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# TECHNOGENIC SEISMICITY AS A CLIMATIC FACTOR

## Abstract

The hypothesis of technogenic seismic degassing of the subsoil is proposed. Technogenic seismicity manifests itself at depths exceeding the depth of subsoil development and over a large area. The focal zone (foci) of technogenic earthquakes are voluminous bodies of macroscopic dimensions, in which the reactivation of existing and the formation of new cracks and faults occur due to the transition of the massif into a critically stressed state. Such geomechanical transformation of the massif creates conditions for its degassing and release of some of the gases contained in it into the atmosphere. The example of the Kuzbass region in Siberia shows that technogenic seismic degassing can affect areas of hundreds of square kilometers to depths of 2-4 km or more, where methane resources are concentrated in the amount of billions of $m^3/km^2$. According to the estimates made, the geomechanical transformation of the massif as a result of seismic activations in the Tom-Usinsk region of Kuzbass is observed up to depths of 4-5 km and an area of up to 150 $km^2$, which can provoke the emission of methane into the atmosphere up to 10^10 $m^3$. Based on the analysis of methane resource reserves in the coal-bearing deposits of Kuzbass and the areal manifestation of technogenic seismicity, a conclusion is made about the importance of technogenic seismic degassing of the massif for climate change. This allows us to consider technogenic seismicity as a climatic factor. In the near future, the hypothesis put forward may be tested by satellite monitoring methods currently being developed.

**Key words:** technogenic seismicity, foci, critically stressed state, methane resources, massif degassing, methane emission, climate change

## 1. Introduction

This section focuses on the fact that the impact of technogenic seismicity on the environment is primarily understood as a seismic effect, that is, tremor and deformation of the Earth's surface. The impact on the atmosphere is considered to be local and limited. Further, by technogenic seismicity, the author means two categories of seismic phenomena, which in the classifications of technogenic seismicity are called “induced” and “trigger” (McGarr and Simpson, 1997; Adushkin and Turuntaev, 2015).

The seismic effect and deformations of the earth's surface are understood as the direct impact of technogenic earthquakes and rock bursts on the environment. Only these two factors are mentioned, for example, in the review papers on rock bursts by B. Chernik (Czernik, 1964), I. Batugina, and I. Petukhov (Batugina, Petukhov, 1990), T. Li (Li et al., 2007), A.Keneti and B. Sainsbury (Keneti and Sainsbury, 2018), A.V. Lovchikov (Lovchikov, 2016).

A historical example of the impact of dynamic phenomena on the atmosphere can be found in the work of Malyshev Yu..N. and co-authors. Methane and carbon dioxide were released into the atmosphere through mine shafts and affected the population and wildlife during sudden gas outbursts in mines (Malyshev et al., 1996).

In other cases, attention is focused on the reactivation of tectonic faults caused by mining operations, whereby such faults become conduits for mine gases migrating to the surface. However, these cases usually are not associated to technogenic seismicity. For example, H. Cui and co-authors describe a case of tree mortality within the zone of a fault reactivated by subsidence process (Cui et al., 2010). A. Batugin et al. (2021) provide an example of the ignition of a coal-waste dump located within a geodynamic zone. Surface expressions of tectonic faults are recognized as favorable sites for the emission of mine gases into the atmosphere from both active and abandoned mines (Kachurin et al., 2015; Pokryszka et al., 2005; Tauziède et al., 2002; Vasilenko et al.,2016). During seismic reactivation of faults, mine gases may be emitted into the atmosphere due to the piston effect (Batugin et al., 2023). Although this list may not be exhaustive, it generally reflects the prevailing view that the direct impact of a technogenic seismicity on the atmosphere is insignificant and episodic.

The indirect impact of technogenic seismicity on the environment, including the atmosphere, is understood as the risk of accidents at hazardous facilities caused by seismic activity. The possibility of indirect effects of technogenic seismicity on the environment and, in particular, on the atmosphere is beyond the scope of this study. The purpose of this work is to demonstrate that technogenic seismicity can act as a significant factor in the degassing of the subsurface, having a global impact on environmental conditions and climate change.

## 2. Theory and Method

This section demonstrates that rock mass destruction and anthropogenic fracturing constitute the principal technological approach employed in coal seam degassing. Similarly, seismic processes lead to the geomechanical transformation of the rock mass within focal zones, which represent macroscopic volumetric bodies containing newly formed and reactivated pre-existing fractures and faults. An important characteristic of technogenic seismicity is its occurrence at depths exceeding depth of mining and across substantially larger areas. Consequently, the development of technogenic seismicity leads to geomechanical transformation of the rock mass over extensive areas and at considerable depths.

