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Induced Seismicity of the Bachat Coal Mine and the Stress State of the Earth's Crust

A. A. Emanov[a, b], *, A. F. Emanov[a], **, Y. L. Rebetsky[c], *, O. V. Kuprish[a], ****, A. V. Fateev[a, b], *****, and E. V. Shevkunova[a], ********

[a] *Altai-Sayan Branch of Geophysical Survey of the Russian Academy of Sciences, Ac. Koptyug prosp., 3, Novosibirsk, 630090 Russia*

[b] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, Ac. Koptyug prosp., 3, Novosibirsk, 630090 Russia*

[c] *Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Bolshaya Gruzinskaya str., 10/1, Moscow, 123995 Russia*

**e-mail: Alex@gs.nsc.ru*

***e-mail: Emanov@gs.nsc.ru*

****e-mail: Reb@ifz.ru*

*****e-mail: Kuprish@gs.nsc.ru*

******e-mail: Fateev@gs.nsc.ru*

*******e-mail: Elenash@gs.nsc.ru*

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Abstract—A man-induced seismic activation occurring near the Bachat open-cast coal mine in Kuzbass is studied. The Bachat earthquake of June 18, 2013 (M_L = 6.1) is the world's largest man-made earthquake related to the extraction of solid minerals. It created a powerful aftershock process. More than 3000 earthquakes have been recorded. It was found that the seismic process in the area of the mine as of 2020 is continuous and non-stationary: there are periods of background seismicity with relatively small and infrequent events, and periods of activations with earthquakes that are felt throughout the entire Kemerovo region ($M_L \geq 4$), and an increased (by 2–3 times) frequency of small events. The duration of seismic activations is 1–3 months. Focal mechanisms of 76 events were determined for the mine area. The fact of mismatch between the model of the stress state of the Bachatsky open-cast coal mine area as recovered from the mechanisms of aftershocks and the mechanism of the main shock of the Bachat earthquake is found.

Keywords: induced seismicity, Bachat earthquake, Kuzbass, stress state of the earth's crust

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INTRODUCTION

Mining has a strong impact on the earth's crust, and induced seismicity occurs in all regions of the world (Adushkin, 2015, 2016; Adushkin and Turuntaev, 2015; Emanov et al., 2009, 2016, 2018; Kozyrev et al., 2002; Mirzoev et al., 2009; Holub, 2007; Srinivasan, 2013; Malovichko and VanAswegen, 2013; Trifu, 2013).

The Bachat coal mine has been producing coal since 1948. To date, more than 350 million tons of coal have been mined. By 2013, the size of the excavation was 2.2 × 10 km with a depth of about 350 m.

The Bachat earthquake that occurred on June 18, 2013 in the Kemerovo region with a local magnitude M_L = 6.1 in the vicinity of the Bachat coal mine, is the world's largest man-made earthquake related to the extraction of solid minerals. It gave rise to a powerful aftershock process.

The area of the Bachat coal mine was identified as a zone with a constant level of induced seismicity long before the Bachat earthquake. In the area of the coal mine in 2012 (before the Bachat earthquake), an experiment was carried out with 25 temporary stations, which made it possible to obtain information with greater accuracy about the coordinates of events and their depths, as well as to study their mechanisms (Emanov et al., 2016). The aftershock process of the Bachat earthquake was recorded at 10 temporary stations in the mine zone together with 17 stationary stations in Kuzbass and with the involvement of all stations in the region. Continuous seismological studies with a dense network of stations in the area of the Bachat open-cast coal mine provide information about an object with high man-induced seismic activity under conditions of continuous impact on the subsoil of ongoing coal mining. Coal production at the open pit annually exceeds 10 million tons, the planned depth of the open pit reaches 550 m with a significant expansion of its area.

The main task of this work is to restore the stress state of the sedimentary cover in the mine area from the focal mechanisms of earthquakes. Two factors contribute to the solution of this task. The first is a large number of earthquakes in the mine area, and the second is a good coverage of the mine by seismological stations. In this case, it is possible to determine a sufficient number of focal mechanisms to restore the state of stress. It should be noted that this is a unique case for induced seismicity.

