ISSN 0747-9239, Seismic Instruments, 2018, Vol. 54, No. 4, pp. 479–487. © Allerton Press, Inc., 2018.
Original Russian Text © A.A. Emanov, A.F. Emanov, A.V. Fateev, E.V. Leskova, 2017, published in Voprosy Inzhenernoi Seismologii, 2017, Vol. 44, No. 4, pp. 51–62.

Simultaneous Impact of Open-Pit and Underground Mining on the Subsurface and Induced Seismicity

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Abstract—In the fourth quarter of 2016, the system for monitoring induced seismicity in the Kuznetsk Basin (Kuzbass) began to record increasing seismic activity in the area of the Kaltan open-pit coal mine, which was struck by a series of seismic events felt in cities and settlements of the Kuzbass. In addition to the existing monitoring network, a temporary network of stations has been established, which has significantly increased the accuracy and representativeness of technogenic earthquake records. Markedly expressed seismic activation near open mine works (the Kaltan open-pit mine) has been revealed. The seismically activated area covers several open mine works and their vicinity. The strongest earthquakes have occurred outside the open-pit mine at the boundary of the dump. Inside the activated area, near the operating underground mine works (the Alarda mine), local seismic activation represented by low-energy technogenic earthquakes has been recorded. The largest number of perceptible earthquakes occurred in the fourth quarter of 2016. According to the monitoring data, the number of earthquakes with magnitudes 2.5–4 decreased in early 2017, but since February 2017, seismic activation has increased around the underground mine works, which was manifested as a significant increase in the number of low-energy technogenic earthquakes. In fact, the technogenic seismic hazard has shifted from open mine works towards the area of the operating underground mine.

Keywords: induced seismicity, Kuzbass, earthquakes, industrial blasts

DOI: 10.3103/S0747923918040035

INTRODUCTION

Induced seismicity accompanies the extraction of both solid and liquid minerals (Nikolaev, 1994; Ponomarev, 2008; Kozyrev et al., 2009; Luo et al., 2010; Adushkin and Turuntaev, 2015; Adushkin, 2016). As a rule, in coal mining, underground and surface mines operate in close proximity to each (Kholub, 2007; Adushkin, 2015; Emanov et al., 2009, 2017). Coal production in the Kuznetsk Basin (Kuzbass) has the strongest technogenic impact on the Earth's crust and consequently triggers large-scale induced seismicity in this region (Emanov et al., 2009, 2017; Adushkin, 2015). For this territory, the network of stationary seismic stations providing automatic real-time information was significantly expanded from one station in 1997 to 15 state-of-the-art digital stations in 2015–2017 (Emanov et al., 2015a, 2015b).

The automated seismological data collection and processing system at the Altay-Sayan Branch of the United Geophysical Service, Russian Academy of Sciences (ASB GS RAS), began development in 1998, when the first digital seismic stations appeared (Emanov et al., 2013). The introduction of new data transmission and processing technologies, as well as continuous updating of the hardware system, made the network's seismic stations autonomous and considerably improved the quality, volume, and efficiency of data input and processing. Today, the Center for Seismological Data Collection and Processing (Novosibirsk) is represented by several dozen computerized machines that collect, process, and monitor the quality of seismological information, as well perform any other service functions. The center accumulates data from approximately 300 stations of the Global Seismographic Network. The data are processed in two flows: one for automatic processing of teleseismic events and the other for regional seismicity. The existing system automatically determines the parameters of strong events in the region in the first minutes, and subsequent notifications verified by a specialist are forwarded to interested persons in 3–5 min with respect to the origin time.

As the number of stations in the Kuzbass increases in the aggregate with the updated system of registration and processing of seismological data, the number of recorded events in Kemerovo oblast' increased many-fold compared to the previous period (until 2013). The existing configuration of the seismic network makes it possible to control seismic activity in the Kuzbass at the level of the low magnitude limit $ML = 1–2$, which helps reveal a series of local segments for which, along with industrial blasts, the seismic process is recorded. Since it is confined to mineral mining regions, it is included into the induced seismicity category.

In this paper, seismic activation implies an increase in the number of seismic events (earthquakes, technogenic earthquakes, mine percussions, etc.) in a certain confined region. The use of more sensitive equipment shows seismic activations at a lower energy level. The purpose of seismological monitoring in the Kuzbass is to discover new seismic foci, to establish their correlation with industrial anthropogenic activity, and to notify the authorities of industrial enterprises and the regional administration on taking timely measures to decrease risks to the population.

The present monitoring system detects the occurrence of seismic activations and relays them to mining plants in real time (with a 1–2 min delay to process incoming information). For a deeper understanding of the physics of the processes, additional networks of temporary stations have been set up near activated mine works. Such research was performed near the city of Polysaevo in 2007–2009 (Emanov et al., 2009), near an open mine works in the area of the Bachat open-pit mine in 2013–2016 during the largest seismic activation (Emanov et al., 2017), and in the other areas of the Kuzbass (Emanov et al., 2012).

