

The Effect of Gas Migration From Deep Geological Formations Into Mine Workings During the Evolution of Mining-Induced Seismicity

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Research Article

Keywords: Methane, Gas migration, Critically stressed rock mass, Rock mass permeability, Gas emanations, . Mining-induced seismicity, Hypocenter depth, Computer modelling

Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11389607/v1>

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Additional Declarations: The authors declare no competing interests.

THE EFFECT OF GAS MIGRATION FROM DEEP GEOLOGICAL FORMATIONS INTO MINE WORKINGS DURING THE EVOLUTION OF MINING-INDUCED SEISMICITY

Key points

- Seismicity below mining levels indicates a critically stressed massif and its failure at a greater depth.
- A conceptual mechanism links stress- and seismicity-induced changes in rock-mass permeability to potential deep gas migration.
- Numerical simulations illustrate gas migration under prescribed permeability changes and adopted model assumptions.
- The scenario-based Bachat methane-volume estimate indicates the possibility of gas migration from depths of several kilometres, in quantities comparable to the emission from the seams under development.

Abstract. From the experience of coal mining, there are known cases of gas emissions into mine workings and onto the surface, the volumes of which greatly exceed the calculated expected values. In this work, we link the intensification of gas emissions to mining workings with the process of transition of the coal strata deep sections to a critically stressed state, which is accompanied by deformation of the rock mass and is recorded by seismic activity. Seismic activity at depths exceeding the depths of mining operations has now been detected at many deposits by means of seismological monitoring. On this basis, we accept the working hypothesis that the evolution of the critically stressed state of the earth's crust in areas of mining operations manifests itself as its spread to ever deeper horizons. As the area of mining operations increases, this process proceeds from top to bottom, covering ever deeper horizons of the earth's crust, accompanied by fracture formation, contributing to their degassing and the flow of gases into mine workings from deep parts of the subsoil. Computer modelling illustrates how an increase in rock-mass permeability may facilitate gas migration from deeper horizons towards mine workings and the surface. The model provides a simplified representation of the proposed mechanism under the adopted assumptions. Using the situation in Kuzbass as a case study, the paper demonstrates a gradual increase in the depth of seismic activity manifestation, reaching depths of 5–6 km beneath the Bachat open-pit mine. The scenario-based methane-volume estimate indicates the possibility of methane migration from depths of several kilometres, with quantities comparable to the emissions from the seams recently under development. The results support consideration of this mechanism as a possible explanation for reported gas anomalies in Kuzbass mining areas.

Keywords: Methane; Gas migration; Critically stressed rock mass; Rock mass permeability; Gas emanations; Mining-induced seismicity; Hypocenter depth; Computer modelling

Introduction

In this section, we want to show that the explanation for the numerous cases of increased methane emissions into mine workings and onto the surface, recorded in mining practice, is linked to ideas about the geomechanical transformation of the rock mass in the mining area, which constitutes the first few hundred metres from the earth's surface. Gas emissions from coal-bearing strata located at depth, does not affected by geomechanical unloading processes, are not considered, with the exception of areas of tectonic faults.

Coal mining is accompanied by various hazards (Balovtsev et al., 2020; He et al., 2022; Kobylkin and Pugach, 2022; Rasskazov et al., 2020), among which the emission of methane into the atmosphere occupies an important place (Gavrilenko et al., 2004; Robinson, 2000). Assessing the emission of mine gases to the surface is of great social and environmental importance in areas where coal deposits are mined (Borowski et al., 2025; Kachurin N.M., Shkuratsky D.N., Fisherman L.L., 2015). It is traditionally believed that methane in underground coal mining is released into the mine atmosphere from the mining area, worked and overworked areas, from worked-out spaces, and from abutment pressure zones (Viktorov et al., 2005), (Fig. 1).

The depth of the rock mass unloading zone in underground coal mining is calculated according to regulatory documents, and usually does not exceed the first few hundred metres, which is consistent with practical data. For example, with a longwall width of 90 m, the flow rate of degassing wells attenuates at a depth of 80-100 m (Melnikov N. N., 2018).

