Russian Journal of Earth Sciences, Vol. 22, ES6010
https://doi.org/10.2205/2022ES000819

Exploring the Nature of Seismic Events in the Underground Gas Storages Area of the Volga Federal District

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Received 21 November 2022; accepted 11 December 2022; published 31 December 2022.

Seismicity during UGS operation had not yet been known in Russia. This work presents studies on the manifestation of seismicity in the area of three underground gas storages (UGSs) located in the south-eastern part of the East European Platform (European part of Russia). The tectonic structure of this region, geodynamic conditions and technological characteristics of "Vostochnoye", "Zapadnoye", "Uzhnoye" UGS are presented. An analysis of the situation with the manifestation of seismicity allows us to conclude that it is technogenic in nature, a feature not previously noted on Russian UGSs. There is a wide list of signs indicating the relationship between the mode of operation of UGSs and the nature of seismicity: prior to the start of UGS operation technogenic seismicity in this area was not known; there is a clear correlation between UGS operation and seismicity; the epicenters of seismic phenomena are located in the geodynamic influence zone of the UGS; in the region there are Earth crustal faults that experienced activation in late Cenozoic time and respond to strong earthquakes of neighboring tectonic areas, which consequently indicates their predisposition to reactivation; the change in pressure in the UGS reservoir is sufficient to induce seismicity. The phenomenon of increasing seismic activity during the gas extraction period is noted, which is explained by the effect of softening of the containing massif and its subsequent push-like deformation when the gas pressure in the reservoir is reduced. Despite the weak seismicity, which does not pose a threat to UGS facilities and adjacent territories, it is proposed to include seismic observations in the complex geodynamic monitoring at Russian UGS to establish patterns over a long period of time.

Keywords: underground gas storage; operation mode; active tectonic faults, earthquake, technogenic seismicity, seismological monitoring.

Citation: Batugin, Andrian, Viktor Ogadzhanov, Sergey Khan, Stepan Shevchuk, Sergey Kostikov, and Anton Oborin (2022), Exploring the Nature of Seismic Events in the Underground Gas Storages Area of the Volga Federal District, *Russian Journal of Earth Sciences*, Vol. 22, ES6010, doi: 10.2205/2022ES000819.

1 Introduction

The seismicity associated with human engineering (man-made seismicity) is one of the current pressing global problems with technical, social and environmental aftermath. One of the classifications of man-made seismicity is the Adushkin-Turuntaev classification [*Adushkin and Turuntaev*, 2015], where seismic events arising self-arbitrarily in the rock mass containing and surrounding the area of its operation are attributed to induced man-made (technogenic) seismicity. Bearing in mind this form of seismicity, in this paper we use the term "technogenic seismicity" for it. There are also classifications of man-made seismicity by type of engineering activity. In the work [*Nikolaev*, 1973], such types of engineering activities as oil production, underground developments, the creation of large reservoirs, atomic explosions are mentioned. Examples of seismic phenomena related to these activities are considered in detail in the works of [*Adushkin and Turuntaev*, 2015]. The works [*Doglioni*, 2018; *Grigoli et al.*, 2017] also

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Table 1: Types of engineering activities that cause technogenic seismicity in Russia and the world

Type of engineering activity causing technogenic seismicity	References in world practice	References in Russia
Filling reservoirs	[*Carder*, 1945; *Dong et al.*, 2022; *Gupta*, 2002; *Malekzade and Rokni*, 2021]	[*Nazarova*, 2018; *Nikolaev*, 1973]
Mining operations	[*Butler and Simser*, 2017; *Cook*, 1966; *He et al.*, 2012; *Lizurek et al.*, 2015; *Rong et al.*, 2021]	[*Eremenko et al.*, 2017; *Kozyrev et al.*, 2020; *Petrov et al.*, 2021; *Rasskazov et al.*, 2020]
Development of hydrocarbon deposits	[*Liu et al.*, 2022; *Nicholson and Wesson*, 1992]	[*Adushkin and Turuntaev*, 2015; *Punanova and Rodkin*, 2022]
Blasting	[*Dodge*, 2018; *Hamilton et al.*, 1972]	[*Adushkin and Turuntaev*, 2015; *Gorbunova*, 2021]
Operation of UGS	[*Benetatos et al.*, 2013; *Cesca et al.*, 2014; *Tang et al.*, 2015]	Not marked

give examples of the seismicity occurrence during the operation of underground gas storage (UGS), which was not yet known for Russia (see Table 1). One of the seismic phenomena with a magnitude (M) equal to 7 and a hypocenter depth of 15 km, presumably of a technogenic nature, occurred in 1985 in the USSR (Uzbekistan) at the Gazli gas field, which after the end of production was used as a UGS [*Simpson and Leith*, 1985]. However, the man-made nature of this event is disputed, since due to changes in stresses caused by engineering activities, they are too small at such depths [*Foulger et al.*, 2018]. According to [*Bossu et al.*, 1996], this event in the Gazli region is associated with the development of natural tectonic processes.

At the same time, more than two dozen UGS are being operated in Russia, and new facilities are being built. UGS perform an important function in the system of reliable gas supply to the population and export supplies. According to Russian legislation, UGS are classified as hazardous industrial facilities, for which, like other types of underground storage facilities, geodynamic monitoring must be carried out, which means observations of the movement of the Earth's surface in the areas of their location [*Federal Law of 21.07.1997 No. 116-FZ*, 1997; *Gvishiani et al.*, 2021]. Seismic observations are included in geodynamic monitoring at foreign UGS [*Scala et al.*, 2022], in Russia there are proposals to supplement traditional geodynamic monitoring for UGS with observations of seismicity [*Nikonov*, 2003], but so far this issue is under discussion and no evidence of technogenic seismicity during the operation of UGS in Russia has been cited. It is suggested that for a more complete account of geological hazards, it is necessary to take into account registered, historical and simulated earthquakes [*Ismail-Zadeh*, 2016]. Based on the analysis of the situation on Russian UGSs, the authors of this article believe that the manifestation of technogenic seismicity during their operation becomes a new reality that must be taken into account to ensure industrial and environmental safety. The main purpose of this article is to establish the presence of the influence of Russian UGS on the seismic regime of the territory and to justify the need for seismological monitoring during their operation.

2 Study area

2.1 Geotectonic position of UGS location area

There are three UGS facilities in the south-eastern part of the East European platform - “Vostochnoye”, “Zapadnoye”, “Uzhnoye”. According to modern ideas, there are long-developing tectonic structures on the East European Platform [*Grachev et al.*, 2006] and a distinctive feature of the tectonic structure of the region where the mentioned UGS are located is the articulation of large geostructures here: the Volga-Ural anteclise, the Pachelma aulacogen, the Caspian Depression, (Figure 1 and Figure 2). These geostructures are intersected by the European-African tectonic belt [*Ogadzhanov and Ogadzhanov*, 2014], which has a submeridional direction on a planetary scale and is elongated in the area of the Precambrian East Eu-