THE SEISMIC PROCESS IN THE AREA OF THE BACHAT COAL MINE

After the Bachat earthquake, more than 3000 aftershocks were recorded in the mine area complete upwards of $M_L = 0.5$. In Fig. 1 the events are mapped; we see that the aftershock area is spatially confined to the mine and its longer axis is oriented along it. In Figs. 1a, 1b, two types of data presentation are given. Figure 1a shows a map of epicenters, which clearly displays the location of the main event and the largest aftershocks. In the southeastern part of the activation zone, there is a branch towards one of the dumps. The depths of the earthquakes range from 4 km to the bottom of the mine. The depth uncertainty does not exceed 1 km. This result is achieved due to the presence of stations in the mine area, which are installed directly above the seismic area, and due to dozen of stations around the mine, as well as by adjusting the earth velocity model for the study area (Emanov et al., 2016, 2018). The largest earthquakes with $M_L = 3.5$–4.0 are concentrated in the southeastern part of the mine where the main shock occurred. Figure 1b shows a map of the density of earthquake epicenters in the area of the Bachat open-cast coal mine. In the epicenter map, the larger earthquakes and the main shock are concentrated in the southeastern part of the mine, but the highest density of earthquakes is observed from the central part of the mine and extends in the northwestern direction. In fact, the largest earthquakes more often occur at the edge of the mine and southeast of the activation in the center of the mine in the form of a large number of earthquakes of significantly lower energies. On both sides of the roadway in Fig. 1b, areas of increased density of earthquakes that are displaced to the side are recorded. They extend towards the dumps located near the mine.

The depth of the Kuznetsk depression, according to deep seismic sounding (DSS) data, reaches 11 km (Krylov et al., 1971). Accordingly, all events take place in the sediments of the basin. Deep seismic sounding data on wave velocities in the Kuznetsk Basin are used in the velocity model to locate the hypocenters. The study of the stress state by the focal mechanisms can be carried out for the upper part of the sediments of the Kuznetsk depression in the area of the mine.

The evolution of the seismic process in time is shown in Fig. 2. In fact, the aftershock process is superimposed on the seismicity induced by mining under the conditions of the state of stress at depth in the Kuznetsk depression. Based on the materials of the study of induced seismicity in the mine area, conclusions have already been drawn (Emanov et al., 2016) about the properties of the seismic process supplemented in this article.

• The seismic regime of man-induced activation near the Bachat mine is continuous and non-stationary: we identified periods of the background seismicity level with a reduced energy of large earthquakes and a lower frequency of small events, and periods of activation with strong and large earthquakes and an increased frequency of smaller events. Duration of seismic activity is about 1–3 months. Over the past five years, four activations were recorded (Emanov et al., 2016), and three of them generated large earthquakes: February 19, 2012 with $M_L = 4.3$; April 5, 2013 with $M_L = 3.9$; and June 18, 2013 with $M_L = 6.1$. The last activation ended with a series of felt earthquakes with local magnitudes of 3.0–3.5.

• A more detailed study of seismicity near the Bachat mine (in this work) made it possible to assert that the highest density of hypocentersi is observed under the coal mine from its center in the form of an elongated area extending to the northwest, and the largest earthquakes occurred outside this area in the southeastern part of the coal mine and are more often confined to the side, and not to the center.

Since continuous monitoring of the seismic process is carried out in the area of the Bachat earthquake, in Fig. 2, one can see that in December 2018 and January 2019, one more activation of the subsurface of the section was observed with events of magnitudes about 4. Later on, in 2019 and in 2020, man-made earthquakes had magnitudes below three. Data processing over a network of regional stations is faster than using a local network. The local network was processed until November 2018, and this is reflected by a step in the number of small events in Fig. 2. The regional network in the area of the Bachat open-cast mine yields a complete reporting of events upwards of $M_L = 1$. From $M_L = 0$ upward, the catalog becomes complete after processing the local network in the area of the mine. The emergence of seismic activation in the subsurface of the mine can be seen from the data of the regional network, but the study of possible prediction of the emergence of new activations requires recording the smaller earthquakes. This paper presents materials updated relative to the publications of previous years due to continuous monitoring until the present, which