INDUCED SEISMICITY IN THE KUZBASS IN 2016

In 2016, the ASB GS RAS, had 18 seismic stations operating in Kemerovo oblast, dedicated to seismological monitoring of the Kuzbass, one of the densest areas of the Altay-Sayan regional seismic network. Most of the Kuzbass seismic stations were set up jointly with coal companies directly at enterprises engaged in commercial mineral extraction in the vicinity of open workings and underground mines (Fig. 1) (Emanov et al., 2015a, 2015b).

The largest accumulation of technogenic earthquakes in the region in 2016 was recorded near Polysaevo (Fig. 1), where over several years (2007–2010), the ASB GS RAS, conducted seismological observations with temporary networks of stations, resulting in multiple detection of seismic activations confined to coal mining areas (Emanov et al., 2012). In 2016, near Polysaevo, approximately 80 relatively weak events were recorded in the magnitude range of $0.9 \leq ML \leq 2.6$, which occurred primarily in January.

In addition, at the level of weak and moderate earthquakes ($ML \leq 3$), seismically active regions were found in the city of Mezhdurechensk, the village of Bol'shaya Talda, and the Krasnobrod, Kiselev, and Bachat open-pit mines; seismic events were also recorded northwest of the city of Novokuznetsk (Fig. 1).

The year of 2016 was marked by a decline in seismic activity in the epicentral area of the Bachat earthquake of June 18, 2013, at 11:02 ($ML = 6.1$) at the edge of the Bachat open-pit coal mine, one of the largest in the Kuzbass (Emanov et al., 2017). Here, 35 seismic events in the magnitude range of $0.5 \leq ML \leq 2.2$ were localized, most of them (23) in January–February.

In October–November 2016, simultaneously with the decrease in the number of earthquakes at the Bachat open-pit mine, seismic activity also intensified at other open-pit mines in the Kuzbass. For example, on November 9, 2016, an event with $ML = 3.8$ was recorded at the Salair Ridge 10–15 km from large coal mining enterprises (the Krasnobrod and Kiselev open-pit mines), and a series of earthquakes with magnitudes greater than 3.5 was recorded near the Kaltan open-pit coal mine near the village of Malinovka (Fig. 1).

SEISMIC ACTIVATION IN THE AREA OF THE KALTAN OPEN-PIT COAL MINE (2016)

Coal has been extracted in the Kaltan open-pit coal mine in southern Kemerovo oblast (Fig. 1) since 1957. Currently, operations are in two fields: Osinniki and Kaltan, which are two closely located independent open-pit mines (Fig. 2). The open-pit mines produce ~3.5 mln t of coal per year on average. In the same region, coal is extracted from the Alarda (Alardinskaya) mine. It yields ~3.6 t of coal per year on the average.

In the fourth quarter of 2016, the system for monitoring induced seismicity in the Kuzbass began to record intensifying seismic activity in the area of the Kaltan open-pit coal mine, which was struck by a series of seismic events felt in cities and villages of the Kuzbass. By December 2016, ASB GS RAS, had set up a network of five temporary seismic stations in the area of seismic activity for a more accurate and representative study of the energy patterns. In February 2017, the number of stations increased to eight (Fig. 2). It is interesting that as soon as the temporary network of the seismic stations was installed, it began to record seismic activity in the area of the Alarda mine that had not been revealed by the stationary network of seismic stations.

To obtain highly accurate information on technogenic earthquakes, it is necessary first to increase the