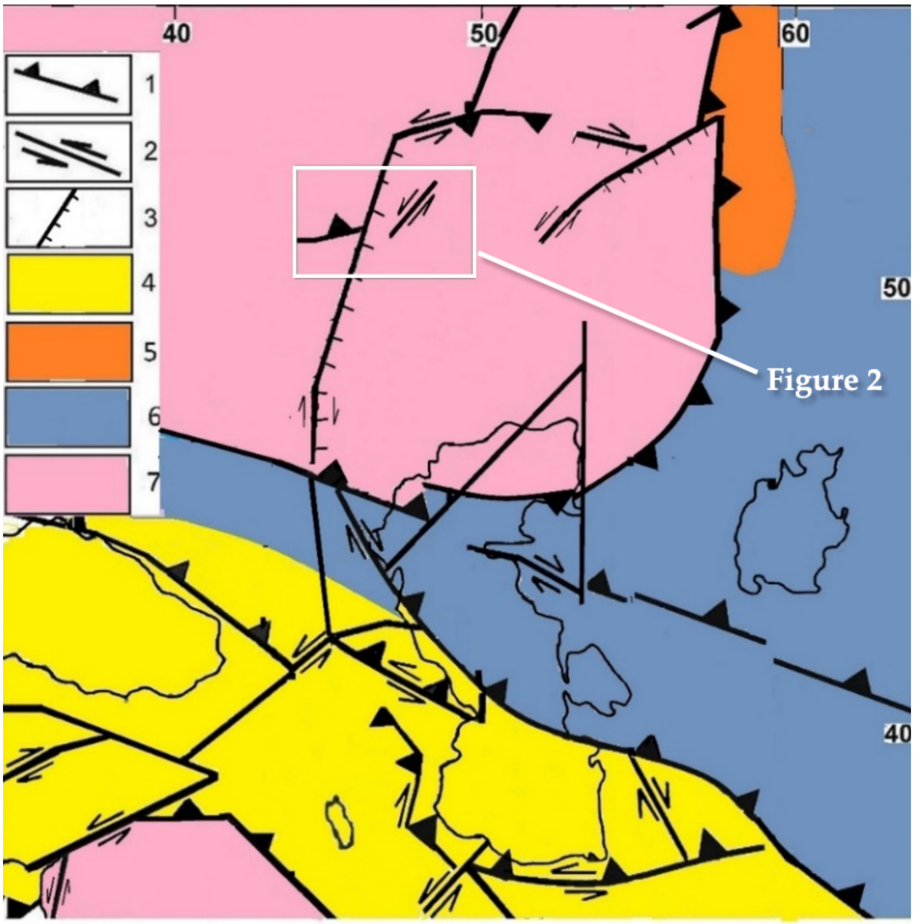

Figure 1: The position of the main zones of the Late Cenozoic deformations of the European-African through tectonic belt is compiled taking into account [*Leonov et al.*, 2001]. Deformation zones: 1 – prevailing compression deformations; 2 – prevailing shear deformations; 3 – prevailing tensile deformations; the main geostructures: 4 – Alpine geosynclinal; 5 – Hercynian geosynclinal; 6 – Epihercynian platform; 7 – Precambrian platform. The rectangle shows the area where the UGSs are located.

ropean platform from the Kama River through the Middle and Lower Volga regions, the epihercynian platform area, the Caucasus-Anatolian segment of the alpine folded area and further into the Arabian part of the African platform [*Sarkisyan*, 1982; *Shatsky*, 1948].

In a number of works, this belt is identified with a through fault, which in its northern part is called the Main East European Fault [*Eppelbaum and Katz*, 2020]. This belt experienced activation in Late Cenozoic time and Late Cenozoic crustal deformations are associated with the tectonic structures of this belt, Figure 1.

2.2 Stratigraphic, structural-tectonic, geodynamic characteristics of the “Vostochnoye”, “Zapadnoye”, “Uzhnoye” UGS location areas

Five structural floors stand out in the sedimentary cover of the Middle and Lower Volga Region: Riphean, Devonian, Carboniferous, Mesozoic-Paleogene and Neogene-Quaternary.

The “Zapadnoye” and “Vostochnoye” UGS were created in reservoirs of coal deposits. In 1966, the “Vostochnoye” gas storage was created in the deposits of the Tula horizon. Currently, the gas storage at this UGS are used as high-bottomed gas and oil deposits of the Bobrikovsky and Kizelovsky horizons and the developed gas deposit of the Tula horizon. The Protvinsky horizon of the lower carboniferous, which underlies the spent gas deposit of the Cheremsky-Prikam horizon of the lower middle carboniferous, is used to pump industrial effluents.

The “Zapadnoye” UGS was commissioned in 1967. In accordance with the current project, the joint operation of the Tula and Bobrikovsky-Kizelovsky horizons is provided.

The “Uzhnoye” UGS was created in the reservoir formations of the same name in the sediments of the formations D_2V + VI Vorobyov and D_2IVb

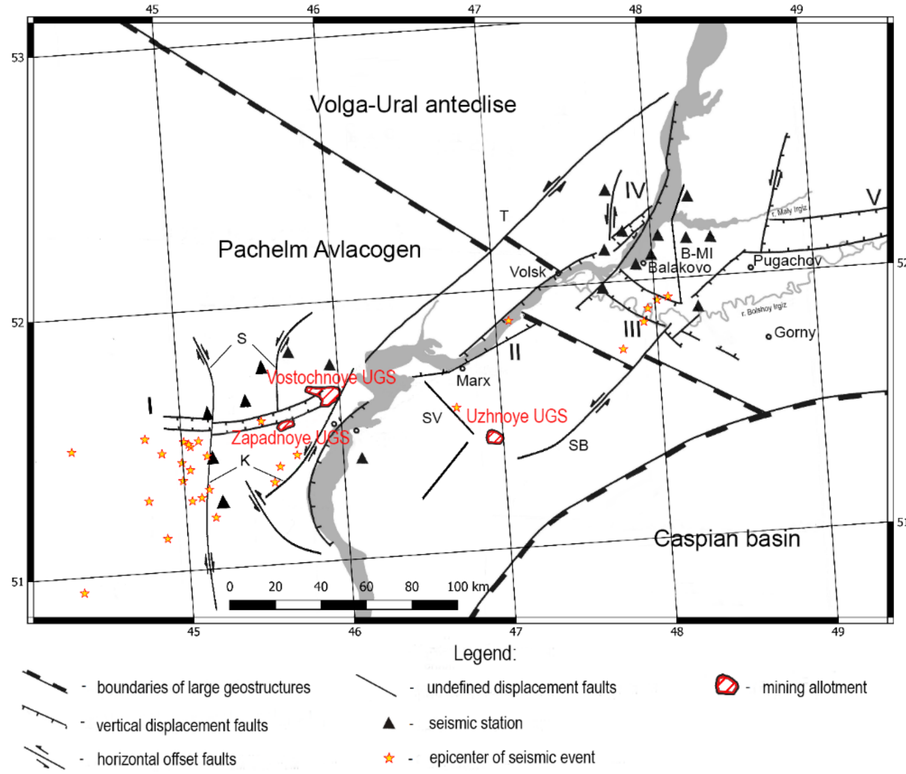

Figure 2: The scheme of tectonics elements of the UGS location area (according to *Leonov et al.* [2001] with the additions of the authors). Graben: I – Elshano-Sergievsky, II – Marxovsky, III – Balakovsky, IV – Tersinsky, V – Irgiz. The latest tectonic dislocations: S – Saratov, K – Karamysh, SV – Stepnovsky, SB – Stepnovsky-Balakovo, T – Tersinskaya, B-Mi – Balakovo-Malo-Irgizskaya.

and D_2IVa Ardat layers of the Zhivet tier belonging to the Devonian structural ETA. Reservoir deposit D_2V + VI is confined to linear reservoir water system of limited dimensions with water-elastic mode. Tectonically, the "Vostochnoye" and "Zapadnoye" UGS are confined to the eastern part of the Elshano-Sergievsky graben (Figure 2).