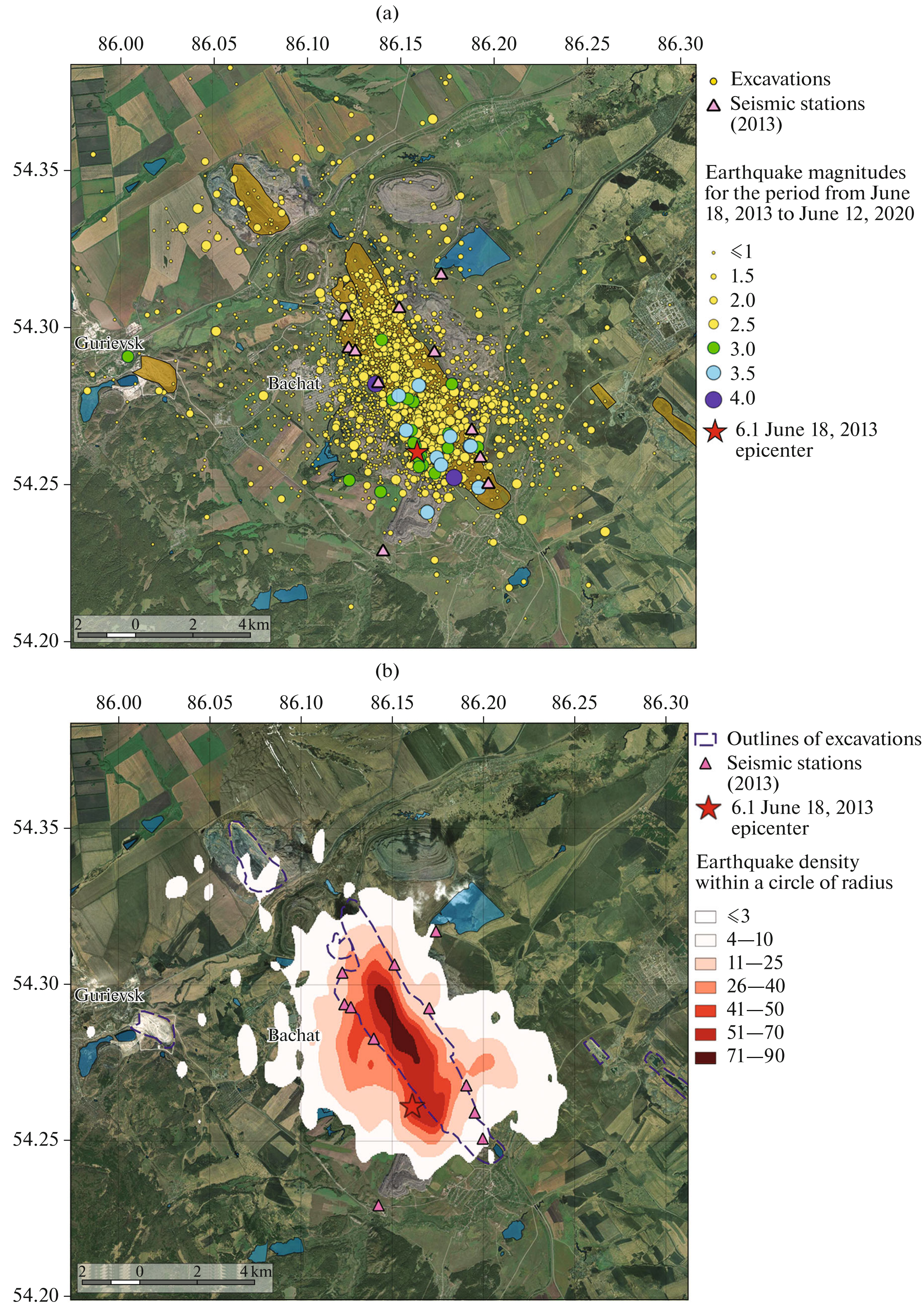


Fig. 1. Map of earthquake epicenters in the area of the Bachat open-cast coal mine from June 18, 2013 to June 12, 2020 (a) and a map of earthquake density in the area of the Bachat coal mine from June 18, 2013 to June 12, 2020 (b).

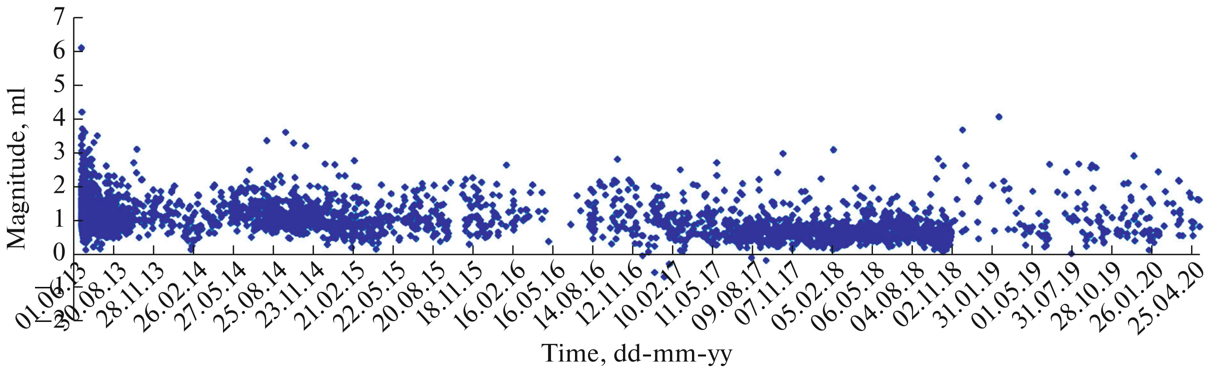


Fig. 2. Development of the seismic process in time after the Bachat earthquake (all earthquakes at a distance of up to 20 km from the section for the period from June 18, 2013 to June 12, 2020).

allows you to clarify previously drawn conclusions and substantiate new ones.

In this study, first of all, we are interested in events for which it is possible to confidently determine the focal mechanisms. The majority of small earthquakes are recorded by an insufficient number of stations to determine the mechanism, but even the determination of the focal mechanisms of some of the events makes it possible to form a sufficient sample to study the stress state of the subsoil in the mine area.