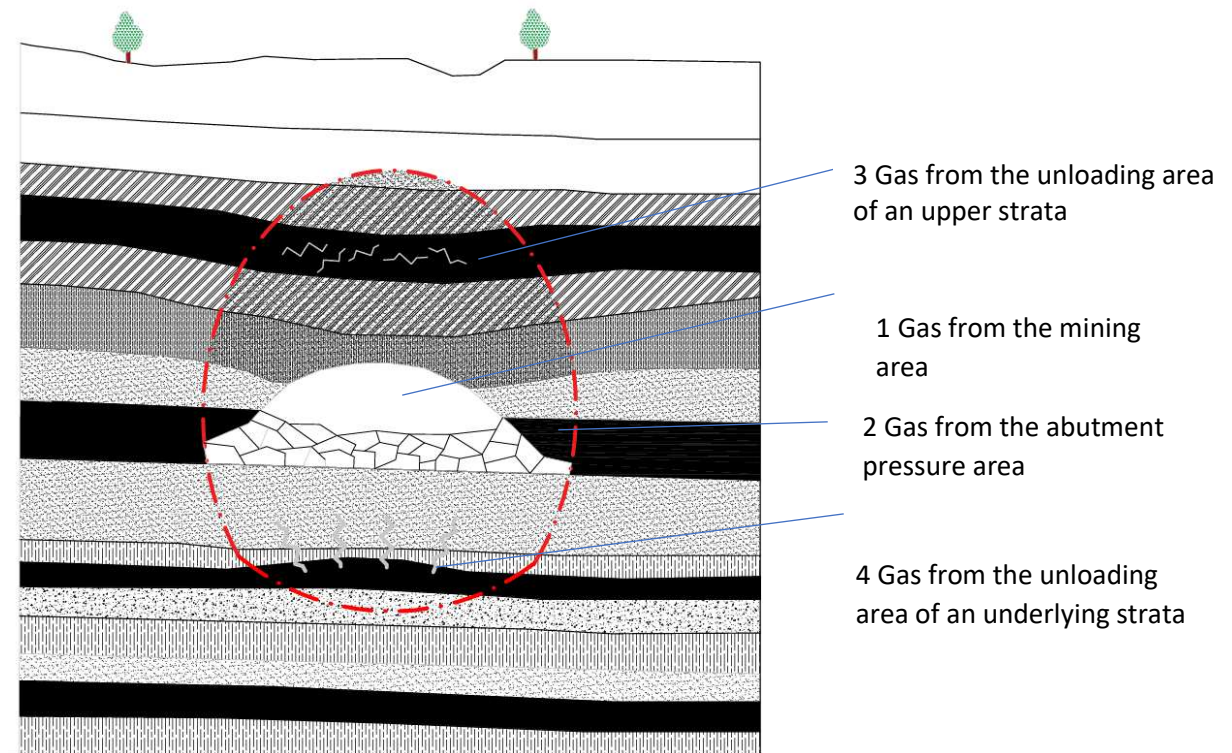


Figure 1. – Methane release areas of a coal massif strata during mining (based on materials from (Viktorov et al., 2005)).

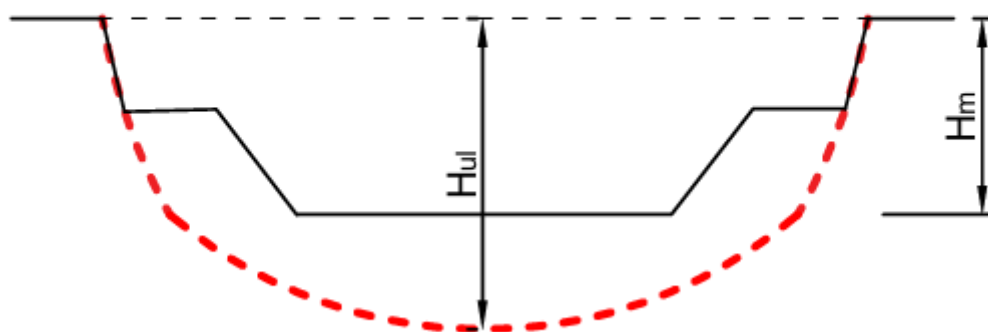


Figure 2. Schematic representation of the depths of mining areas (H_m) and unloading areas (H_{ul}) in open-pit mining (based on materials from (Melnikov N. N., 2018).

In open-pit coal mining, it is assumed that methane is released from the mined seams, as well as from areas containing coal seams that fall within the unloading zone under the bottom of the coal seam, Fig. 2 (Melnikov N. N., 2018). The potentially possible volume of methane emissions is calculated taking into account the difference in the gas content of the massif before and after unloading. The depth of the unloading zone, for example, $H_{ua} = 280$ m at a cutter depth of $H_m = 200$ m and $L = 300$ m. The maximum depth of the unloading zone during the operation of the cutter is estimated to be no more than several hundred metres.