### 2.1 Coal Seam Methane and Principles of Mine Degassing

Methane is a greenhouse gas contributing to global climate change and ranks second after $CO_2$ in terms of climatic impact. According to various estimates, the coal industry emits

24–40 million tons of $CH^4$ annually into the atmosphere, accounting for approximately 10% of total global anthropogenic methane emissions (Puchkov, 1997).

Modern coal seam degassing technologies enable the extraction and utilization of 30–95% of coal methane, including methane from mine ventilation systems (Borowski et al., 2025; Gao, 2019), which constitutes a significant argument in favor of further coal industry development. Methane in coal-bearing strata predominantly occurs in a bound state. To ensure mining safety, rock mass degassing is conducted using hydraulic fracturing, hydraulic loosening, pneumatic impact, and related technologies. The essence of these technologies consists in activating pre-existing fractures in coal and generating new fractures in order to convert methane into a free state and facilitate its migration (Amez et al., 2023; Puchkov, 1997). Thus, destruction of coal and coal-bearing rock masses represents the most effective method of degassing. The natural gas content of coal seams at depths exceeding 500 m often reaches 20 $m^3$/t or more, while degassing measures can reduce gas content sometimes by more than 30% (Slastunov et al., 2022).

## 2.2 Geomechanical Nature of Seismicity and the Shape of Earthquake Foci

Coal mining practice indicates that approximately 20% of methane is emitted into mine workings from abutment pressure zones (Skritsky, 2017). The area extending from the working face to the maximum abutment pressure is considered an area of a critically stressed coal seam conditions in which geomechanical transformation has occurred, accompanied by the formation of induced fractures and reactivation of pre-existing ones (Petukhov et al., 1968). This critically stressed zone constitutes a potential source of dynamic phenomena (rock bursts), which occur when instability conditions are satisfied (He et al., 2018; Petukhov, 1972). If instability conditions are not met, the existence time of the critically stressed rock mass area is unlimited.

The concept of critically stressed crustal zones is also employed to explain the nature of seismicity. C.S. Scholz considered continental seismicity to be evidence that the Earth's crust exists in a state close to seismic failure, while earthquake foci represent regions "on the verge of failure" (Scholz, 1991). G.A. Sobolev and V.A. Ponomarev expressed a similar viewpoint, arguing that sections of the Earth's crust are in a condition "close to the long-term strength limit." According to T. Dahm and co-authors, a standard assumption in the analysis of induced seismicity is that crustal faults remain in a stress state close to failure due to continuous tectonic loading (Dahm et al., 2010). Based on investigations of rock burst phenomena, I.M. Petukhov argued that the Earth's crust from the surface down to a certain depth is already in a critically stressed state (Petukhov, 1991). J. Townend and M. Zoback expressed a similar opinion, stating that induced seismicity indicates that "in general, the brittle crust in intraplate regions is critically stressed" (Townend and Zoback, 2000). B.G. Tarasov considers this state to be "beyond the fracture strength limit" (Tarasov, 2021). Thus, according to modern concepts, there are areas in the Earth's crust where the massif is in a critically stressed state or close to it, and these areas are potential sources of dynamic phenomena (rock bursts and earthquakes).

Earthquakes are generally interpreted as slip along faults (Scholz, 1990; Kocharyan and Kishkina, 2020;), whereas the earthquake foci itself represents a certain volume within the Earth's crust characterized by "rapid multidirectional displacements" (Shebalin, 1987), i.e., a three-dimensional area of crustal destruction. Estimates of earthquake focal geometry suggest that the foci (focus area) may be represented by an ellipsoid with long-to-short axis ratios of 3:1 (Sadovsky, 2004), or in some cases 1:1 (Beresnev and Atkinson, 2002), with dimensions ranging from several kilometers to tens of kilometers depending on earthquake magnitude M.

Focal areas of fault-slip type rock bursts directly investigated through mine workings also constitute volumetric structures within which dynamic displacements occurred simultaneously along several differently oriented faults existing prior to the rock burst. In some cases, focal dimensions reached approximately 500 m in plan and up to 200 m vertically (Batugin, 2017). Apparently, critically stressed areas within rock masses may also exhibit more complex volumetric geometries described by the theory of self-organized criticality (Bak et al., 1988) or fractal sets (Qiao, 2023). Thus, in the present study these zones are considered as macroscopic volumetric formations within the Earth's crust.

Empirical relationships between focal size L and earthquake magnitude M of the form $\lg L = aM + b$ have been established, as discussed, for example, by E. Bugaev (2011). For example, in M.A. Sadovsky's formula, $a = 0.57$, $b = 2.64$, and the dimension is L-cm (Sadovsky, 1983). These relationships indicate that focal dimensions of seismic events with magnitudes between 1 and 6 range from tens of meters to approximately ten kilometers.