INITIAL SEISMOLOGICAL DATA FOR STUDYING THE STATE OF STRESS

The catalog of focal mechanisms contains 76 determinations for events that occurred after the Bachat earthquake. In fact, the entire area of the mine is covered. Earthquakes with $M_L \geq 3$ were recorded by all stations of the Altai-Sayan region (about 60 stations), and the orientation of the nodal planes was determined confidently. At lower earthquake energies, the reliability of determinations depends on the signal-to-noise ratio that the network can provide. Fault-plane solutions were also obtained for smaller events in the case of a reduced noise level at the stations and a sufficient number of reliable wave arrivals. The high accuracy of determining the depths of events is an additional factor in increasing the accuracy of determining the focal mechanisms.

The focal mechanisms of some events are presented in Fig. 3. One can see their differences from each other and from the mechanism of the main shock of the Bachat earthquake. This fact suggested elucidating the causes of such differences using methods of restoring the stress state of the subsoil under the mine from focal mechanisms (Rebetsky, 2007).

Note that in this work, we used the results of experimental studies detailed information about which is published in the annual Earthquakes of Russia, which provides information about stations and their coordinates, catalogs of earthquakes with complete information about events and location accuracy, data on mechanisms and their accuracy (Emanov et al., 2020) as an appendix to the collection on a CD. This information is presented in the form of numerical tables. In the yearbooks after 2013, all information on the seismological data used in this article is available. By combining data from different collections, the reader can check our results or carry out his own research.

STRESS CALCULATION TECHNIQUE

Stress inversion from data on earthquake mechanisms in the area of the Bachat mine was performed using the STRESSseism program. The algorithm of this program is based on the method of cataclastic analysis (MCA) of displacements, which allows calculating not only the parameters of the stress ellipsoid (orientation of the principal axes and the shape of the ellipsoid), but also the normalized values of the spherical (pressure with an opposite sign) and deviatoric (maximum shear stresses) components of the stress tensor (Rebetsky, 1996; Rebetsky, 2007).

The MCA algorithm provides for the creation of homogeneous samples of earthquakes, which characterize the quasi-uniform phase of deformation in an earth volume, which is the main element of the first stage of this method. The formation of such a sample should take place in a three-dimensional space of parameters (the distance from the hypocenter to the point of calculation, the time of occurrence and the magnitude of the earthquake). The MCA has rules for selecting events to make a homogeneous sample. First of all, they are associated with the requirement of a relationship between the distance from the hypocenter to the point of stress calculation (nodes of a uniform grid in the study area) and the magnitude of the earthquake, which determines the size of its unloading volume. Based on this requirement, earthquakes are selected in the initial sample of events for each calculation point. Further, for the expanding window on the time scale, the events are checked for joint consistency. For this, the defining MCA inequalities are