Thus, mine gas emissions are assessed based on the productivity of the mining enterprise, taking into account the natural and residual gas content of coal seams and the size of the geomechanically transformed massif. However, in practice, there are situations when methane release in the mine space exceeds the volume of gas contained in the coal seams being mined. For example, O.N. Malinnikova and co-authors (Malinnikova et al., 2014) present the results of the gas content studies in the worked-out space of the Osinnikovskaya mine. Areas with increased gas release were discovered, the nature of which the authors attribute to the migration of methane from adjacent coal seams along the Pilot fault. In open coal pit in Kuzbass, there have been repeated cases of methane ignition during blasting operations with flames reaching heights of 50-80 m and subsequent fires in the benches (Melnikov N. N., 2018). High methane emission values are explained by an increase in the gas content of coal seams at depths of geomechanical unloading under the bottom of the coal open-cast mine. T.A. Vasilenko and co-authors mentioned cases of sudden methane emission that have been occurred three years after the cessation of ventilation of mine workings and 23 years after the filling of shafts (Vasilenko T. A., Voloshina N. I., Kolchik I. E., Molodetsky A. V., 2016). The risks of mine gas exposure to the population and the environment remain in many coal basins around the world in areas where mines have been closed (Gavrilenko et al., 2004; Karacan et al., 2011; Pokryszka Z., Tauziède C., Lagny C., Guise Y., Gobillot R., Planchenault J-M., 2005). Besides methane, mines release other gases into the atmosphere, notably radon. Recent studies indicate that radon concentrations in the near-ground atmosphere above mining areas can significantly exceed regional background levels and may pose a risk to human health (Klingel and Kemski, 1999; Korshunov and Mironenkova, N. A. Kabanov, 2015).

Explanations for the effects of sudden gasification of the Earth's surface are based on ideas about the gas migration along tectonic faults, technogenic cracks, and old mine workings [(Che'cko et al., 2021; Korchagina T.V., Efimova N.V., Gabin A.B., 2017)]. Among the processes contributing to the emergence of such effects are the piston-like expulsion of gases during the rise of water in abandoned mines [(Pokryszka Z., Tauziède C., Lagny C., Guise Y., Gobillot R., Planchenault J-M., 2005)], piston effect of expelling gases from areas of tectonic faults during their reactivation, wave-like development of displacement processes (Melnikov N. N., 2018). The effect of the methane concentration rising in mine fields is associated with the destruction of rocks as a result of mining. Methane, previously enclosed in the pores and closed cracks of coal and rocks, becomes able to migrate to the Earth's surface through macro cracks.

According to available estimates, approximately 20% of the total methane emissions originate from the abutment pressure zones. (Skritsky, 2017). The maximum release of methane from the abutment pressure zone is observed at the 4–10 m from the face. As is well known, in the zone of maximum abutment pressure, coal (and rock) undergoes a transition to a critically stressed state, which is accompanied by deformation and increased fracturing (Petukhov et al., 1968), which contributes to the release of methane from coal seams.

Mechanochemical reactions leading to methane synthesis in areas of high rock pressure are also considered as causes of increased methane release. The possibility of methane synthesis during an outburst was first noted by Müller R.L. (Muller, 1959). According to his estimates, with an activation energy of 35 kcal/mol (147 kJ/mol), it is possible to obtain very significant methane emissions (about 58 m³/t) formed from radicals and hydrogen atoms detached from the coal fringe (Malinnikova, 2011). G. Feit and co-authors (Feit et al., 2002)), investigates the phenomenon of excess gas release over the natural gas content of a coal seam during an

outburst. After examining data on sudden emissions for the period from 1986 to 2005, authors concluded that the amount of gas released exceeds the natural gas content by an average of 4.5 times, with a maximum of 11.1 times, which the authors attribute to the synthesis of methane due to mechanochemical reactions in areas of high rock pressure.

Thus, in mining practice, there have been cases of methane entering the atmosphere of mines and open pits in quantities exceeding the calculated values. Theoretical and experimental studies have established that methane is actively released when the stress state of the rock mass changes and the processes of its deformation and destruction occur. The main process responsible for methane emissions from coal is the process of man-made fracturing, which is initiated in areas of maximum abutment pressure and areas of geomechanical unloading (Feit et al., 2002). On the other hand, it has been established that the stress state of the upper part of the Earth's crust is formed due to modern tectonic processes occurring at the global level, for example (Batugina and Petukhov, 1990), which is not taken into account in existing estimates of methane emissions into mine workings and the Earth's surface.

The purpose of this work is to consider one of the possible, little-studied mechanisms of degassing of the Earth's interior in areas of anthropogenic impact, which is the result of the interaction of global geodynamic processes and local geomechanical processes arising during mining operations.