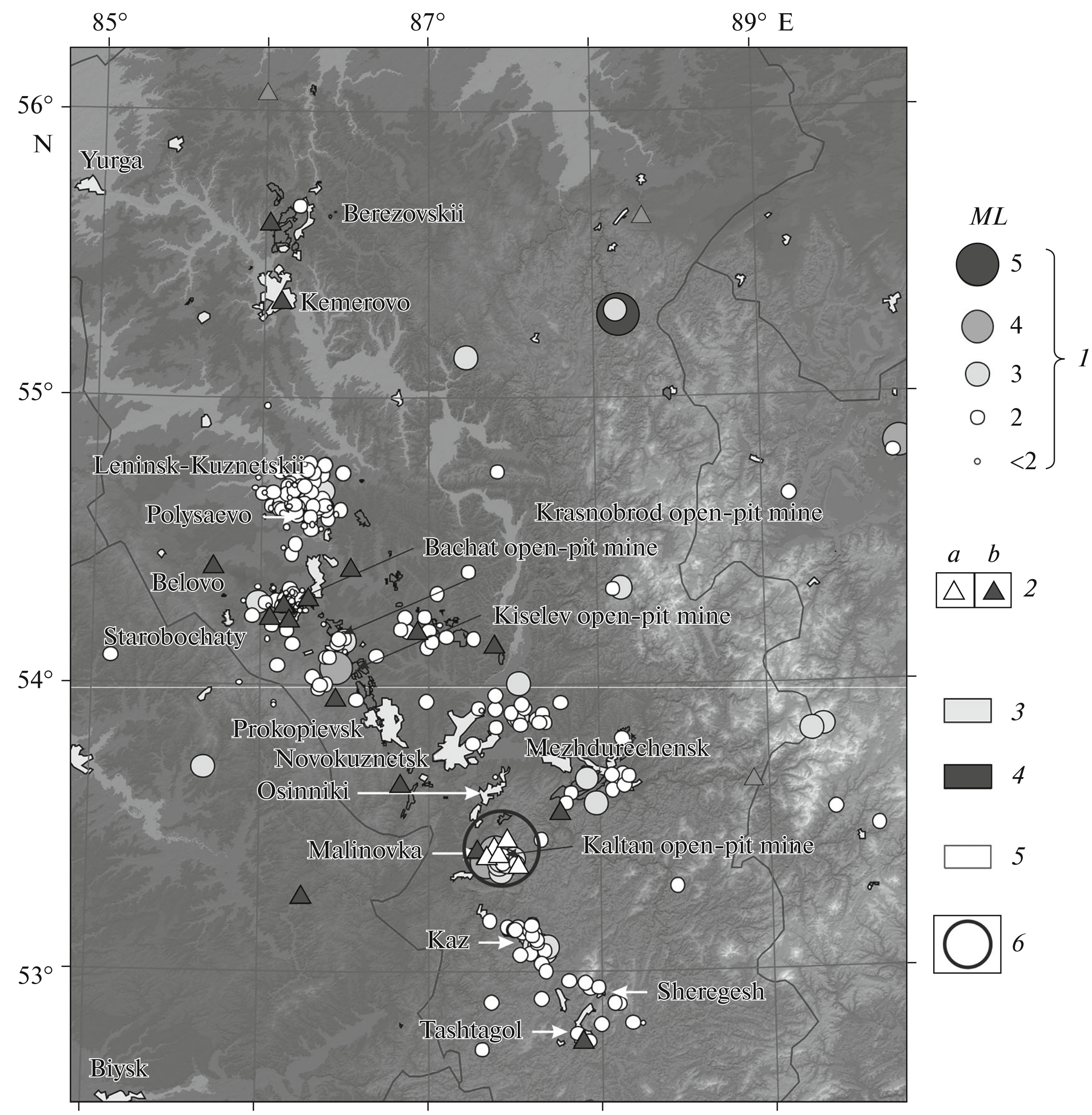

Fig. 1. Locations of stations of seismic monitoring network in Kuzbass and earthquake epicenters in Kemerovo oblast in 2016. Arbitrary notes: (*1*) earthquake epicenters; (*2*) seismic stations: (*a*) temporary; (*b*) stationary; (*3*) settlements; (*4*) open-pit coal mines; (*5*) administrative boundaries; (*6*) study area.

number of stations in the activated region; second, to use state-of-art methods for locating events oriented toward dense networks; and third, to construct reliable velocity models of the Earth's crust in the seismic activation area. The results obtained in the vicinity of the Kaltan open-pit coal mine include all three lines of research.

Up to now, we have obtained and processed the data from the stations of the temporary seismic network over four months of observations: December 1, 2016–April 1, 2017 (Figs. 2–5). The accuracy in determining the locations of hypocenters inside the network ranged from hundreds of meters to 2 km (about 1 km on average) both in coordinates and the depth. Figure 2 shows a general map of the technogenic earthquake epicenters over the observation period. It shows segments of open-pit mining and the locations of temporary and stationary seismic stations, whose data were taken into account during processing. It is interesting that the Kaltan field of the Kaltan open-pit mine is free of technogenic earthquake epicenters. The technogenic earthquakes are confined to two segments of the Osinniki field of the Kaltan open-pit mine and the Alarda mine area between them. The seismic process at the site is accompanied by simultaneous impact on the subsurface of both the open coal-mine works and underground mines where coal is mechanically extracted. The events in the area of the Alarda mine are characterized by lower energies and are grouped and found within the area activated by open mine works.