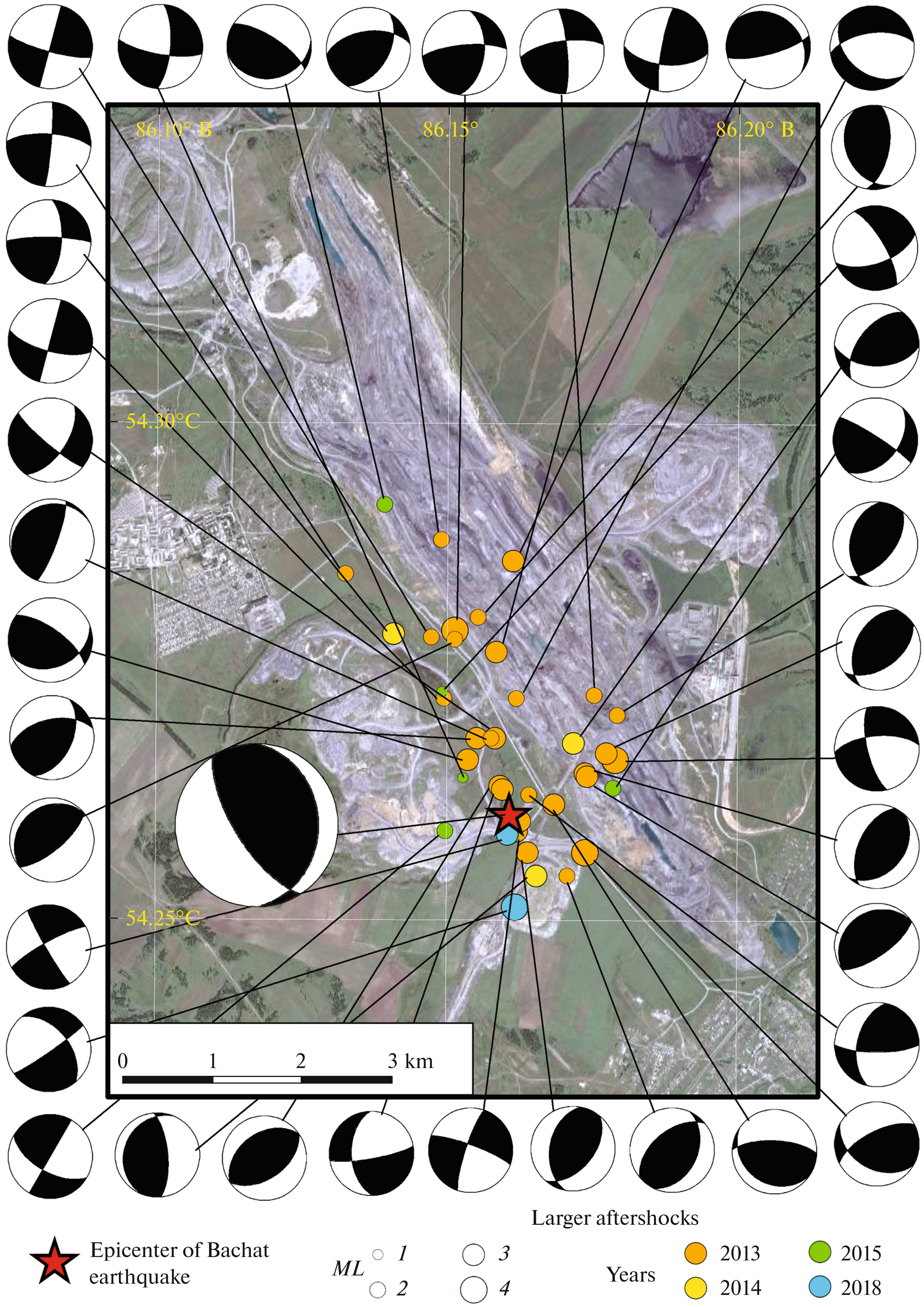


Fig. 3. Focal mechanisms of some aftershocks of the Bachat earthquake.

used, which are derived from two fundamental laws of plastic flow: 1) the dissipation of elastic energy is positive; 2) the orderliness of the formation of plastic deformations on the sought stress tensor. These provisions of the theory of plasticity in MCA are extended to fracture flow, when a micro-act of plastic deformation is understood as one act of brittle fracture (Rebetsky, 2007).

After creating a homogeneous sample of earthquake source mechanisms using the same MCA inequalities that were used to form a homogeneous sample, the principal stress axes are localized on the lower hemisphere of unit radius. The algorithm of this part of the MCA is in many respects similar to the relevant methods of J. Angellier and O.I. Gushchenko (Gushchenko, 1979a, b). On its basis, sectors are distinguished on the hemispheres, in which the principal compression and tension axes can be located. In parallel with this, the parameters of the tensor of seismotectonic deformation increments are calculated from events in the homogeneous sample. This tensor is further used to find the only solution for the areas of possible orientation of the principal stress axes.

THE STATE OF STRESS IN THE EPICENTRAL AREA OF THE BACHAT EARTHQUAKE

The calculation of stresses in the area of the Bachat deposit was carried out using a uniform grid of 0.002 × 0.002 degrees. The choice of such a small grid interval is due to the density of the network of temporary stations and the accuracy of determining the coordinates of events. Based on the STRESSseism program algorithm, 376 homogeneous samples were created from the catalog of focal mechanisms, for which the parameters of the stress tensor were calculated. In this case, the size of the stress-averaging window, which was selected automatically, was in the range from 0.5 km to 2 km laterally. On the time scale, the averaging window was 6 years (from 2013 to 2018). Such a period of time for the analysis was chosen as corresponding to the period of the greatest aftershock activity in the region of the Bachat earthquake. In addition, it is due to the need for a sufficient number of calculated focal mechanisms to form homogeneous samples. The minimum number of events in the sample was 6. In Fig. 4 the parameters of the stress tensor are shown in the form of principal compression axes (see Fig. 4a) and principal tension axes (see Fig. 4b), the geodynamic type of stress (these are possible states from compression and shear to tension, see Fig. 4c) and the Lode–Nadai coefficient, which determines the shape of the stress ellipsoid (see Fig. 4d).

Against the background of the general trend of the principal compression in the northwestern and southeastern directions with low dip angles (0°–7°), there are areas in the northwest and north–northeast of the computation area with steeper dip angles (8°–30°), in the south-western part there is an area with the steepest dip angles (up to 60°). The principal tension has a wide range of plunge angles, with a general mainly southwestern strike. It is these angles of dip for the algebraically greatest principal stress (negative compression) that lead to the appearance of different geodynamic types of stress states from tension and shear to horizontal compression.

It is important to note that the strike of the principal compression axes obtained from the reconstruction results differs significantly from the orientation of the axis of the greatest compressive stress (P axis) of the focal mechanism of the Bachat earthquake source (see Fig. 3). In this case, the strike of the axis of the T-focal mechanism has an orientation corresponding to that obtained by the reconstruction of stresses. Especially these correspondences, including steep dip angles (from 60°–90°), are noticeable in the southeastern sector of the computation domain.