The eastern part of the Elshano-Sergievsky graben from the south limits the geodynamically active block, where the amplitudes of the latest tectonic movements reach 850–875 m. The Elshano-Sergievsky graben is a complex flexure-breaking zone, which has a long formation period and manifests itself in the latest stage of development. As an example, the profile through the fault of the southern side of the Elshano-Sergievsky graben is given Figure 3 according to [*Gorkov*, 2016; *Shebaldin*, 2008], completed by the authors with materials of interpretation of geophysical data. The Elshano-Sergievsky graben is confined to a linear zone of fractured anticlinal uplifts, which includes the Elshano-Kurdyumsky and Peschano-Umetsky uplifts. By drilling wells within the Elshano-Kurdyumsky uplift, 14 bursting disturbances were found, some of which can be considered as breaks in the discharge-shift kinematics that control the placement of oil and gas deposits. Faults experience activation at the latest stage of tectogenesis, as indicated by high amplitudes of anomalies of the latest tectonic movements elongated in the direction of the fault zone of the Elshano-Sergievsky graben.

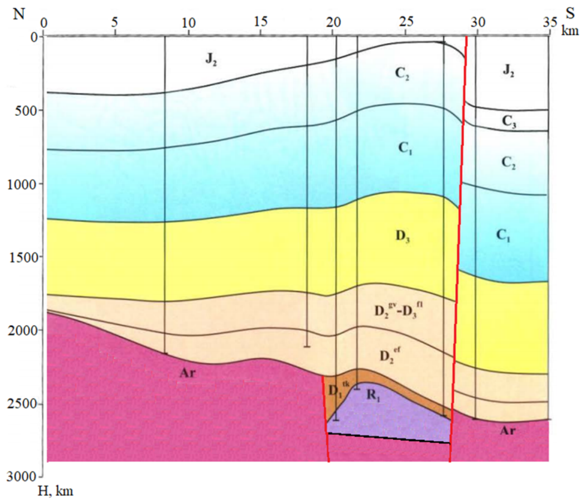

Figure 3: Geological section through Elshano-Sergievsky graben.

"Uzhnoye" UGS is located within the southeastern part of a large tectonic rampart extended in

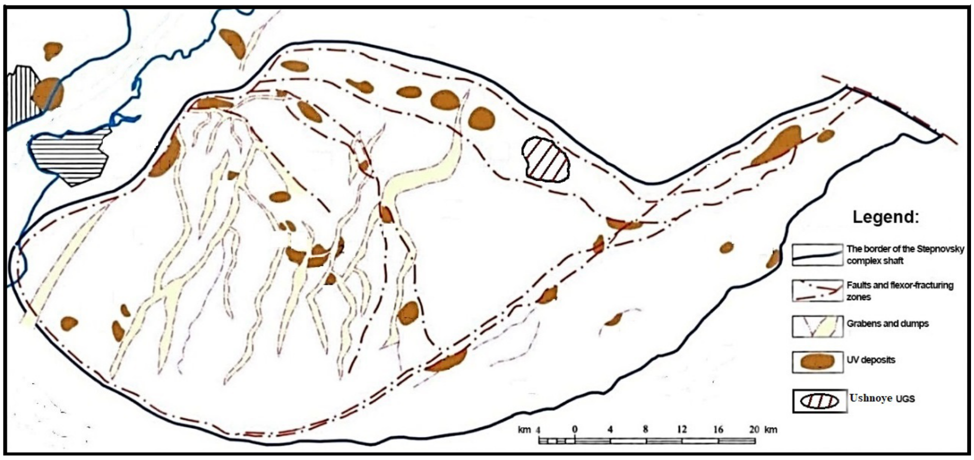

Figure 4: Stepnovsky tectonic rampart diagram.

the direction from northwest to southeast along the line of the latest zone of a faulting (SV area in Figure 2). In its southeastern part, the Stepnovsky tectonic rampart changes its direction of extension to the northeastern one (Figure 4) [*Shebaldin*, 2008] and coincides with the anomaly of new tectonic movements with slip distance of + 450–550 m, shown on the map [*Kovalsky and Vostryakov*, 1981], extending further northeast along the line of the latest fault (II in Figure 2). Within the Stepnovsky tectonic rampart, there are two tectonic lines of deployed anticlinal subsections of the NW–SE and one tectonic line of the NE–SW, which in its northeastern continuation coincides with the fault of the northeastern extension (II in Figure 2). from the Stepnovsky tectonic rampart (Figure 5). In the structure of Stepnovsky uplift, six main blocks are distinguished. The blocks are separated by faults with slip distances from 20 to 80 m, between which crushing zones are identified, represented by numerous local faults with slip distances of the order of 6–10, less often up to 20 m. Based on the drilling materials of the oil and gas field, the area of the D_2V + VI reservoir is disturbed by a series of faults that break it into separate blocks.

Thus, it can be seen from the above that the area where the UGSs under consideration are located is characterized by the presence of heterogeneous discontinuities that determine the division of the Earth's crust into tectonic blocks, and the presence of anomalies of the latest and modern movements of the Earth's crust that are relatively high for platform territories.

2.3 Seismicity of the location areas of the "Vostochnoye", "Zapadnoye" and "Uzhnoye" UGS

According to the Global seismic hazard map [*Giardini et al.*, 1999], the Volga region belongs to seismically active with a peak acceleration of soil movement up to 0.4 m s^{-2} and with a repetition period of tectonic earthquakes once every 475 years. Earthquakes of the historical and instrumental observation period are known here. During the period of instrumental observations, the earthquake that occurred on the right bank of the Volga River about 160 km in the direction of its channel to the southwest of the "Vostochnoye" UGS, which occurred on December 24, 1991 with a magnitude of 3.5, is known to be the strongest and closest to the area of the location of the UGS.

In the area of the UGS location, since 1995, a group of seismic stations (Figure 2) have started observing seismicity at the geodynamic ground of this region, created by the Lower Volga Research Institute of Geology and Geophysics of the Ministry of Natural Resources and Ecology of Russia. Additionally, since November 2005, the Geophysical Service of the Russian Academy of Sciences has commissioned a seismic station located 50 km southwest of the "Vostochnoye" UGS. Based on the results of observations, earthquake catalogs were compiled. The obtained results of observations are summarized in the works [*Ogadzhanov et al.*, 2013; *Sharov et al.*, 2007].

The data of instrumental observations of local seismicity revealed earthquakes with a magnitude of more than 5 [*Ogadzhanov et al.*, 2013]. The manifestation of seismicity in this area is associated with local geodynamic processes, in particular, the regional direction of the field of local seismicity, as well as the extension of the corresponding newest faults, has a predominantly north-eastern orientation. In addition, it is assumed that local manifestations of seismicity can be induced by the influence of strong earthquakes with foci in the alpine folded region of the through European-African tectonic belt. For example, strong earthquakes of Krasnovodskoye (1895) with a magnitude of 7.9, Caspian (November 25, 2000) with magnitudes of 6.1 and 6.4 are known; Balkhanskoye (December 6,

2000) with a magnitude of 7.3. The facts are given that during the Caspian earthquakes of November 25 and Balkhansky on December 6, 2000, at distances of 1300 and 1500 km from their epicenters, respectively, there were noticeable shocks that could not be explained from the standpoint of classical ideas about the attenuation of seismic waves with an increase in the distance from the epicenters of the earthquake. In the time range from tens of minutes to several days relative to the time of the main push of these strong earthquakes, earthquakes generated by faults of the Volga region arose [*Ogadzhanov*, 2002; *Sharov et al.*, 2007]. The strongest concussions during the earthquakes of November 25 and December 6, 2000 were recorded in the eastern part of the Elshano-Sergiev graben, where the "Vostochnoye" and "Zapadnoye" UGS are located. During the period of geodynamic activation preceding the Balkhansky earthquake on December 6, tremors in the eastern part of the Elshano-Sergievsky graben began to be felt 30–40 minutes before the main shock in the focal zone of this earthquake. Based on the results of these studies, a conclusion was made about the geodynamic influence of the zones of earthquake foci of the geosynclinal part of the through tectonic belt on the activation of faults in its platform part [*Ogadzhanov*, 2002].