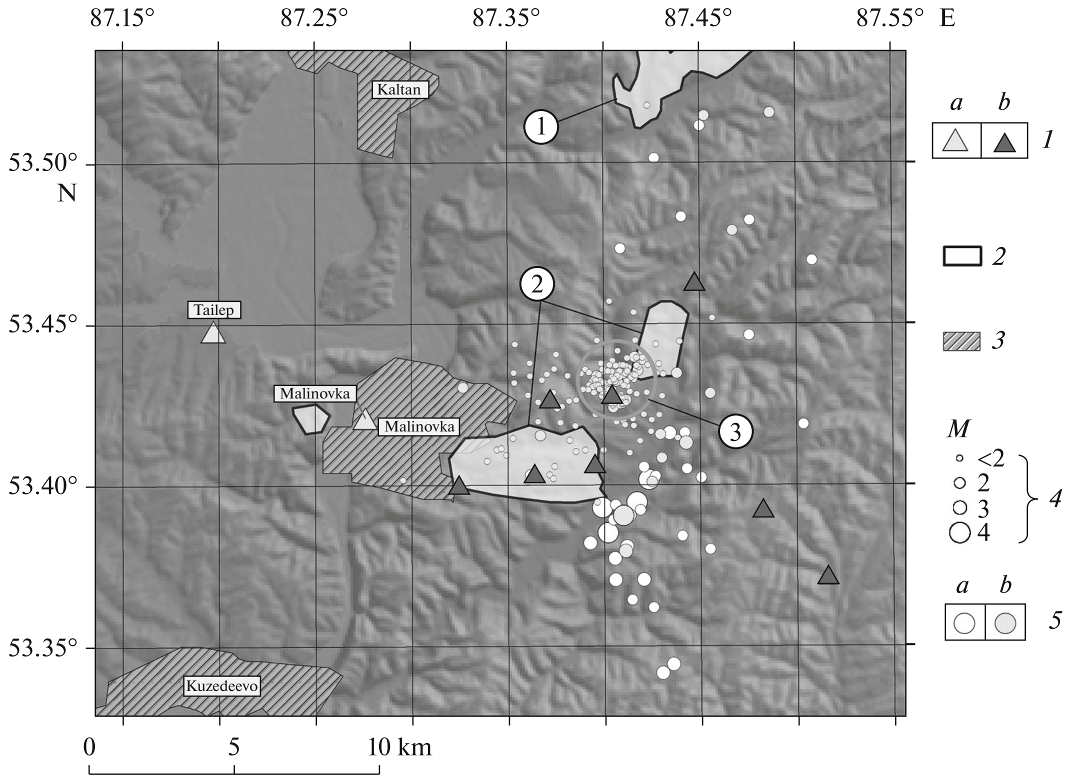

Fig. 2. Study area and location of earthquake epicenters. Arbitrary notes: (*1*) seismic stations: (*a*) stationary; (*b*) temporary; (*2*) open-pit coal mines and surface mines; (*3*) settlements; (*4*) earthquake epicenters; (*5*) seismic events *a* recorded before establishment of stations of temporary seismic network; (*b*) recorded during first 1.5 months of operation of stations from temporary seismic network. Circled numbers: (1) Kaltan field of Kaltan open-pit coal mine; (2) Osinniki field of Kaltan open-pit coal mine; (3) underground coal mining region at Alarda mine.

In other experiments with local networks of seismic stations in the Kuzbass, we studied technogenic earthquakes near underground mines (Emanov et al., 2009, 2012, 2015a) and the strongest seismic activation in the vicinity of the Bachat open-pit mine (Emanov et al., 2017). Open-pit mines were also found near the underground mine works, but simultaneous seismic activation has not been recorded in the subsurface near the underground and open mine works on the local site until recently.

In processing, seismic events were divided into technogenic earthquakes and industrial (surface mine) blasts. Acts of blasts were confirmed by data obtained directly from mine workers; information on industrial blasts was provided by coal plant administrations and was checked for the occurrence of sound waves in seismograms. Figure 3 shows detailed information on seismic events in the area of experimental research with the temporary network of seismic stations. In the study area, the subsurface of the Kuzbass was affected by the following:

(1) an underground mine with mechanical coal extraction;

(2) a change in the topography caused by open mine works, including open-pit mines in the form of hollows and dumps shaped as artificially piled up hills;

(3) industrial blasts.

In the spatial distribution of epicenters of industrial blasts and technogenic earthquakes, we see seismically activated areas that do not coincide with spots of blasting operations. Most of the blasts are detonated near the Korchakol'sk open-pit coal mine west of Malinovka, where induced seismicity is not recorded now, and to the north, where seismic activation is moderate.