## 2.3 Regularities of Induced Seismicity Manifestation

This subsection addresses the fact that hypocenters of technogenic earthquakes occur at depths exceeding mining levels or other anthropogenic sources of subsurface impact, and also at considerable distances beyond them. This feature has repeatedly attracted scientific attention (Batugin, 2021). Hypocenters of fault-slip rock bursts at the Severouralsk bauxite deposit were located several hundred meters deeper than mining zones; at the "Laohuntai" mine, seismic activation extended to depths of 2 km (Li et al., 2007); in the vicinity of the "Oktyabrskaya" and "Polysaevskaya" mines, to depths of 2–3 km (Emanov et al., 2009); near the "Araldinskaya" mine, to 4 km (Emanov et al., 2007); and in the area of the Bachat open-pit coal mine, to depths of 5–6 km (Emanov et al., 2020a). This list may be continued.

C.S. Scholz explained the occurrence of earthquakes beneath a reservoir in South Carolina by suggesting that numerous small crustal areas close to a critical state existed there (Scholz, 1991). I.M. Petukhov and I.M. Batugina explained such effects by the increase in the thickness of critically stressed crustal layers under the influence of engineering activity (Petukhov and Batugina, 1999). Thus, the development of seismicity at depths exceeding mining levels and at considerable lateral distances (several to tens of kilometers) from mining operations is an objective reality.

## 3. Hypothesis of Technogenic Seismic Degassing of the Subsurface: The Kuzbass Case Study

The above-mentioned characteristics of a technogenic seismicity suggest that seismic and geomechanical transformation of the rock mass may result in degassing to considerable depths, potentially throughout the entire coal-bearing formation and across large areas. This hypothesis is considered using the Kuzbass coal-mining region as an example.

Methane resources within the coal-bearing formations of Kuzbass have been estimated down to a depth of 1.8 km and amount to approximately 13 trillion $m^3$, representing about 14% of global coal seam methane resources. In some areas, the cumulative thickness of gas-bearing coal seams reaches 90–120 m (to depths of 1.8 km), with methane contents of up to 25–30 $m^3/t$. Methane resource density within the coal-bearing strata reaches 3.0 billion $m^3/km^2$ (Trofimova and Cheremisina, 2015).

Technogenic seismicity in the Kuzbass region began to manifest itself in the late twentieth century (Bryksin and Seleznev, 2012; Lazarevich and Polyakov, 2003) and gradually evolved into a regional hazard. In 2013, the largest technogenic earthquake in mining history occurred at the Bachat open pit with a magnitude of 6.1 (2013). There were also seismic activation zones with a magnitude of 4-5 (Emanov et al., 2020a; Yakovlev et al., 2016). Hypocentral depths of seismic events in northern Kuzbass reach 1.5 km, in central Kuzbass 1.5–5 km, and in southern Kuzbass up to 5 km. The aftershock area of the Bachat earthquake (2013) extends at least 10 km laterally and to depths of 5–6 km (Emanov et al., 2023). Some activation areas, such as those near the Bachat open pit mine and the city of Polysaevo, have persisted for more than 10-15 years, whereas others near mining enterprises have existed for one to three years (Emanov et al., 2020b). Migration of seismic activation areas has also been observed, apparently associated with interactions between tectonic and technogenic stress fields and the sequential transition of new crustal sections into a critically stressed state. As a result, the coal-bearing massif sequentially transitions into a critically stressed condition over extensive areas and to depths of several kilometers, thereby creating conditions for its technogenic seismic degassing.

Figure 1 presents a schematic distribution of seismic event epicenters in southern Kuzbass within the mining fields of the “Raspadskaya-Glubokaya” mine and the “Raspadsky” and “Raspadsky-Koksovy” open-pit coal mines during the seismic activation period of 2022–2023, according to Emanov et al. (2024).