Also, manifestations of seismic activity within the geodynamic ground of this region were associated with cyclical changes in external geophysical fields, namely gravitational due to the influence of celestial bodies and electromagnetic due to solar activity [*Ogadzhanov and Ogadzhanov*, 2013]. In addition, it was suggested that, in addition to natural facts, local weak seismic performance could be due to explosions of mining enterprises, which was taken into account when recognizing seismic events of a natural and technogenic nature [*Ogadzhanov et al.*, 2013]. Thus, previous studies were aimed at finding a geotectonic interpretation of the seismicity process in a given area, the impact of UGS operation on the seismic regime was not taken into account.

3 Joint analysis of seismicity and operating modes of UGS

The most representative period from 2005 to 2007 was chosen for studies of the influence of UGS on seismicity. During this time period, 29 seismic events were recorded, of which 22 occurred near the "Vostochnoye" and "Zapadnoye" UGS, 5 – near the "Uzhnoye" UGS and 2 between all considered UGS. The main feature of the operation of underground storage facilities is the cyclical nature of the process. In this regard, we will consider the relationship between the cyclical operation of the "Vostochnoye", "Zapadnoye" and "Uzhnoye" UGS and seismic activity in the areas of their location.

Figure 5, Figure 6 and Figure 7 show seismicity of UGS location area against the background of formation pressure change over time (operation mode). In Figure 5 and Figure 6, the periods of the end of the injection period and the end of the gas extraction period are indicated by vertical lines.

Figure 8, Figure 9 and Figure 10 shows the number of seismic events by month against the background of changes in formation pressure.

The presented results make it possible to judge the connection of seismic activity with periods of increase and decrease of formation pressure at UGS.

4 Discussion

The questions of establishing the technogenic nature of seismicity are quite complex, as evidenced by numerous discussions, including those already mentioned in this article [*Bossu et al.*, 1996; *Simpson and Leith*, 1985]. Nevertheless, signs have been identified and described in which the earthquake can be attributed to man-made. So, in the work [*Davis and Frohlich*, 1993] listed 7 signs of a technogenic earthquake. It is proposed to separate natural and technogenic earthquakes according to a complex of geological and seismological data [*Dahm et al.*, 2012], modelling results [*Dahm et al.*, 2015].

We will carry out a formal analysis of the possible nature of seismicity in the area under study, using the data available to us and adapting the existing developments in this matter to the specifics of UGS, Table 2.

Let us explain the estimates presented in Table 2.

1. Seismological observations in this area in 2005–2007 were carried out outside the work of the UGS and their man-made nature was never studied. Therefore, we put "no" in the first row of the table.

2. There is a clear correlation between UGS operation and seismicity, Figure 11, Figure 12 and Figure 13.

For the formal evaluation of the observed bond, we can use the Spearman test [*Glantz*, 1994]. Convert Figure 11 data into the following variable rows: operation period: 1st, 2nd, 3rd, 4th; number of seismic events: 1, 3, 9, 12.

To estimate the Spearman rank correlation (R_s), it is necessary to arrange the data in the given rows in ascending order and replace their values with ranks, that is, their numbers in the ordered series. Let us present the original, ordered and ranked

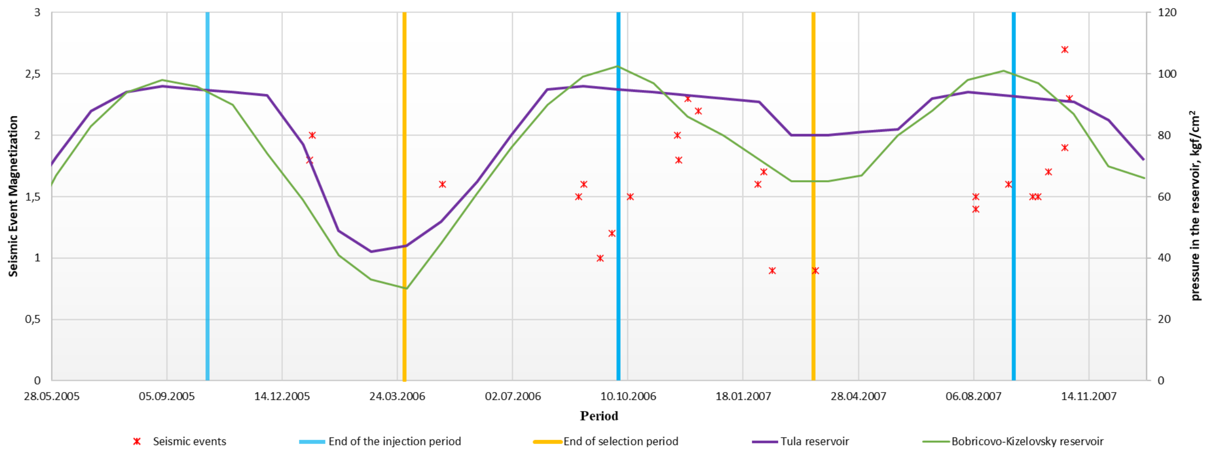

Figure 5: Seismicity at the "Vostochnoye" UGS, during its operation in 2005–2007.

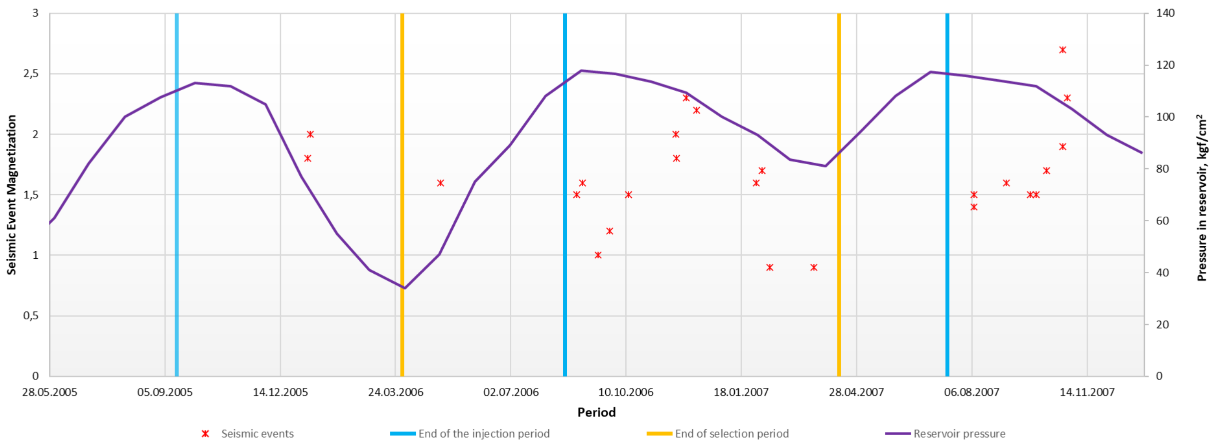

Figure 6: Seismicity at the "Zapadnoye" UGS, during its operation in 2005–2007.

