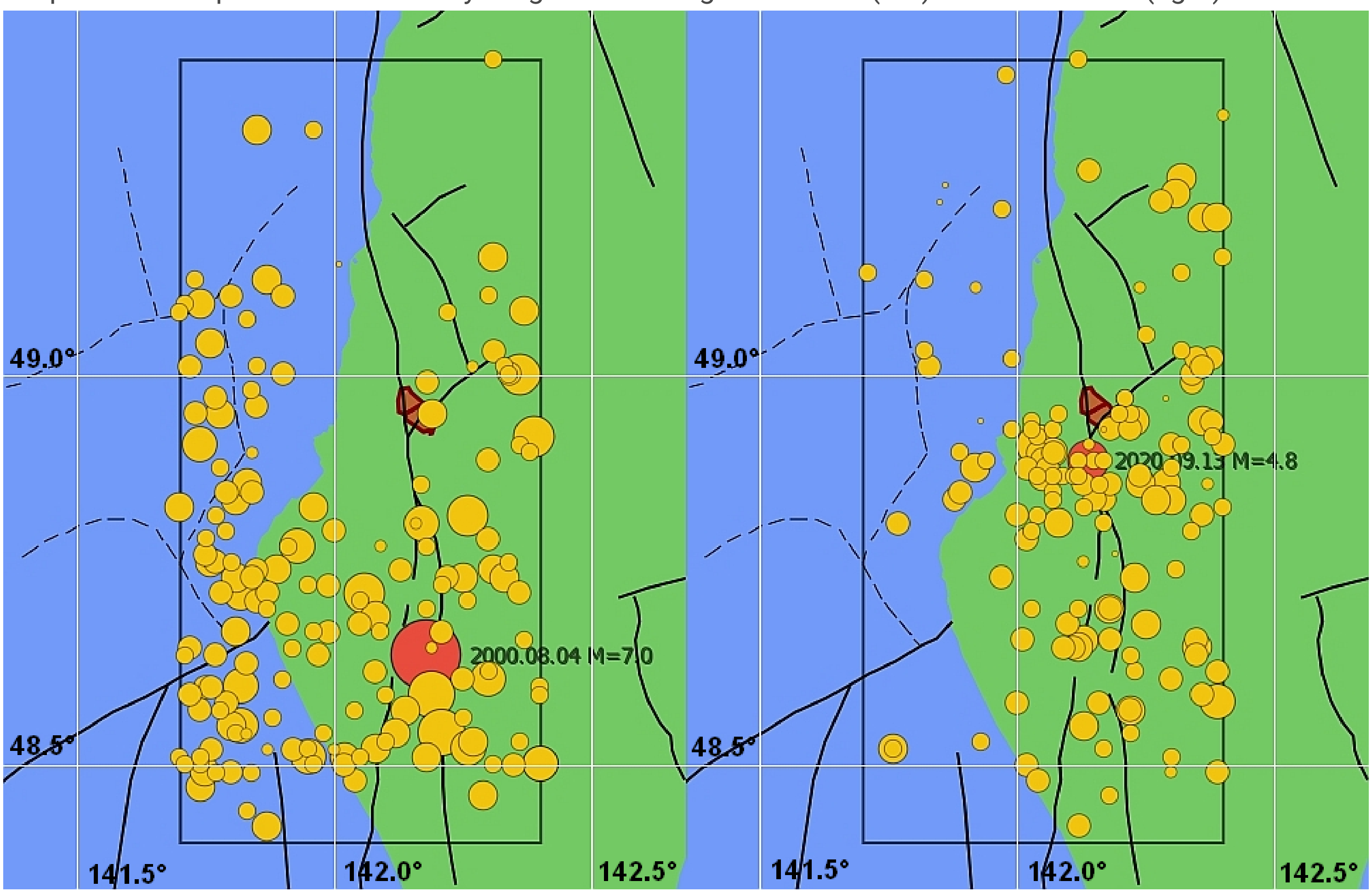

Figure 5

Earthquake epicenters during 2000-2010 (left) and 2011-2020 (right). Sectors of the Solntsevsky coal mine are marked with red polygon, the strongest earthquakes of each decade are highlighted in red