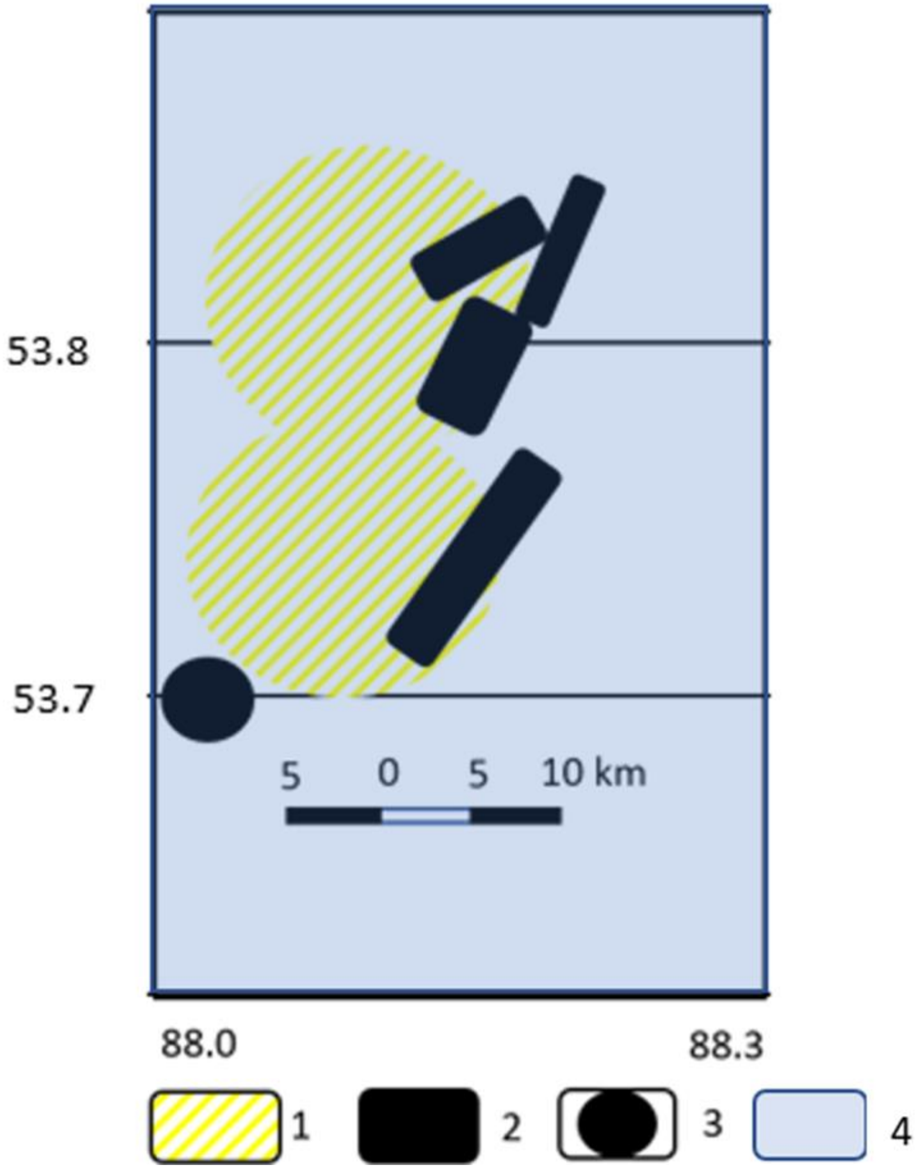

Figure 1. Schematic distribution of the seismic activation area within a region of high methane resource density in the Tom-Usinsky district of Kuzbass.

1 – seismic activation area with hypocentral depths up to 4 km (the depth of maximum activation is 1.5–2 km); 2 – underground and open-pit mining fields; 3 – the city of Mezhdurechensk; 4 – methane resource density area. Data for items 1–3 according to A. Emanov et al. (2024), item 4 according to G. Trofimova and V. Cheremisina (2015).

A total of 3243 earthquakes were recorded with energy ranging from 0.5 M to 3.8 M northeast of Mezhdurechensk, near mines and quarries between July 5 and December 31, 2022. In 2023, the seismic process continued to develop and seismic activity increased further. Hypocentral depths reached 5 km, with the maximum concentration occurring within the 1–2 km interval. According to Figure 1, the area affected by this induced seismic activation exceeded 150 km2.

The methane resource density Q down to a depth of H = 1,8 km exceeds 1,200 million $m^3/km^2$ in the Tom-Usinsky district of Kuzbass (Trofimova and Cheremisina, 2015). It may therefore be assumed that the entire coal-bearing strata underwent geomechanical transformation during the development of technogenic seismicity. Methane resources R over such an area S =150 $km^2$ and depth H amount to

$$R = Q \times S = 1200 \times 10^6 \times 150 = 1.8 \times 10^{11} \ \mathrm{m}^3.$$

The degassing coefficient of the coal-bearing strata during its transition into a critically stressed state is assumed to be k = 0.1, based on practical experience in coal seam degassing and methane emissions from abutment pressure zones. Consequently, methane emissions into the atmosphere from this single area alone may have reached $1.8 \times 10^{10}$ m3.