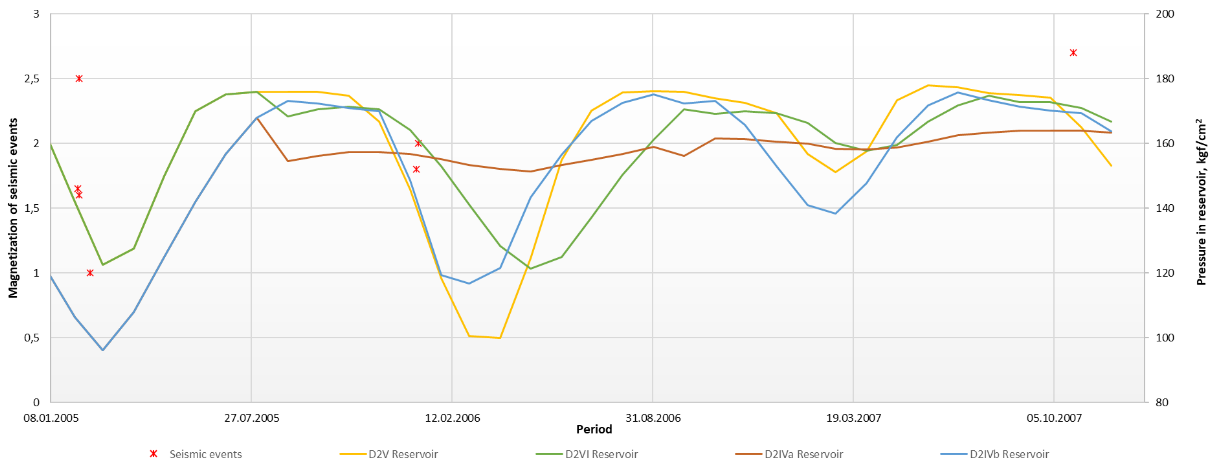

Figure 7: Seismicity at the "Uzhnoye" UGS, during its operation in 2005–2007.

Table 2: Assessment of the technogenic nature of the seismicity at the "Vostochnoye", "Zapadnoye" and "Uzhnoye" UGS (adapted developments from the works [Dahm et al., 2012; Davis and Frohlich, 1993]).

Sign of the man-made nature of the earthquake	Execution for UGS locations			Notes
	Vostochnoye	Zapadnoye	Uzhnoye	
1. Have seismic events of similar genesis been noted in this area?	No	No	No	Researched for the first time
2. Is there a correlation between the operation of UGSs and humility?	Yes	Yes	Yes	See Figure 11, Figure 12 and Figure 13
3. How close are epicenters located from the UGS? Or: are the epicenters located in the geodynamic influence zone of the UGS?	Yes	Yes	Yes	See Figure 2
4. Had there been any seismic events near the UGS?	Yes	Yes	Yes	See Figure 2
5. Are there any activated faults nearby?	Yes	Yes	Yes	See Figure 2
6. Is the change in pressure in the UGS tank sufficient to increase the seismicity?	Yes	Yes	Yes	See Figure 14 and Figure 15

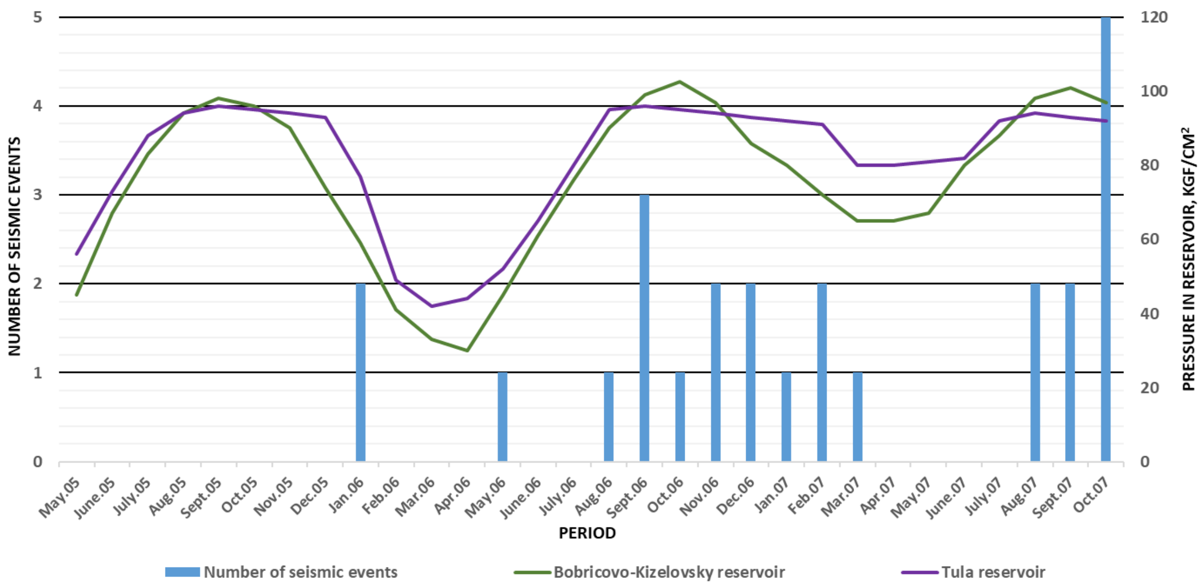

Figure 8: Monthly averaged seismic activity at the "Vostochnoye" UGS.

values of the two variables in question in the form of a Table 3.

According to Table 3, we calculate the original Spearman rank correlation coefficient by the formula:

$$R_s = 1 - \frac{6\sum d^2}{n^3 - n} = 1 - \frac{6\sum d^2}{n(n^2-1)},$$

since $d = 0$, we get $R_s = 1$.

The value of the rank correlation coefficient $R_s = 1$ indicates that there is a relationship between the operating period of the UGS and the number of seismic events in a given area.

We evaluate the validity of this conclusion, that is, whether the obtained value of R_s is explained by various kinds of accidents, in other words, we test the hypothesis of no connection, $R_s = 0$.

In our case, the critical region of the Spearman rank correlation coefficient is defined for different significance levels and sample volumes and the variables have only $n = 4$ gradations (Table 4).

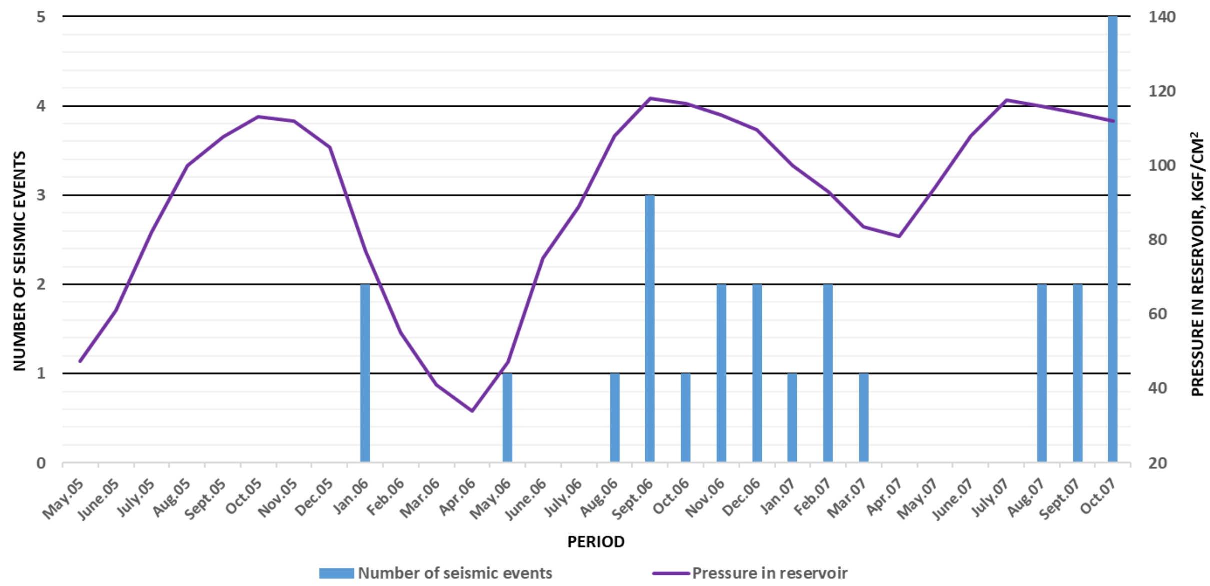

Figure 9: Monthly average seismic activity at the "Zapadnoye" UGS.