Such a mismatch in the orientation of the axis of the principal compression of the relieved stresses, the focal mechanism of the Bachat earthquake, and the axis of the same name according to the inversion results, requires clarification. It is important to note here that the P and T axes of the focal mechanism determine the orientation of the relieved stresses. In this case, the greatest compression is subhorizontal, and the axes of the principal tensile stresses are subvertical. Since the vertical stress is formed by the weight of rocks, it can be assumed that in this direction it will change little after a strong earthquake.

There are two approaches to interpreting the results of restoring the stress state of a local area of the Kuznetsk Basin sediments under the exploited Bachat coal mine. One is based on a model of an environment in which the stress state does not depend on the magnitude of earthquakes, and the second is based on a model of the earth's crust with a stress state hierarchy (Osokina, 1987). In the second case, the stress state model for large earthquakes is one, and for earthquakes with smaller magnitudes, it is different. The study of crustal stresses is dominated throughout the world by the use of the first model (Rebetsky, 2007). This can be explained by insufficiently dense networks of stations and the lack of the required amount of data on the mechanisms of earthquake sources for the application of a more complex hierarchical model.

In the study of the aftershocks of the Chuya earthquake, when dozens of stations in the aftershock area recorded more than 50 thousand events with magnitudes from 0 to 7.3, the data were sufficient to apply the hierarchical stress state model, and the theoretical predictions of D.N. Osokina were fully proved, resulting in a hierarchical model of two levels for the block structure of the entire aftershock area of the Chuya earthquake (Leskova and Emanov, 2013, 2014). The boundary between events of two hierarchical levels was about $M_L \sim 4$. For the Bachat mine, there is not a sufficient number of earthquakes with magnitudes greater than 4, and there is no way to substantiate the use of a hierarchical model of the stress state of the mine's interior. We found that the mechanism of the main event does not correspond to the stress state model obtained by the mechanisms of aftershocks. In the