## 4 Discussion

According to the approach of the Intergovernmental Panel on Climate Change (IPCC), methane emissions are estimated by multiplying emission factors by the mass of coal extracted. Countries either use the emission factors recommended by the IPCC or develop their own factors (Mironov et al., 2024). Seismic processes are not taken into account. Studies addressing the relationship between gas emissions from the subsurface and seismic as well as geodynamic processes occurring within the Earth do exist (Obzhirov, 2018); however, they concern only natural processes in crustal fault zones. Against this background, the contribution of technjgenic seismicity to atmospheric pollution appears to remain unaccounted for and underestimated.

In the previous section, the example of only one area of technogenic seismic activation demonstrated the potentially significant scale of unaccounted methane emissions into the atmosphere. The total area affected by technogenic seismicity in Kuzbass has not been estimated; however, based on schemes compiled by different authors, it may be assumed to cover at least 10% of the region. In the southern part of Kuzbass alone, Emanov A.F. and co-authors (Emanov et al., 2020b) identified areas of seismic activation with a total area estimated by the present author at approximately 1500 $km^2$ (the total area of Kuzbass is 26700 $km^2$).

At present, it is difficult to estimate the volume of rock mass affected by technogenic seismicity within these areas and the distances between earthquake occurrences. According to available estimates, within a circle of 4 km radius, as many as 30–70 earthquakes occurred in seismic activation areas during a single year (from 01.05.2020 to 23.05.2021) (Emanov et al., 2020b), i.e., on average approximately one earthquake per square kilometer, although earthquake distribution is clearly uneven. It has been noted that the seismic regime in Kuzbass undergoes continuous spatial and temporal changes (Emanov et al., 2020b), indicating that increasingly larger portions of the rock mass are transitioning into a critically stressed state. The maximum concentration of hypocenters of technogenic seismic events in Southern Kuzbass is observed at depths of 1–2 km, while in the area of the Bachat earthquake depths reach 4–5 km. By analogy with the development of processes within the abutment pressure zone, it may be assumed that the transition of the rock mass into a critically stressed state develops successively from one focus zone to another. Based on the above considerations, we adopt the working hypothesis that within the seismic activation area, from the Earth's surface down to the maximum depths of seismic manifestations, the crust is in a critically stressed state, as proposed in (Batugin, 2021). This allows a preliminary estimate of methane emission E into the atmosphere caused by technogenic seismicity in Kuzbass using the following equation:

$$E = R \times S \times k \quad , \qquad (2)$$

where E is methane emission into the atmosphere caused by technjgenic seismic processes, $m^3$; R represents methane resources in the subsurface, $m^3$; S is the specific area affected by induced seismic processes; and k is the coefficient of subsurface degassing caused by technjgenic seismic processes.

Methane resources in the subsurface of Kuzbass down to a depth of 1.8 km (i.e., to the depths affected by induced seismic processes) are estimated at R = 13 trillion $m^3$ (Trofimova and Cheremisina, 2015). Methane resources are unevenly distributed spatially; however, for a preliminary estimate, we assume S = 0.1 and k = 0.1. According to these assumptions, a manifestation in technogenic seismicity in Kuzbass alone could lead to methane emissions of 0.13 trillion $m^3$, or 1.3 × 10^11 $m^3$ into the atmosphere. This is almost two orders of magnitude greater than the annual methane emission in Kuzbass estimated at 2 × 10^9 $m^3$ (Tailakov et al., 2022). Although this is a rough estimate, it demonstrates that a technogenic seismicity may contribute climatically significant methane emissions to the atmosphere.

Methane is also emitted into the atmosphere during oil and gas production (Khilyuk et al., 2000). According to estimates by the World Resources Institute (https://www.wri.org/insights/methane-gas-emissions-climate-change), the oil and gas sector accounts for approximately 14% of global methane emissions. It has been noted that methane emissions occur throughout the entire oil and gas supply chain; however, such a source as gas migration into the atmosphere associated with the development of technogenic seismicity is neither mentioned nor considered. However, as is known, technogenic seismicity occurs during oil and gas extraction, sometimes over large areas and at significant depths (Ellsworth, 2013).Thus, an important potential source of methane emissions into the atmosphere remains insufficiently investigated and unaccounted for in the oil and gas industry as well.

At present, technogenic seismicity is recognized as a global issue and manifests itself in various types of human activity over extensive areas and depths (Foulger et al., 2018). Based on the proposed hypothesis, it may be assumed that not only methane but also other gases, including radon, migrate into the atmosphere in areas of technogenic seismicity, potentially posing risks to public health. Since the existence of critically stressed rock mass areas is not necessarily accompanied by significant seismic events, gas emissions from deep subsurface horizons may occur even in the absence of observable seismicity. It is possible that this process is continuously present in nature, providing what V.I. Vernadsky described as the “gaseous respiration of the Earth.”