2. Phenomenological model of the critically stressed state formation at great depths in areas of mining operations

In this section, we analyze the geodynamic processes in the earth's crust in a mining area from the point of view of its critically stressed state concept, which we have previously used to analyze the nature of technogenic earthquake with deep hypocenters (Batugin, 2021a).

The first measurements of stresses in rock formations in Scandinavia (Hast, 1958), the USSR (Batugin and Shamanskaya, 1965), China (Yang et al., 2021) and other countries showed that horizontal stresses can exceed vertical stresses by several times. Evidence that these horizontal stresses can be sufficient to cause sections of the Earth's crust to reach a critically stressed state is technogenic seismicity (Townend and Zoback, 2000). With regard to the upper part of the Earth's crust C. H. Scholz noted that the continuous nature of seismic activity on the continents is one of the proofs that the Earth's crust is almost everywhere in state close to seismic destruction, i.e. on the verge of a critical state (Scholz, 1991). He considered the occurrence of technogenic seismicity under and near a reservoir in South Carolina as an example of the fact that "there were probably many small areas under this reservoir that were on the verge of destruction." Such areas close to the critical state (state of failure) are assumed to be, for example, faults in the Earth's crust, which, according to T. Dahm and other experts, is a standard assumption in the analysis of technogenic seismicity (Dahm et al., 2010). This view can be traced in the works of other authors (Ellsworth, 2013; Sobolev, G.A., Ponomarev, 2003).

Based on the results of his research into rockburst phenomena, I.M. Petukhov believed that the Earth's crust from the surface to a certain depth is already critically stressed (Petukhov, 1991). J. Townend and M. Zoback expressed a similar point of view (Townend and Zoback, 2000) and argued that faults in the Earth's crust that are in a critically stressed state affect the fluid regime of the Earth's interior.

Next, we demonstrate that the evolution of the critically stressed state of the Earth's crust in mining areas leads to this state propagating to progressively deeper horizons. This process proceeds from top to bottom, contributing to the degassing of the subsurface at depths significantly exceeding the depths of mining operations and ensuring the flow of gases from these depths into the mine workings through channels formed during the deformation of the rock mass. It should be noted that the attainment of a critically stressed state in a given rock mass volume does not invariably result in dynamic phenomena. While this condition is necessary for the initiation of a dynamic event, it is not sufficient. This is well documented in the practice of mining rockburst-hazardous deposits: for instance, a section of a coal seam—from the face to the zone of

maximum abutment pressure—typically remains in a critically stressed state; nevertheless, coal extraction from this zone does not necessarily trigger dynamic events. The zone of a critically stressed state is considered to be a zone of a specific plastic deformation, i.e. area with displacements along the surfaces of natural and technogenic fractures. A dynamic phenomenon (rock burst) will occur in this zone only if the condition of instability is met (Pan and Wang, 2022; Petukhov and Linkov, 1979). For selected sections of the Earth's crust, we propose an analogy: as the stress state evolves under tectonic forces or anthropogenic influences, previously sub-critically stressed crustal segments progressively transition to a critically stressed state. At the moment of this transition, inelastic deformation develops within the segment, accompanied by crack formation and structural degradation.

There are theoretical results that allow us to assume the development of the process described above. Figure 3 shows a graph of stress changes at depth Z as a function of the size of the object a on the surface, giving the load P_0 , constructed on the basis of the formula obtained by Davis and A. Selvaddurai(Davis and Selvadurai, 1996)

$$\sigma_z = P_0 \left[1 - \frac{Z^3}{(a_0^2 + Z^2)^{3/2}} \right], \quad (1)$$

where P_0 is the surface load applied over a zone of radius a , and z is the depth at which the stress state changes.