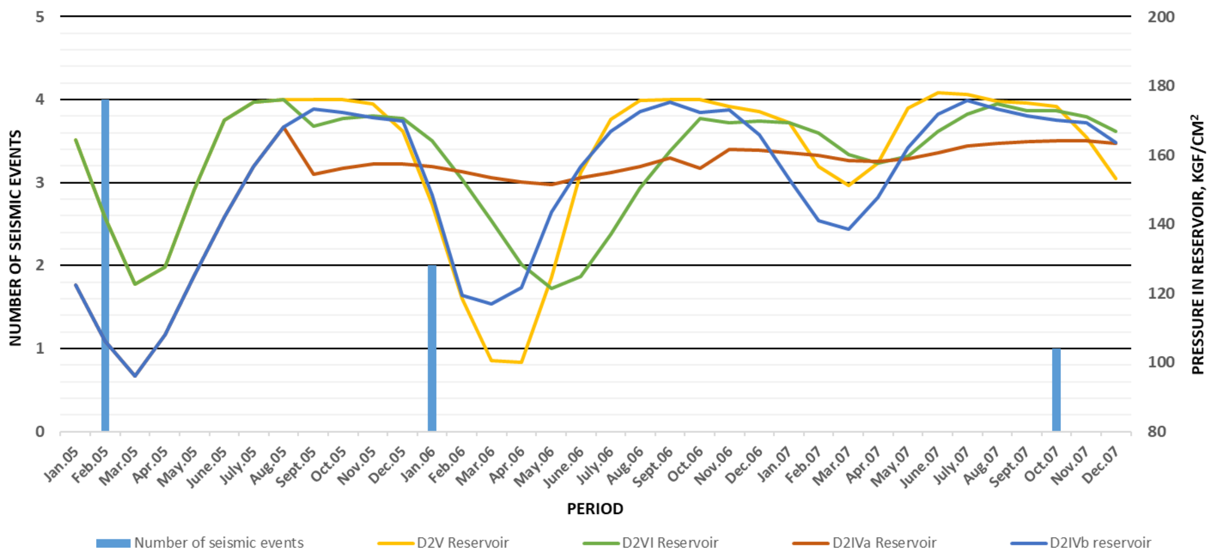

Figure 10: Monthly averaged seismic activity at the "Uzhnoye" UGS.

Table 3: Data for calculating Spearman rank correlation coefficient

First variable values			Second variable values			Rank difference, d
Original	Ordered	Ranks	Original	Ordered	Ranks	
1st	1	1	1	1	1	0
2nd	2	2	3	3	2	0
3rd	3	3	9	9	3	0
4th	4	4	12	12	4	0

With $n = 4$, we conclude from Table 4 that the presence of the relationship between variables in the task under consideration can be recognized only at the significance level $q = 0.2$, i.e., with probability 0.8, the data given in Figure 11 can be considered as evidence that the relationship does occur. Similar conclusions can be drawn from Figure 12 ($R_s = 0.7$) and 13 ($R_s = 1$).

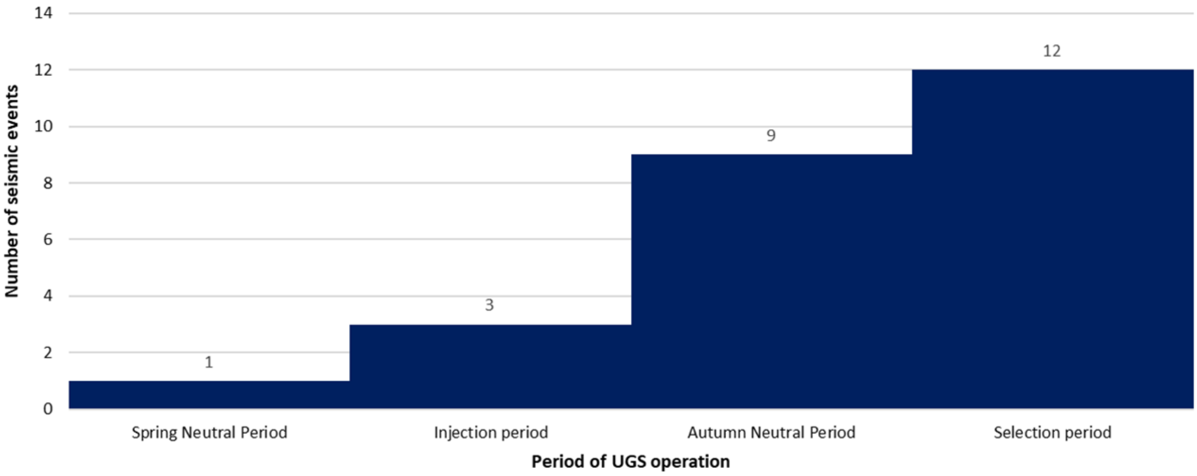

Figure 11: Seismic events at the "Zapadnoye" UGS, during its operation.

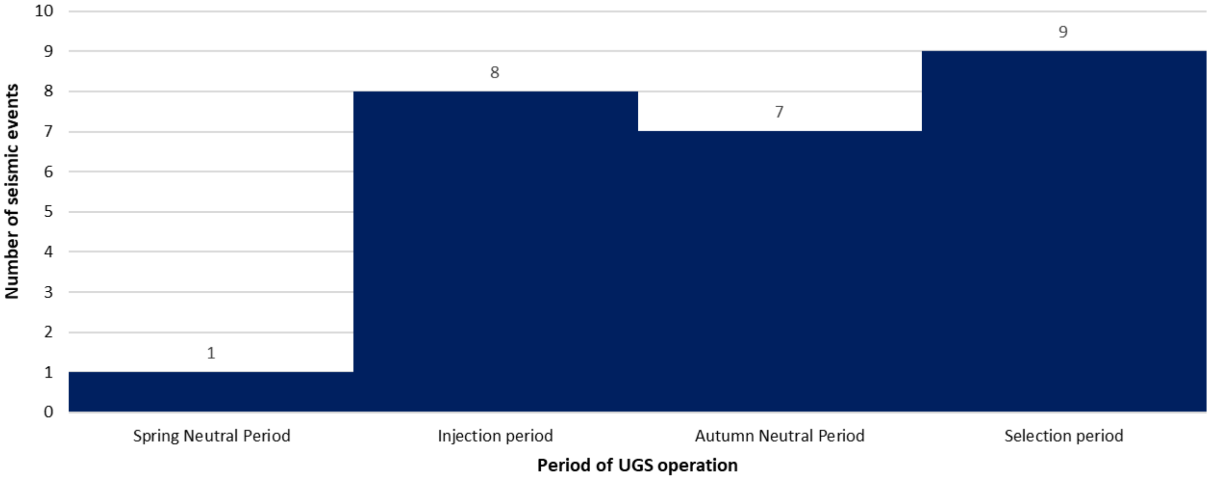

Figure 12: Seismic events at the "Vostochnoye" UGS, during its operation.