In the distribution of epicenters of seismic events in the vicinity of the Kaltan open-pit coal mine, we have distinguished two activations of technogenic earthquakes with different energy levels. One is related to open-pit-type mining operations. The activated area covers the Osinniki field of the Kaltan open-pit coal mine (Fig. 3). The earthquakes of this activation caused perceptible tremors in a large area. The strongest events occurred in the local dump zone in the southern part of the Osinniki field. Note that dumps, which are artificial soil masses, exert a strong local impact on the Earth's crust. Taking into account the shallow depths of the sources (the first few kilometers) and confined nature of the region, reciprocal seismic

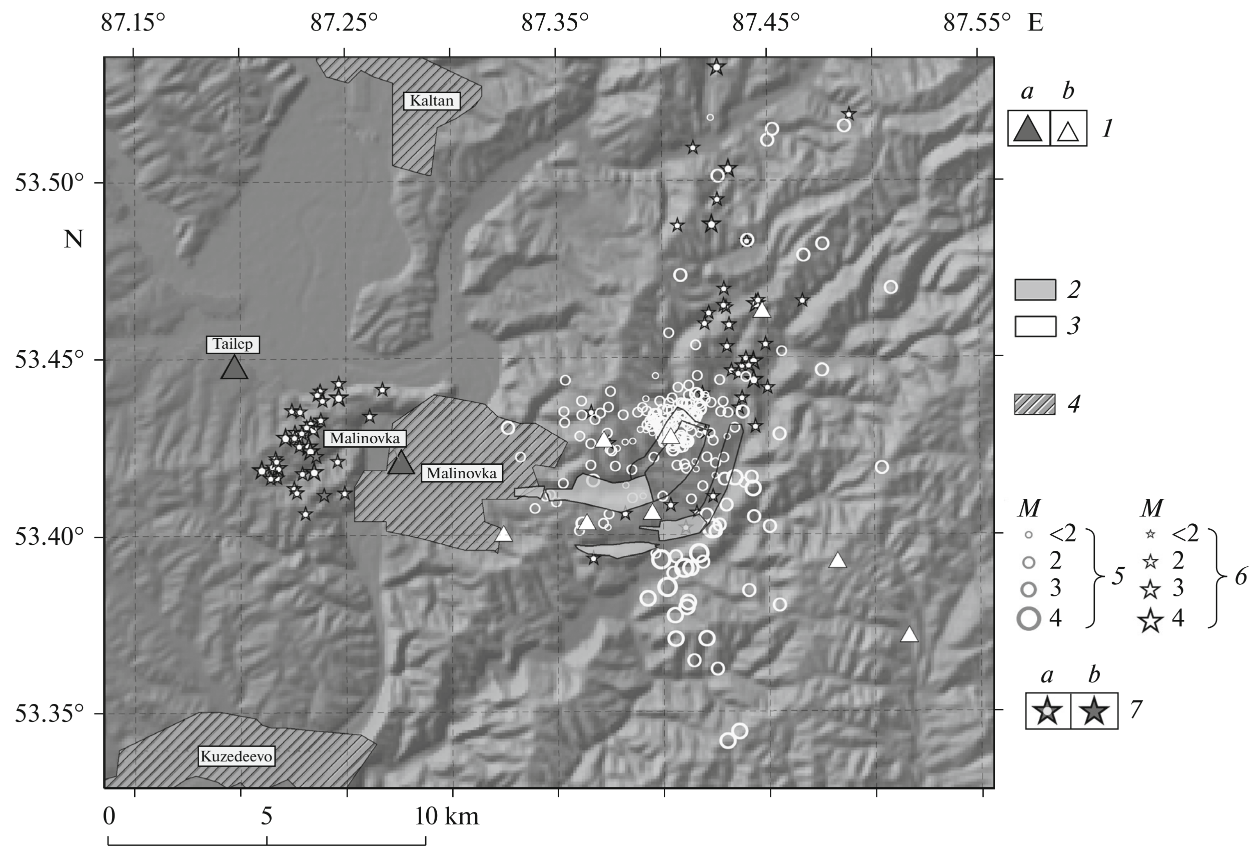

Fig. 3. Map of epicenters of seismic events in Kuzbass in Kaltan open-pit coal mine area from January 1, 2016, to February 20, 2017. Arbitrary notes: (*1*) seismic stations: (*a*) stationary, of strong movements; (*b*) temporary highly sensitive; (*2*) Kaltan open-pit coal mine; (*3*) Alarda coal mine; (*4*) settlements; (*5*) earthquake epicenters; (*6*) epicenters of industrial blasts; (*7*) industrial blasts: (*a*) confirmed; (*b*) hypothetic.

activation can be interpreted as induced seismicity. The largest earthquakes occur south of the dumps, where piled-up masses are high and have not been added to for a long time. In fact, we are deal with the aftereffect of the Earth's subsurface reaction to technogenic impact in the form of rock mass displacement.

The second seismic activation includes earthquakes with $ML < 2$. All earthquakes of this activation are focused in a local segment corresponding to underground coal extraction at the Alarda mine (Fig. 2). In fact, the technogenic seismic activation of one type results in seismic activation of the other type.