Satellite monitoring of regions affected by technjgenic seismicity may help reduce the uncertainty in methane emission estimates attributed to various economic sectors, as noted by researchers (Daniel J. Jacob et al., 2022), and may facilitate future climate policy development.

## Conclusions

The proposed hypothesis of thechnogenic seismic degassing of the subsurface is consistent with existing concepts of geomechanical transformation of rock masses in earthquake source areas and with empirical data on the occurrence of seismic activation at depths exceeding mining levels and over extensive areas. Preliminary estimates based on the Tom-Usinsky district of Kuzbass indicate that methane emissions into the atmosphere from only 150 km$^2$ affected by technjgenic seismicity may reach up to 10^10 m$^3$, while across Kuzbass as a whole they may attain climatically significant levels.

Developing over extensive areas and depths, technjgenic seismicity and the associated transition of the rock mass into a critically stressed state may cause subsurface degassing during various forms of resource extraction, including hydrocarbon production. This process may therefore represent a major source not only of greenhouse gases (methane) released into the atmosphere, but also of enhanced harmful effects of radon and other gases on humans and the environment in different regions of the world.

A more comprehensive and in-depth assessment of gas migration into the atmosphere in areas affected by technogenic seismicity may soon become possible through the application of satellite technologies.

## List of Reference

Adushkin, V.V., Turuntaev, S.B., 2015. Technogenic seismicity – induced and trigger. IDG RAS, Moscow.

Amez, I., León, D., Ivannikov, A., Kolikov, K., Castells, B., 2023. Potential of CBM as an Energy Vector in Active Mines and Abandoned Mines in Russia and Europe. Energies , 2023, 16(3), 1196 16, 1196. https://doi.org/10.3390/en16031196

Batugin, A., 2021. A proposed classification of the Earth’s crustal areas by the level of geodynamic threat. Geodesy and Geodynamics 12, 21–30. https://doi.org/10.1016/j.geog.2020.10.002

Batugin, A., Kobylkin, A., Kolikov, K., Ivannikov, A., Musina, V., Khotchenkov, E., Zunduijamts, B., Ertuganova, E., Krasnoshtanov, D., 2023. Study of the Migrating Mine Gas Piston Effect during Reactivation of Tectonic Faults. Applied Sciences 13.

https://doi.org/10.3390/app132112041

Batugin, A.S., 2021. General features of strong rock bursts and induced earthquakes in critical-stress areas of the Earth’s crust. Gornyi Zhurnal 2021, 22–27. https://doi.org/10.17580/gzh.2021.01.04

Batugin, A.S., Kobylkin, A.S., Musina, V.R., 2021. Investigation of the influence of the geodynamic position of coal-bearing dumps on their endogenous fire hazard. Journal of Mining Institute 250, 526–533. https://doi.org/10.31897/PMI.2021.4.5

Batugina, I. M., Petukhov, I.M., 1990. Bibliography of Rock Bursts. Part 1 (1900-1979). A.A. Balkema Publishers., Rotterdam.

Beresnev, I.A. Atkinson, G.M., 2002. Source Parameters of Earthquakes in Eastern and Western North America Based on Finite-Fault Modeling. Bulletin of the Seismological Society of America 92, 695–710.

Borowski, M., Zwoli ́nska, G., Ladys, K., Cheng, J., 2025. Methane Emissions from Coal Mines: Quantification, Capture, and Utilization Strategies for Atmospheric Impact Mitigation—A Case Study from Poland. Atmosphere 16. https://doi.org/https://doi.org/10.3390/atmos16020174

Bryksin, A.A., Seleznev, V.S., 2012. The impact of technogenic factors on the seismicity of the Kuznetsk Basin region and Lake Baikal. Russian Geology and Geophysics 53, 307–312.

Bugaev, E.G., 2011. On structured and diffuse seismicity, stiffness of earthquake foci, and nonlinearity of magnitude recurrence graphs. Geodynamics & Tectonophysics 2, 244–265. https://doi.org/10.5800/GT2011-2-3-0045

Černik, B., 1964. Statistical analysis of rock bursts over the period 1910-1960., in: HorskeTlaky a Mech. Pohori. Pp.367-385. Praha, pp. 284-295. Discuss. Pp.367-385.

Cui, H., Xue, Z., Jia, X., 2010. Reactivated Faults in Mining Area. Memoirs of the Muroran Institute of Technology 59, 101–106.

Dahm, T., Hainzl, S., Becker, D., Bischoff, M., Cesca, S., Dost, R., Fritschen, R., Kühn, D., Lasocki, S., Klose, C., Meier, T., Ohrnberger, M., Rivalta, E., Shapiro, S., Wegler, U., 2010. How to discriminate induced, triggered and natural seismicity. Seismologie 30, 69–76.