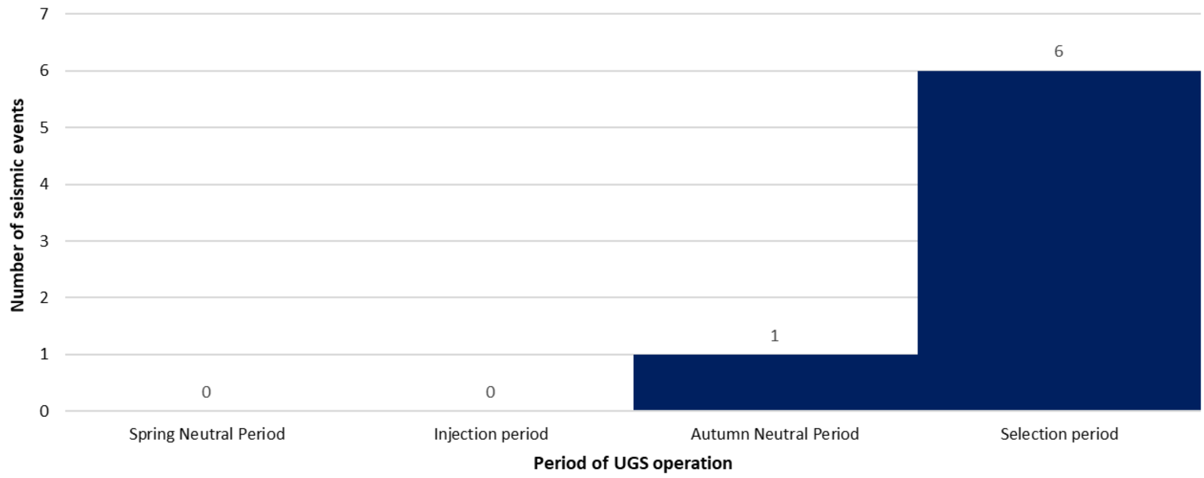

Figure 13: Seismic events at the "Uzhnoye" UGS, during its operation.

As an additional argument, excluding the accidental fall of the periods of operation of UGS and seismic events, let us pay attention to the end dates of the 2006 and 2007 gas injection season at the "Zapadnoye" UGS. In 2006, the pumping was stopped on September 11 and the first seismic event was registered 5 days later. In 2007, gas injection was stopped on July 16, and at the beginning of August, an increase in the level of seismic activity began. A similar time delay was previ-

Table 4: Critical values of Spearman's rank correlation coefficient [*Glantz*, 1994]

	Significance level q								
n	0.50	0.20	0.10	0.05	0.02	0.01	0.005	0.002	0.001
4	0.600	1.000	1.000						
5	0.500	0.800	0.900	1.000	1.000				
6	0.371	0.657	0.829	0.886	0.943	1.000	1.000		
7	0.321	0.571	0.714	0.786	0.893	0.929	0.964	1.000	1.000
8	0.310	0.524	0.643	0.738	0.833	0.881	0.905	0.952	0.976

ously noted in [*Tang et al.*, 2015]. Thus, it can be argued that most seismic events occurred during the period when the gas pressure in the UGS reached a maximum value, that is, at the end of the gas injection season, during the autumn neutral period and in the first months of extraction.

3. The distance R at which the geodynamic influence of man-made objects on the array can be felt is estimated from 3–5 of their sizes r [*Dahm et al.*, 2012] to 20–30 r according to geodynamic monitoring [*Panzhin*, 2020] and even more [*Dobrovolsky.*, 1991]. Since the dimensions of the UGS r considered are the first kilometers, we assumed that the radius of their geodynamic influence area R reaches 100 km in the situation under consideration and analyzed the seismic events that occurred at this distance from the UGS. Taking into account the tectonic structure of the area and the manifestation of seismicity, we believe that the "Vostochnoye" and "Zapadnoye" UGS extends its geodynamic influence to the dislocations of the Elshan-Sergiev Graben and the associated faults of the Saratov and Karamysh-Dono-Medveditsky tectonic zones, and the geodynamic influence of the "Uzhnoye" UGS extends to the newest faults of the Stepnovsky tectonic rampart and Balakovo graben.

Based on this assessment, we assume that all seismic events involved in the analysis could be related to the work of the UGS.

4. The nearest seismic events recorded in 2005–2007 occurred at a distance of less than 20 km from the UGS (Figure 2). Note that the seismological network that existed at that time was created to monitor the seismicity of the region, which did not take into account the requirements for monitoring man-made seismicity, and did not allow for registration.to identify weaker seismic events in the zones of technogenic impact [*Butler and Simser*, 2017].

5. Features of active geodynamic manifestations of the European-African tectonic belt in the area of location of the considered UGS are characterized by the severity within its limits of anomalies of new tectonic movements and a seismicity field extending along the regional direction of the SW–NE prevailing for the area of location of the UGSs [*Ogadzhanov and Ogadzhanov*, 2014]. The European-African tectonic belt within the region under consideration is a collection of various tectonic structures in orientation and kinematics, grouped in a strip of about 100–150 km in the direction of the Volga River; this is clearly illustrated by a diagram of tectonics elements of the UGS area, which shows faults that experienced activity presumably during the late Oligocene-Quaternary (newest) period of tectogenesis (Figure 1 and Figure 2). Evidence of the latest tectonic activity of this regional structure is the severity within its limits of high (up to 900 m) anomalies of the latest tectonic movements and the seismicity field, extending along the regional direction of the SW–NE prevailing for the UGS location area [*Ogadzhanov and Ogadzhanov*, 2014].

The diagram in Figure 2 shows that the seismicity in the studied area of the UGS is confined precisely to the latest faults entering the part of the Euro-Pace-African tectonic belt activated at the present stage.

As is known, faults prone to reactivation at subsurface exploitation facilities are those that are favorably located in regional or local stress fields (depending on their size or rank). Among such faults at the "Vostochnoye" and "Zapadnoye" UGS are the newest faults of the Elshano-Sergievsky graben of the sub-latitudinal range and the graben-sectioning sub-meridional faults of the Saratov and Kara-Myshsko-Dono-Medveditsky dislocations. The faults prone to reactivation, to which the "Uzhnoye" UGS is confined, are the newest faults extending from the north–south of the Stepnovsky shaft and the fault extending in the direction of the South from the Stepnovsky shaft to the Balakovo graben (Figure 2). The magnitude of the amplitudes of the latest tectonic movements in the south-eastern part of the Stepnovsky shaft reaches + 550 m. Based on the given data, it can be believed that the faults of the Stepnovsky shaft experienced activation in the latest period. The analysis of the measurement cycles performed at the geodynamic test site in the south-eastern part of the Stepnovsky shaft made it possible to confirm the location of known fault zones within which the values of modern movements up to 6 mm were established\year [*Kwiatkovskaya et al.*, 2017]. According to the [*Kravchenko*, 2007], the background values for the Middle and Lower Volga region are the values of modern movements of the Earth's crust from 0 to 2 mm year^{-1}, relative to these values the values of modern movements of 6 mm year^{-1} can be considered anomalous. Thus, we believe that in the area of the UGS there are faults of different orders, activated at the modern geotectonic stage of the development of this territory.

6. The stress changes that are minimally significant for the excitation of seismicity include tidal stresses estimated in thousandths of MPa [*Foulger et al.*, 2018]. The pressure changes in the UGS are more than 5 MPa, which is several orders of magnitude higher than the designated threshold level. Changes in gas pressure at UGS are considered sufficient to explain man-made seismicity at UGS [*Plotnikova et al.*, 1996; *Tang et al.*, 2015].

The fact of activation of seismicity during the period of reaching the maximum pressure on the UGS is clearly illustrated for the "Vostochnoye" and "Zapadnoye" UGS in Figure 14 and Figure 15. Thus, a connection is established between the processes of changing the stress state of the array during the operation of UGS and the seismic activity of the area.

As it can be seen from Figure 11, Figure 12 and Figure 13, the largest number of seismic events occurs during the gas extraction period (formation pressure reduction). The observed effect may be related to the phenomenon of the critically stressed state of the massif in the vicinity of the IGS, both when the gas pressure increases and decreases and subsequent possible reactivation of tectonic faults with push-like deformation. The implementation of such a periodic process can be facilitated by the existence of areas of the critically stressed state in the upper part of the Earth's crust [*Batugin*, 2021]. In Figures 5–15, it can be seen that the phases of maximum achievement and subsequent reduction of formation pressure on UGSs are almost completely coincident with the increase in the number of local seismic events.