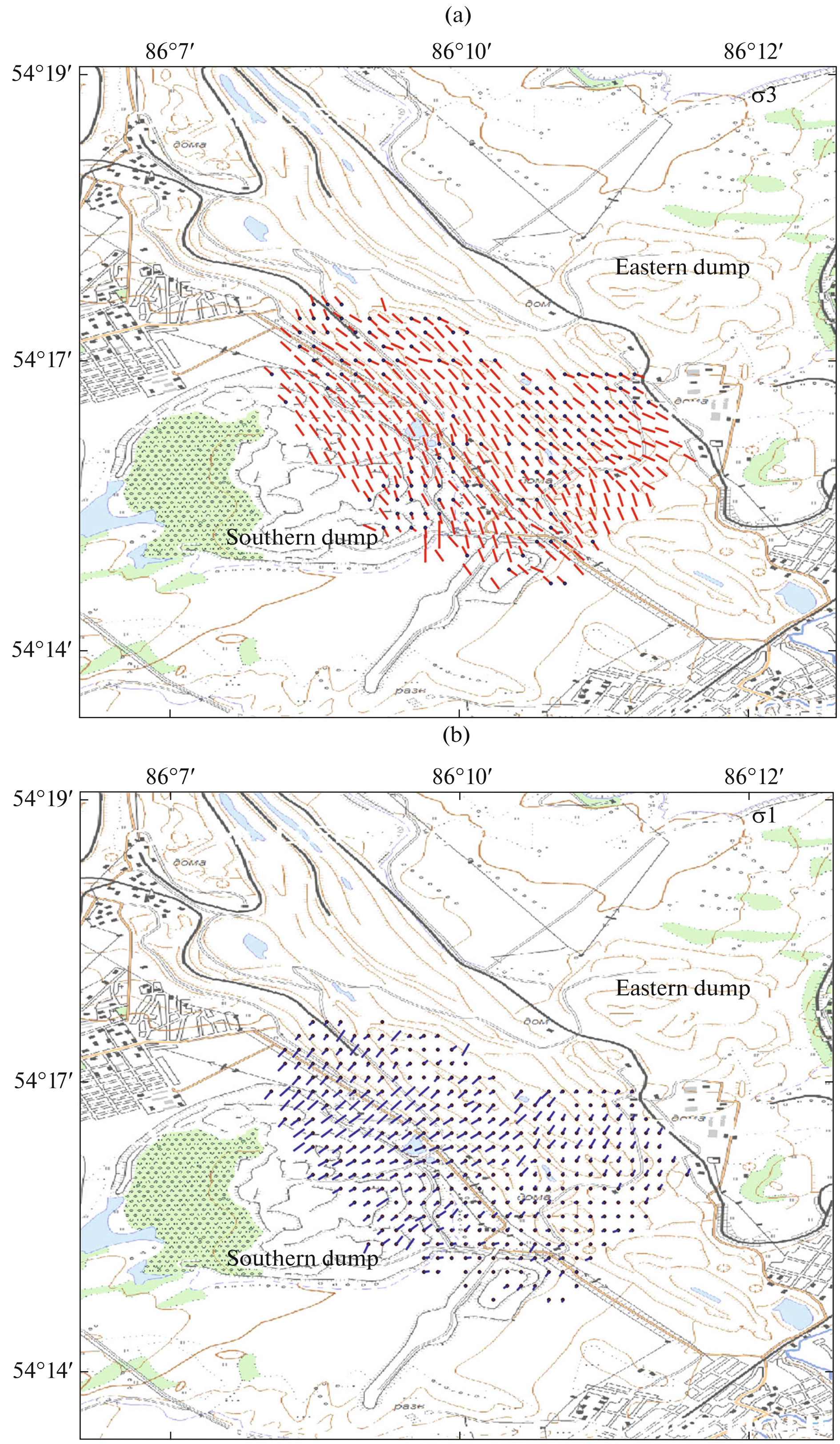
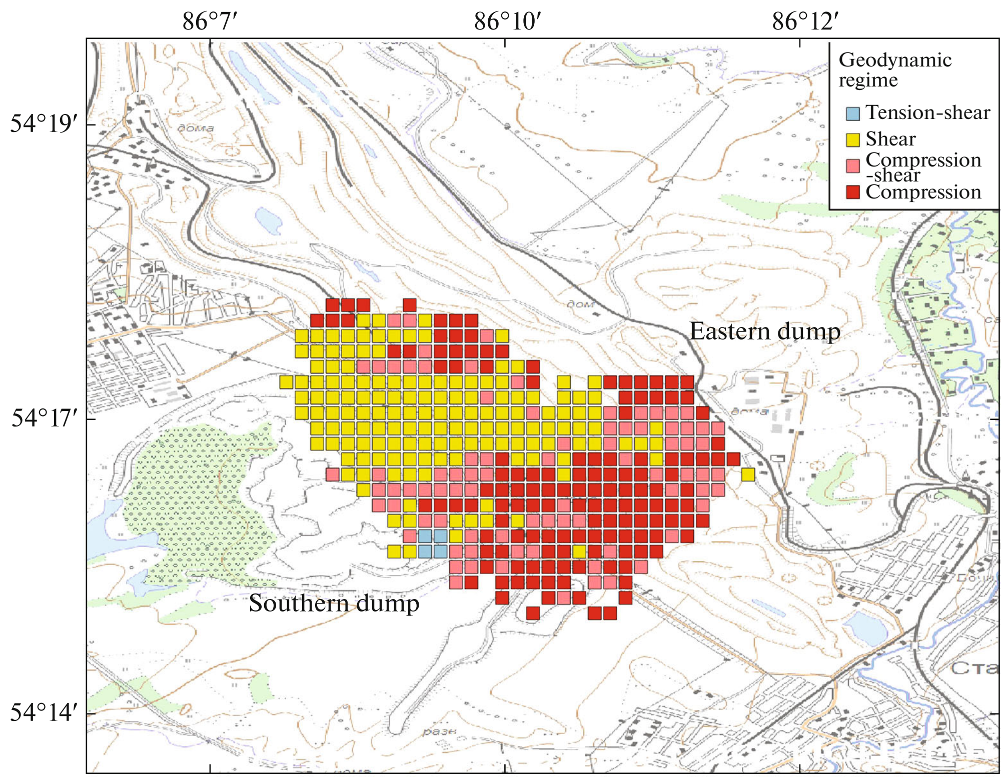


Fig. 4. Stress tensor parameters—the general section scale.

(a, b) Axes of the principal stresses of compression and tension plotted in the direction of their dip; (c) geodynamic type of stress state (yellow denotes horizontal shear, red horizontal compression, light red horizontal shear combined with compression); (d) type of stress ellipsoid (yellow denotes pure shear, red a state close to uniaxial compression, light red a state between pure shear and uniaxial compression; and blue a state close to uniaxial tension).

(c)



(d)