Ellsworth, W.L., 2013. Injection-induced earthquakes. Science. https://doi.org/10.1126/science.1225942

Emanov, A.., Emanov, A.A., Leskova, E.V., Kolesnikov, Y.I., Fateev, A.V., Semin, A.Y., 2007. Seismic monitoring of the Osinniki area (Kemerovo region), in: Earthquakes of Russia in 2005. GS RAS, Obninsk, pp. 63–65.

Emanov, A.A., Emanov, A.F., Shevkunova, E.V., Vateev, A.V., Rebetsky, Y.L., 2023. Volumetric Structure of the Bachat Earthquake (Kuzbass) Aftershock Area and Stress State of Rock Mass under Open-Pit Mine. Russian Geology and Geophysics 64 (S49), 1742–1750. https://doi.org/10.2113/RGG20234624

Emanov, A.F., Emanov, A.A., Fateev, A.V., 2020a. The Bachat man-made earthquake on 18 June 2013 with ML=6.1, I0 =7 (Kuzbass). Russian Seismological Journal 2, 48–61.

https://doi.org/https://doi.org/10.35540/2686-7907.2020.1.05

Emanov, A.F., Emanov, A.A., Fateev, A.V., Shevkunova, E.V., Podkorytova, V.G., Kuprish, O.V., 2020b. Induced seismicity in coal and iron ore regions of Kuzbass. Russian Journal of Seismology 2, 88–96. https://doi.org/10.35540/2686- 7907.2020.3.08

Emanov, A.F., Emanov, A.A., Fateev, A.V., Shevkunova, E.V., Yankaitis, V.V., Ershov, R.A., Polyansky, P.O., 2024. Technogenic seismic activity in the area of the Raspadskaya coal company's mines, in: Earthquakes in Russia in 2023. GS RAS, Obninsk, pp. 123–132.

Emanov, A.F., Emanov, A.A., Leskova, E.V., Fateev, A.V., Semin, A.Y., 2009. Seismic activations during coal mining in Kuzbass. Physical Mesomechanics 12, 37–43.

Foulger, G.R., Wilson, M.P., Gluyas, J.G., Julian, B.R., Davies, R.J., 2018. Global review of human-induced earthquakes. Earth-Science Reviews 178, 438–514. https://doi.org/10.1016/j.earscirev.2017.07.008

Gao, P., 2019. Development and Present Situation of Utilization Technology of Ventilation Air Methane (VAM) Enrichment and Utilization., in: IOP Conf. Ser. Earth Environ. Sci. pp. 238, 012048.

He, M., Ren, F., Liu, D., 2018. Rockburst mechanism research and its control. International Journal of Mining Science and Technology 28. https://doi.org/10.1016/j.ijmst.2018.09.002

Kachurin N.M., Shkuratsky D.N., Fisherman L.L., S.R.V., 2015. Methane release to the earth's surface for territories of mining allotments of the liquidated mines of Kuzbass. Bulletin of the TulSU. Earth sciences 2, 42–48.

Keneti, A., Sainsbury, B.A., 2018. Review of published rockburst events and their contributing factors. Engineering Geology. https://doi.org/10.1016/j.enggeo.2018.10.005

Khilyuk, L.F., Chilingar, G.V., Endres, B., Robertson, J.O., 2000. Gas Migration-Events Preceding Earthquakes. Gulf Publishing Company, Houston, Texas.

Kocharyan, G.G., Kishkina, S.B., 2020. The physical mesomechanics of the earthquake source. Physical mesomechanics 23, 9–24. https://doi.org/10.24411/1683-805X-2020-16001

Lazarevich, T.I., Polyakov, A.N., 2003. Results of the Technogenic Seismicity Study of the Kuzbass Region. MIAB 151–154.

Li, T., Cai, M.F., Cai, M., 2007. A review of mining-induced seismicity in China. International Journal of Rock Mechanics & Mining Sciences 44, 1149–1171. https://doi.org/10.1016/j.ijrmms.2007.06.00

Lovchikov, A., 2016. The strongest earthquakes and rock burst in Russian ore mines. Palmarium Academic Publishing, Saarbrucken.

Malyshev, Y.N., Sagalovich, O.I., Lisurenko, A.V., 1996. Technogenic geodynamics. P. 1. Nedra, Moscow, Russia.

McGarr, Simpson, D., 1997. A broad look at induced and triggered seismicity, in: Gibowicz, S.J., Lasocki, S.R. (Eds.), Rockbursts and Seismicity in Mines. A.A. Balkema Publishers., Rotterdam, pp. 385–396.