Thus, for the areas where the UGSs under consideration are located, it is possible to note the fulfillment of all conditions under which seismic events at subsoil development facilities are classified as man-made.

5 Conclusion

Analysis of the situation with the manifestation of seismicity at the "Vostochnoye", "Zapadnoye" and "Uzhnoye" UGS allows us to conclude that we are dealing with a new type of technogenic seismicity in engineering activities for Russia. There is a wide list of signs indicating the relationship between the mode of operation of UGS and the cyclical nature of the manifestation of seismicity:

- before the start of operation of UGS, technogenic seismicity in this area was not known;
- there is an undoubted correlation between the mode of operation of UGS and seismicity;

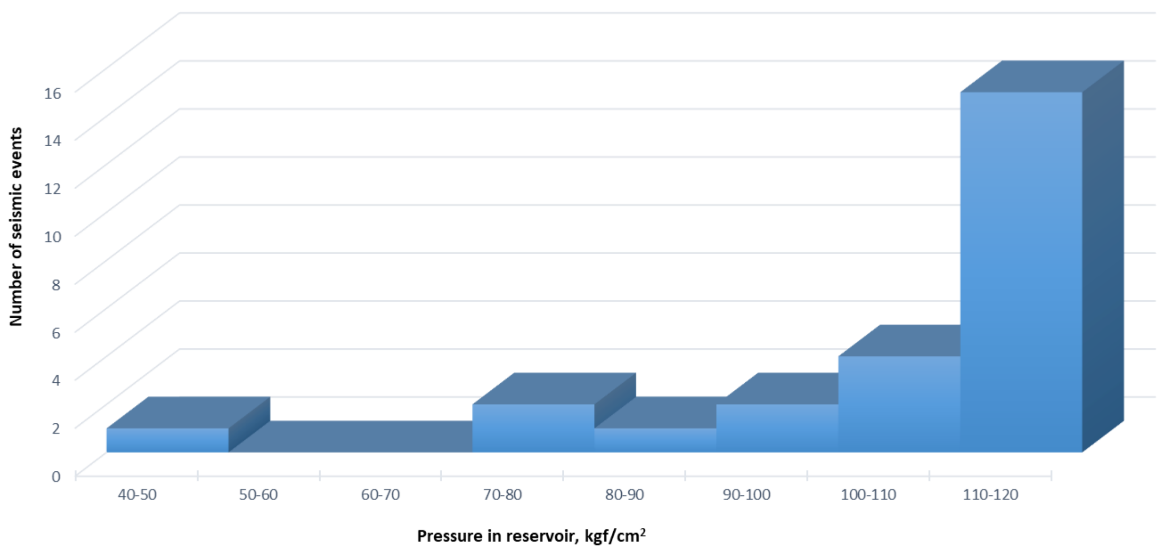

Figure 14: Diagram of the relationship between the magnitude of reservoir pressure and the number of seismic events at the "Zapadnoye" UGS.

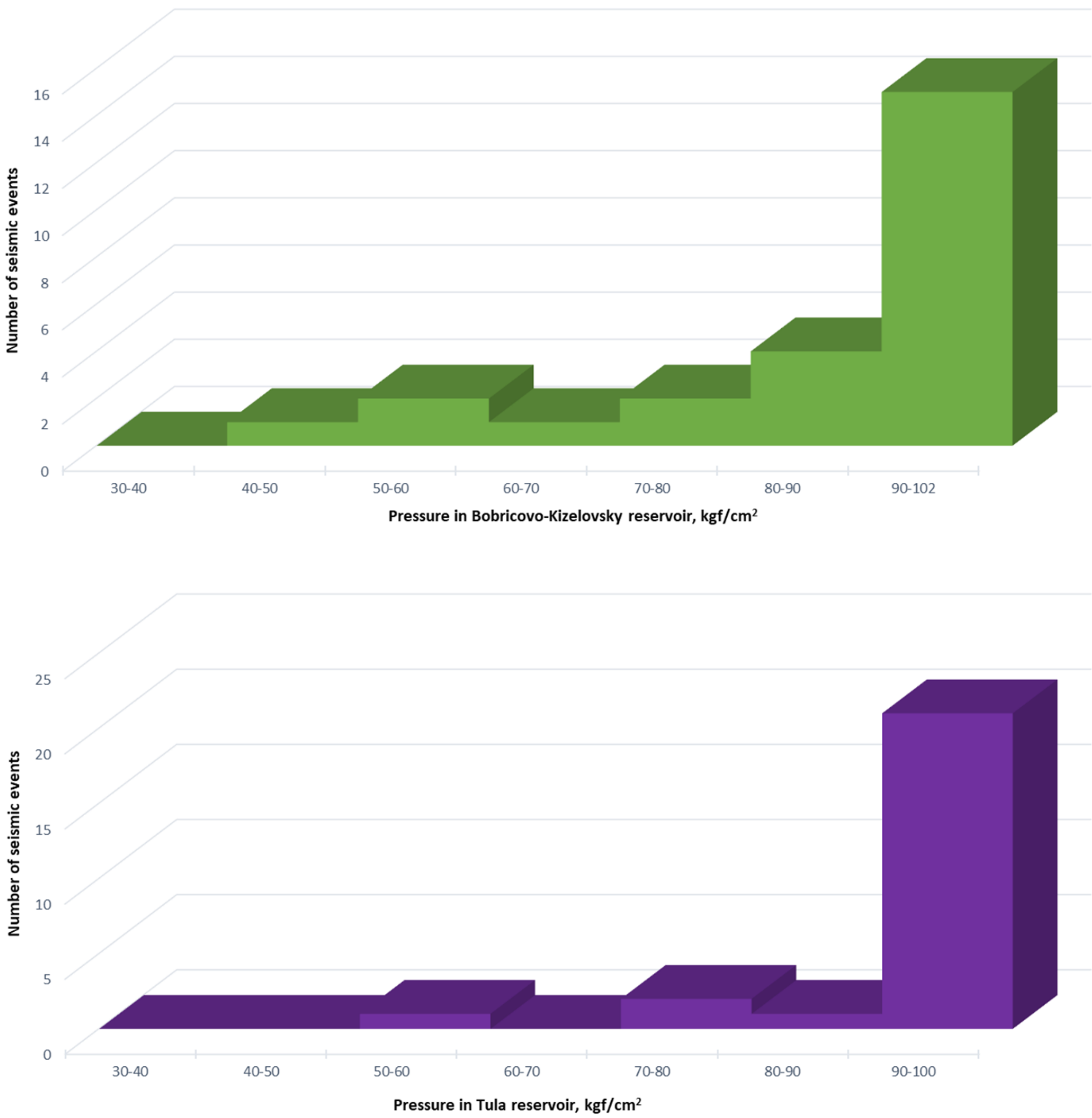

Figure 15: Diagrams of the relationship between the magnitude of reservoir pressure and the number of seismic events for reservoirs at the "Vostochnoye" UGS.

- the epicenters of seismic phenomena are located in the zone of geodynamic influence of UGS;
- there are crustal faults in the region that experienced activation in the Late Cenozoic and react to strong earthquakes of neighboring tectonic regions, which indicates their predisposition to reactivation;
- pressure changes in UGS are sufficient to excite weak seismicity.

Since UGS are environmentally hazardous objects, it is necessary to monitor and study in detail the relationship between UGS operation modes and seismicity, taking into account both the possibility of UGS influence on geodynamic processes and the impact of seismicity on UGS. To study such a connection and forecast the ecological situation in the areas of UGS operation, it is necessary to include observations of seismicity in the complex geodynamic monitoring.

Acknowledgments. Authors extend appreciation to the leadership of National University of Science and Technology "MISiS" and Saratov National Research State University named after N. G. Chernyshevsky for providing necessary support of this research.

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