Figure 4 shows the development of a seismic process over time. It is clear from the data in Fig. 4 that the energy of industrial blasts is $1.5 < ML < 3$ and $2 < ML < 2.5$ on average. The ML magnitudes of technogenic earthquakes are $0 \leq 4$. The representativeness of seismic events recorded by the stationary network of stations (the smallest magnitudes that can be recorded by the system without gaps) is $\sim 1.5 < ML < 2$. Thus, the seismic stations of the stationary networks record most of the industrial blasts, while weak earthquakes with $ML < 1.5$ are not recorded if additional stations are not used (Fig. 4). Figure 4 clearly shows the processing periods for data from the seismic stations of the stationary monitoring system (October 1, 2016–November 30, 2016) and data supplemented with information received from the temporary stations (since December 1, 2016).

Most strong ($ML \geq 3$–4) earthquakes occurred from the middle of October to the end of December 2016. Over 2.5 months (October–November 2016), the regional network of seismic stations recorded six seismic events with magnitudes $ML \geq 3.5$, three of them with $ML \sim 4$ (Figs. 2, 3).

Starting from January 2017, seismicity has been decreasing in the Kaltan open-pit coal mine area: over the first 6 months of 2017, the stationary network recorded only one earthquake with a magnitude $ML > 3$ (Fig. 4).

Note that near the underground mine, no earthquakes with $ML > 2$ are recorded. Seismicity caused by underground coal mining is recorded only if the stationary seismic network is expanded with temporary stations (Fig. 4).

Starting from February 20, 2017, the number of low-energy earthquakes has increased sharply in the

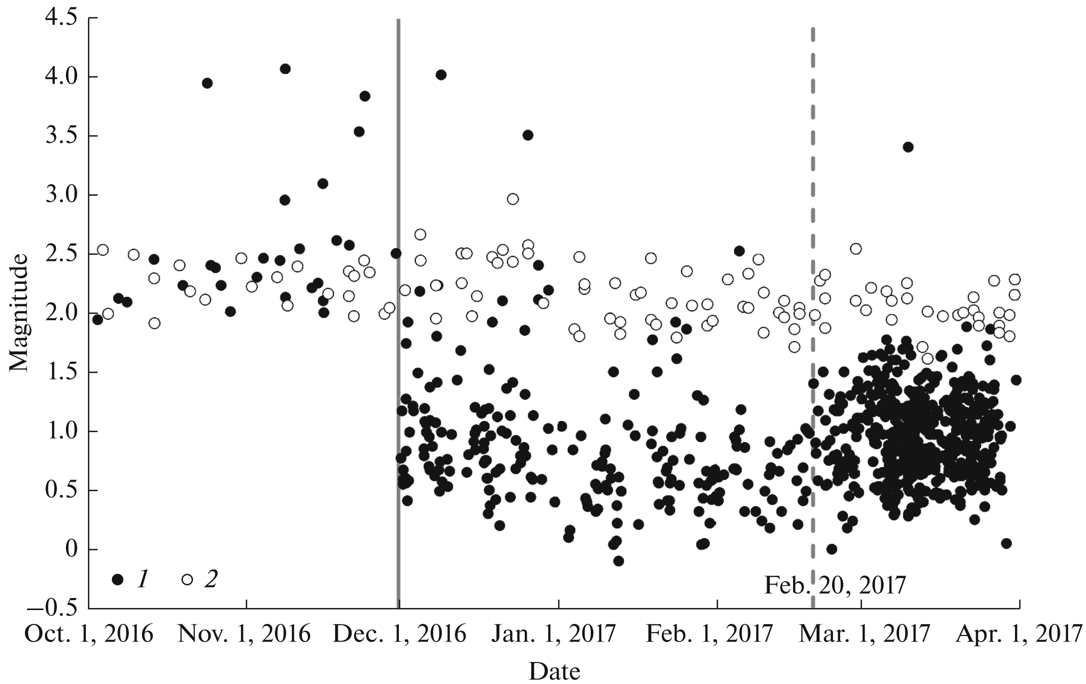

Fig. 4. Development of seismic process in Kaltan open-pit coal mine area with time. Arbitrary notes: (*1*) technogenic earthquakes; (*2*) industrial blasts. Vertical thick line denotes instant temporary seismic network began to operate; dashed line shows instant when data in Figs. 3 and 5 separate.

vicinity of the Kaltan open-pit mine (Fig. 5). In the studied period, seismic activation related to open mine works weakened considerably, and technogenic seismic activity in the Alarda mine area increased significantly. In fact, we have observed weakening of one hazardous process along with intensification of another.

The diurnal variation in the number of events is typical of induced seismicity in underground mines. During routine equipment maintenance, technogenic earthquakes do not almost occur (Emanov et al., 2012; Adushkin and Turuntaev, 2015). The exception was seismic activation near the Raspadskaya mine after an accident (Emanov et al., 2012). The absence of distinct periodicity in the daytime in the earthquake distribution for the Alarda mine area is well seen in the diagram in Fig. 6. Whereas in most mines, the activated segment is under a working face and as work advances, a shift in activation is recorded, in this case, quite a large region adjoining the mine is activated, which likely explains the absence of a markedly expressed minimum in the number of earthquakes during the daytime.