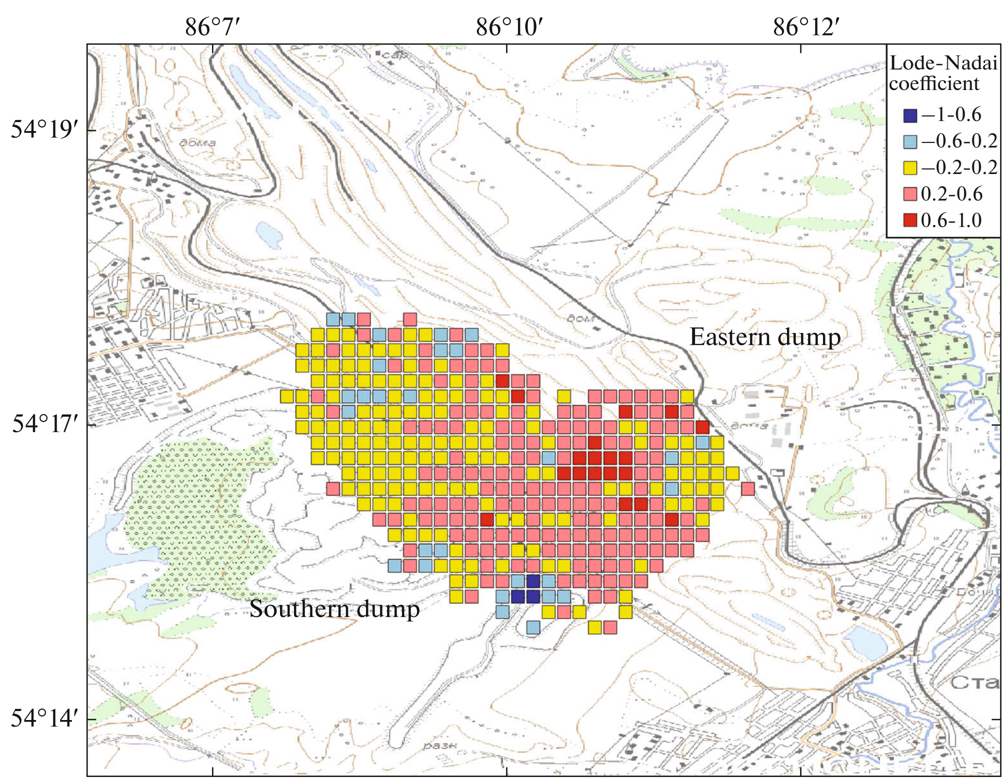


Fig. 4. (Contd.)

case of a hierarchical model of the stress state of the earth's crust, these differences could have a completely different explanation than those presented in this work, but a model without hierarchy is used, therefore further interpretation is carried out within the framework of this model. Aftershocks were used in the constructions. Consequently, the stress state model corresponds to the period after the earthquake, the state of stress before the Bachat earthquake could well be different.

In accordance with the constructed model of the stress state of the upper crust in the area of the Bachat mine, the following interpretation of the results can be given: a strong man-induced earthquake, which had a characteristic source size of about 10 km, produced changes in the stress field. We believe that before the earthquake, the axes of the principal tectonic compression and tension stresses had similar orientations, respectively, to the P and T axes of the focal mechanism of the Bachat earthquake (see Fig. 3). In this case, the axis of the intermediate principal stress is subhorizontal and had a northwestern and southeastern orientation (the direction of intersection of the nodal planes of the Bachat focal mechanism).

Thus, from the performed analysis, it follows that the greatest stress release took place precisely in the northwestern sector of the computation domain, although the rupture of the Bachat earthquake started in the southeastern sector. Consequently, the southeastern sector of the Bachat mine can be considered as the region in which the relaxation of the influence of the Bachat earthquake can be the fastest. The earth in the northwestern sector of the Bachat mine, in which the greatest change in the stress state occurred after the decay of the aftershock process, requires a longer period of time for the stress state to change to the level when conditions for a new large earthquake arise. There is a fairly good consensus on the nature of the Bachat earthquake at this point (Emanov et al., 2016; Batugin, 2018; Kocharyan et al., 2019). The main causative factor was the movement of masses and the creation of a new terrain. In the Altai-Sayan mountainous region, natural seismicity is concentrated mainly in the mountain circumferences of the depressions (Emanov et al., 2006). The development of seismicity in Kuzbass over the past two decades is confined to the territories of mining enterprises and the sedimentary basin of the depression (Emanov et al., 2018). The Bachat earthquake and the ongoing activation of the subsoil near the mine is of a man-induced nature and is associated with a continuous change in the terrain and the stress state of the upper part of the earth's crust.

CONCLUSIONS

• The fact of inconsistency between the stress state model of the region of the Bachat open-cast coal mine, reconstructed by the mechanisms of aftershocks, and the mechanism of the main shock of the Bachat earthquake was established. In accordance with the well-founded model of the stress state, an interpretation is given that, as a result of a strong man-induced earthquake, which had a characteristic source size of about 10 km, a restructuring of the stress field occurred in the open-cast coal mine area.

• The largest stress release took place in the northwestern sector of the mine, although the rupturing of the Bachat earthquake started in the southeastern sector. This sector of the Bachat open-cast coal mine can be considered as the region in which the relaxation of the influence of the Bachat earthquake can occur most rapidly.

• The seismic regime of man-induced activation near the Bachat open-cast coal mine is continuous and non-stationary: periods of the background level of seismicity are identified, with a reduced energy of the strongest earthquakes and a lower frequency of smaller events, and periods of activation with felt earthquakes with magnitudes of ~4 and an increased frequency of small events that was higher by 2–3 times . The pulsating nature of the seismic activity in the subsurface of the mine is probably associated with a strong and continuous man-made impact during coal mining, which provides a change in the stress state of the subsurface.

• The highest density of hypocenters is observed under the mine from its center in the form of an elongated area to the northwest, and the largest earthquakes occurred outside this area in the southeastern part of the mine and were more often confined to the side, and not to the center.

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