Mironov, A.A., Berdin, V.K., Uledova, N.V., Kevbrina, I.A., Gitarskiy, M.L., Bobylev, P.M., Kabanov, N.S., 2024. Updated assessment of methane emissions in the Russian coal industry. Ugol' 12, 26–33. https://doi.org/10.18796/0041-5790-2024-12-26-33.

Obzhirov, A.I., 2018. Seismotectonic origin of Earth degassing, surface gas emission from subsoil and its participating in geological processes in the sea of Okhotsk. Current problems of oil and gas 4, 1–11. https://doi.org/10.29222/ipng.2078-5712.2018-23.art41

Petukhov, I.M., 1991. On the nature of horizontal forces in the Earth's crust., in: Study and Forecast of Displacements and Deformations of Rock Mass, Hydrogeomechanical Processes during Mining of Deposits by Underground and Open-Pit Methods. Institute of Geomechanics (VNIMI), Saint-Peterburg, pp. 237-243.

Petukhov, I.M., 1972. Rockbursts in coal mines. Nedra, Moscow, Russia.

Petukhov, I.M., Batugina, I.M., 1999. Geodynamics of the Earth Interior. Nedra Communications, Moscow, Russia.

Petukhov, I.M., Sidorov, B.C., Raevskaya, G.G., 1968. On the bearing pressure zone. Trudy VNIMI 46, 46:208–212.

Pokryszka Z., Tauziède C., Lagny C., Guise Y., Gobillot R., Planchenault J-M., L.R., 2005. Gas migration from closed coal mines to the surface risk assessment methodology and prevention means, in: Risk Assessment Methodology and Prevention Means /Post-Mining 2005. Nancy, France.

Puchkov, L.A., 1997. Modern problems of coal methane. MIAB. 1998. – 2. – pp. 3-16. MIAB. Mining Inf. Anal. Bull. 10, 3–16.

Sadovsky, M.A., 2004. Selected works: Geophysics and Phypsics of Explosion. Nauka, Moscow.

Scholz, C.H., 1991. Earthquakes and Faulting: Self-Organized Critical Phenomena with a Characteristic Dimension https://doi.or, in: Riste, T., Sherrington, D. (Eds.), NATO ASI Series, Vol 349. Springer, Dordrecht.

Scholz, C.H., 1990. The Mechanics of Earthquakes and Faulting. Cambridge Univ. Press, New York.

Shebalin, P.N., 1987. Seismicity as a Tectonic Process, in: Pushcharovsky, Y.M. (Ed.), Modern Tectonic Activity of the Earth and Seismicity. Nauka, Moscow, pp. 22–37.

Skritsky, V.A., 2017. Methane emission from coal-seam selvage in longwall mining with caving. Interexpo Geo-Sibir 2, 108–111.

Slastunov, S., Kolikov, K., Batugin, A., Sadov, A., Khautiev, A., 2022. Improvement of Intensive In-Seam Gas Drainage Technology at Kirova Mine in Kuznetsk Coal Basin. Energies 15. https://doi.org/10.3390en15031047

Tailakov, O.V., Utkaev, E.A., Makeev, M.P., 2022. Fugitive methane emissions and technologies for their reduction in Kuzbass coal mining. Russian Mining Industry 6, 54–59. https://doi.org/10.30686/1609-9192-2022-6-54-59

Tarasov, B.G., 2021. Post-limit properties and correlation with spontaneous fracture dynamics in rocks. Gornyi Zhurnal 1, 13–19. https://doi.org/10.17580/gzh.2021.01.03

Tarasov, B.G., 2020. The fan mechanism as an initiator of deep-level earthquakes and rock bursts. Gornyi Zhurnal 3, 18–23. https://doi.org/10.17580/gzh.2020.03.03

Tauziède, C., Pokryszka, Z., Barrière, J.P., 2002. Risk assessment of surface emission of gas from abandoned coal mines in France and techniques of prevention. Institution of Mining and Metallurgy. Transactions. Section A: Mining Technology 111. https://doi.org/10.1179/mnt.2002.111.3.192

Townend, J., Zoback, M.D., 2000. How faulting keeps the crust strong. Geology 28, 399–402.

Trofimova, G.I., Cheremisina, V.G., 2015. Organization of commercial methane extraction from coal seams in Kuzbass as a modern expedient task. Symbol of Science 9, 23–36.

Vasilenko T. A., Voloshina N. I., Kolchik I. E., Molodetsky A. V., P.A.A., 2016. Study of the methane content in soil air in the area of geological disturbances under the sediment. Mining Information and Analytical bulletin. 159–166.

Yakovlev, D. V., Tsirel', S. V., Mulev, S.N., 2016. Laws of spreading and operational evaluation procedure for induced seismicity in mines and in mining areas. Journal of Mining Science 52. https://doi.org/10.1134/S1062739116020369