The role of natural processes forming a stress state for the crust of the Kuzbass has been considered in several studies (e.g., (Adushkin, 2015)). Studies on the faults and block structure of the Kuzbass are especially important (Ovsyuchenko et al., 2010; Novikov et al., 2013). Attempts to correlate seismic activation of the basin with the block structure and individual faults seem unconvincing due to the different scales of the studies. A satisfactory explanation can be obtained only by comparing seismic activations of all mining plants in the Kuzbass with its block structure. Currently, detailed experiments with temporary seismic networks point to the predominant technogenic nature of the given seismicity.

In general, the seismicity of Altay-Sayan mountainous region is confined to the mountainous margins of basins. In terms of natural seismicity, the Kuzbass has always confirmed the general patterns (Emanov et al., 2012). The thickness of the deposits of which this basin consists, up to 11 km (Krylov et al., 1971), makes it an even stronger element of the Earth's crust under compression compared to the broken structures of Salair and Kuznetsk Alatau. Induced seismicity forms within the sedimentary layer of the basin and is confined to mine works.

Another criterion is the depth of technogenic earthquakes. Figure 7 shows the depth distribution of seismic events in the area of the Alarda mine and events near dumps. Earthquakes occur at shallow depths in the both cases. Events confined to the mine have two dominant depths, 1 and 2.5 km. The process of induced seismicity in the Kuzbass for underground mines has always been characterized by technogenic earthquakes beneath workings, but also at depths of the first few kilometers in the sediment sequence. In this case, the pattern is preserved.

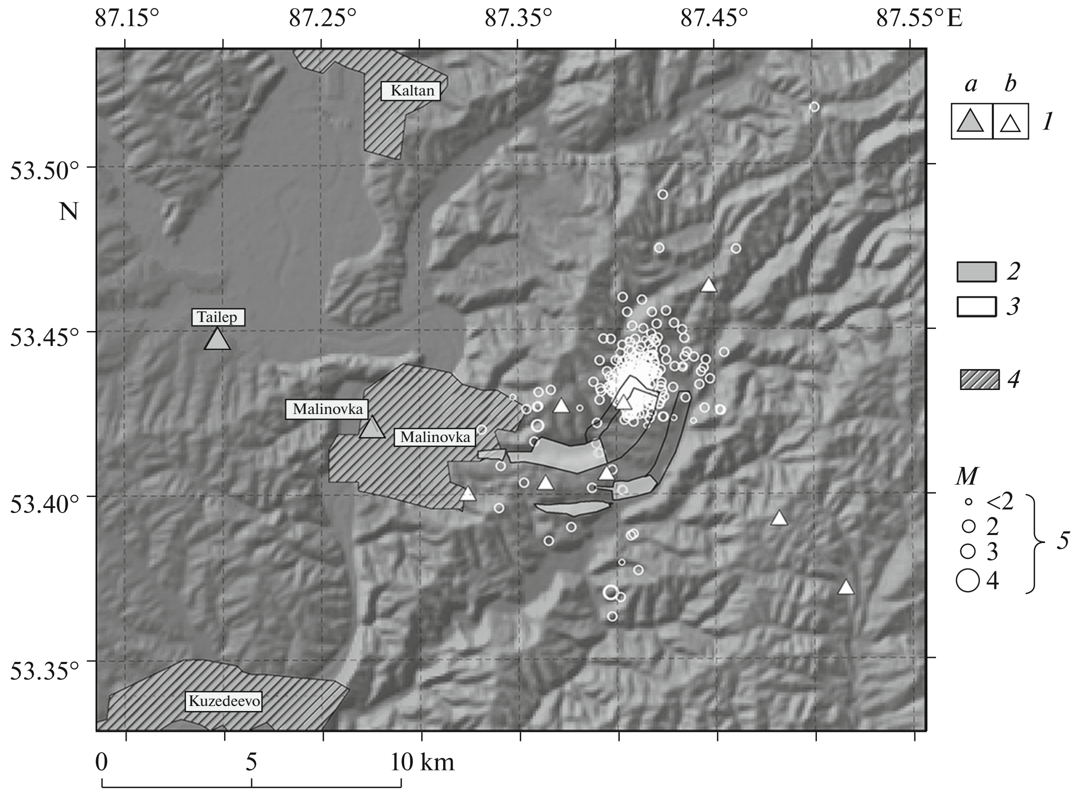

Fig. 5. Map of epicenters of technogenic earthquakes in Kaltan open-pit coal mine, February 20–April 1, 2017. Arbitrary notes: (*1*) seismic stations: (*a*) stationary, strong movements; (*b*) temporary, highly sensitive; (*2*) Kaltan open-pit coal mine; (*3*) Alarda coal mine; (*4*) settlements; (*5*) earthquake epicenters.