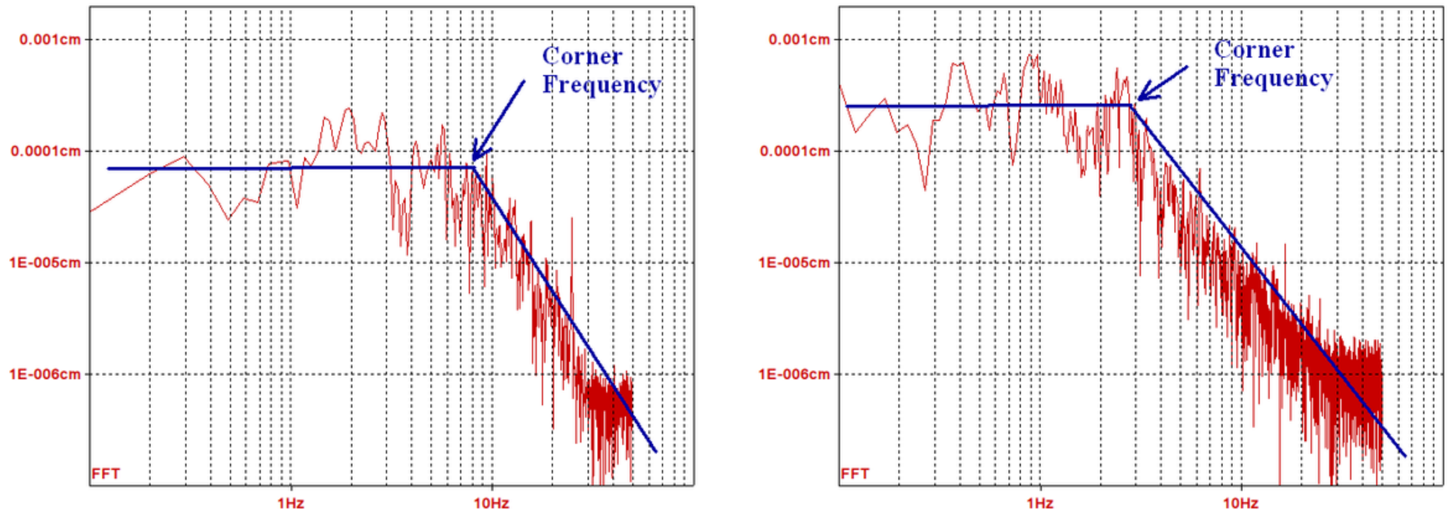

Figure 6

Example of determining the corner frequency value for the velocity spectrum by the data of the «Uglegorsk» seismic station for earthquakes (left) and blasts (right)

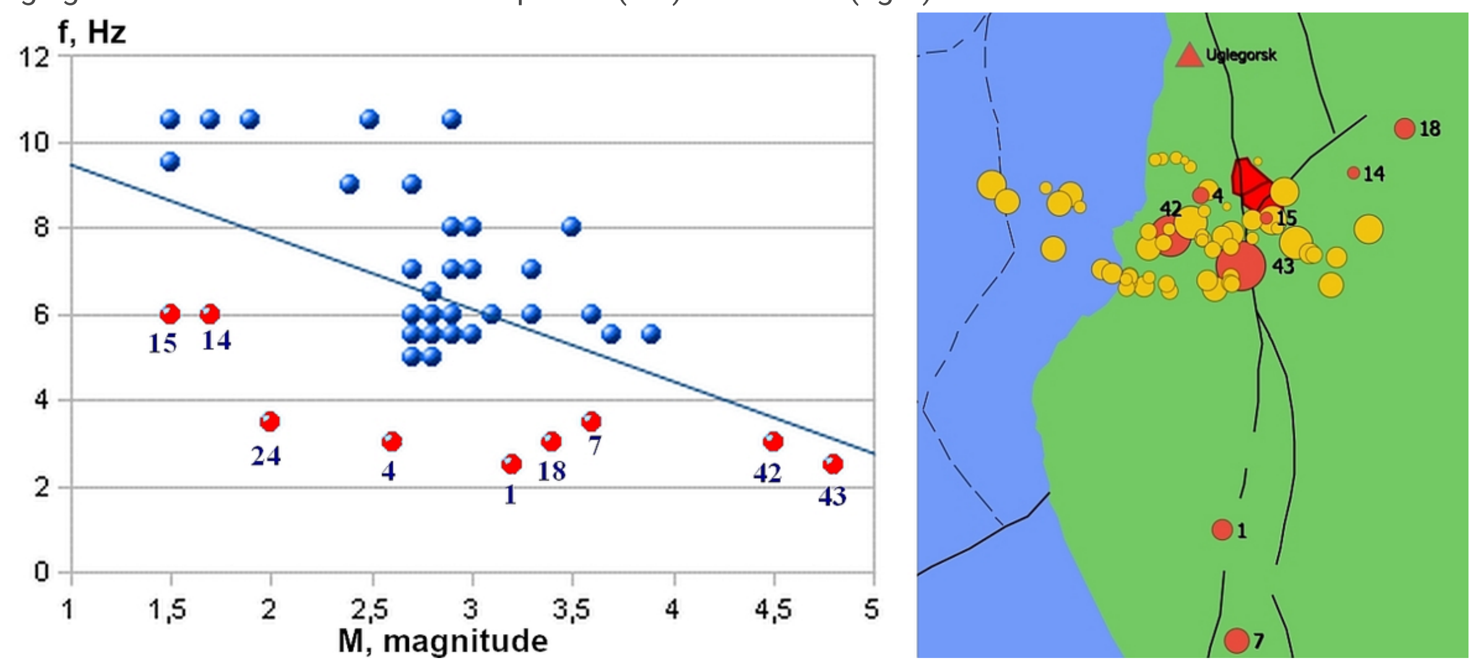

Figure 7

Graph of corner frequency (Y axis) dependence on event magnitude (X axis). Distribution of epicenters of the «anomalous» earthquakes of 2015-2020 (left) and position of the aftershock cloud of September 13, 2020 earthquake