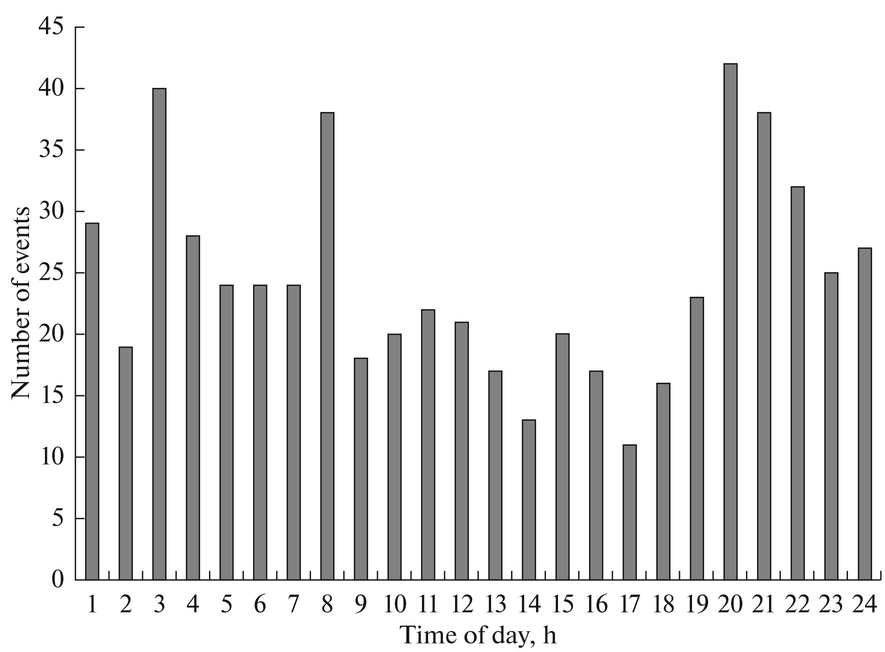

Fig. 6. Diurnal distribution of technogenic earthquakes in Alarda mine area. Total number of earthquakes for particular time of day is indicated regardless of day of occurrence.

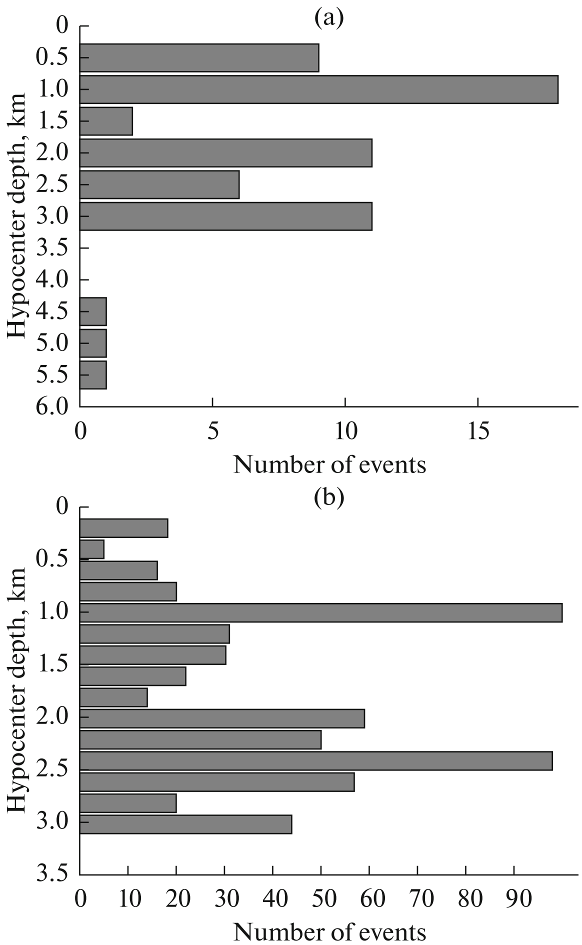

Fig. 7. Depth distribution of seismic foci events (a) in dump area and (b) in vicinity of Alarda mine.

CONCLUSIONS

Seismic activation near the settlement of Malinovka (Kuzbass) results from the response of the geological setting to the simultaneous impact of open-pit and underground coal mining.

Seismicity confined to the Osinniki field of the Kaltan open-pit mine has spread to the area around nearby mine works and dumps. The largest technogenic earthquakes occurred in the south of the activated region, right behind a fully formed dump. It is highly likely that we are dealing with consequences stemming from induced seismicity.

In its characteristics, the seismic process associated with the Alarda mine stands out against the general background of induced seismicity in the region, since it formed as an internal part of common technogenic activation.

Variation in the seismic process with time has been established. The activation associated with open workings weakens and seismic activity in the area of the Alarda mine is intensifying. One type of seismic hazard is replaced with another.

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Translated by L. Mukhortova