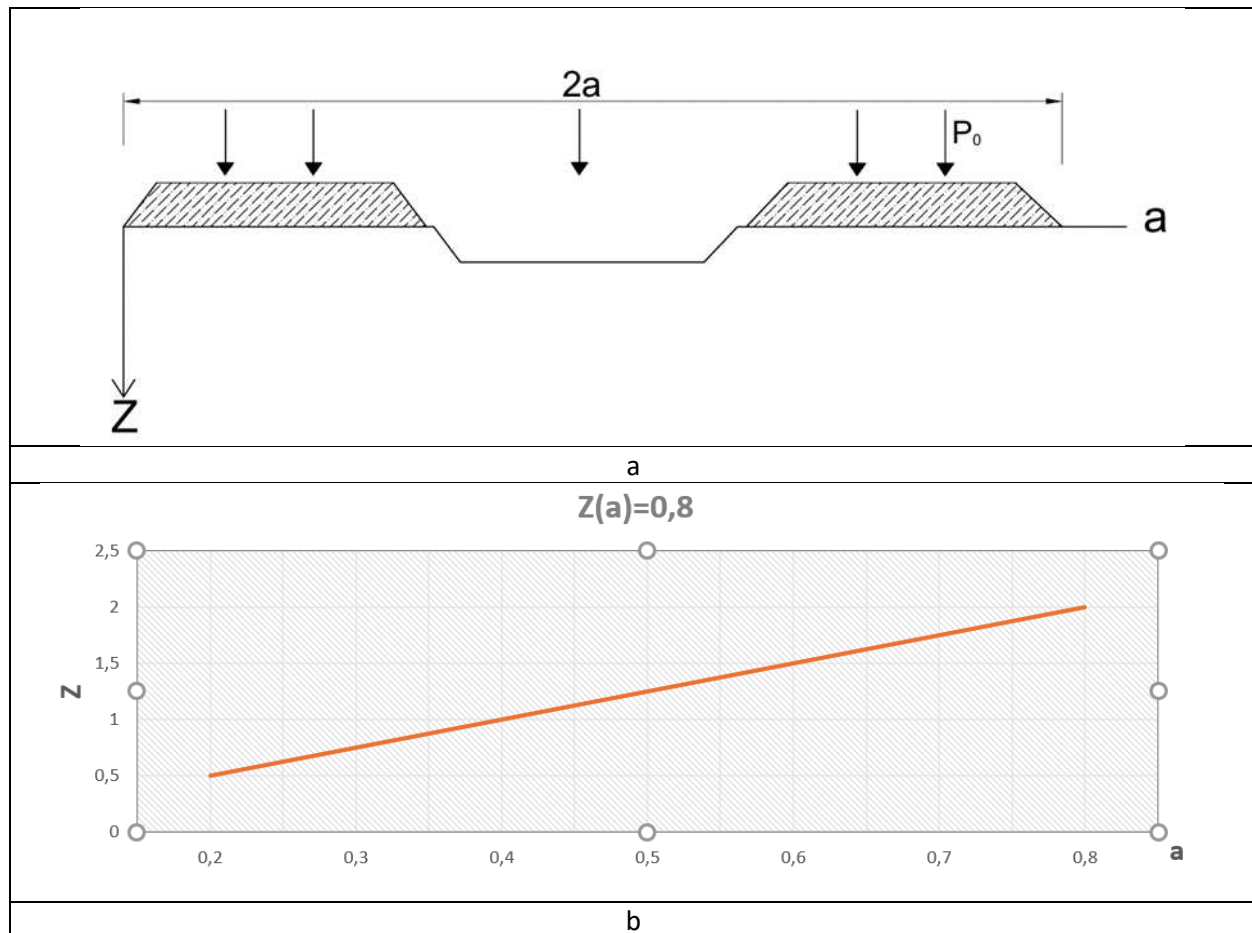


Figure 3. – Davis and Salvadurai's geomechanical model (a) (Davis and Selvadurai, 1996) and the dependence of the increase in the depth of influence Z of an object with dimensions on the surface $2a$, creating a load P_0 (b).

Of course, this model is very approximate, but it reflects an important qualitative trend: with an increase in the size of the source of impact on the surface a , the increment of vertical stresses σ_{zz}/P_0 at a fixed depth Z also increases. It is also true that as the size of the source of impact on the surface a increases, the depth

of change in the stress state Z increases by a fixed value σ_{zz}/P_0 . If we take a dump, a mine, or a quarry, we obtain that as mining operations develop, the depth of change in the stress state in the earth's crust also increases, which, in the case of the existence of a critically stressed (or close to it) areas, will manifest itself as the emergence of seismicity and deformation of the massif at ever deeper horizons. That is, as the size of the source of impact on the surface increases, there may be a sequential transition to a critically stressed state at increasingly deeper horizons in the earth's crust. The transition of the rock mass to a critically stressed state is accompanied, as already mentioned, by its inelastic deformation, the development of fracturing and degassing. Methane and other gases previously trapped inside the rock mass are able to migrate towards the earth's surface through man-made fractures formed from the surface to a depth.

There is also experimental data that can be interpreted as the development of a critically stressed state to a depth in areas of mining operations. First of all, there are numerous cases of technogenic seismicity at depths exceeding the depth of mining operations. For example, the hypocentres of major tectonically induced rock bursts at the North Ural bauxite deposit were located several hundred metres below the zone of mining operations. (Batugin, 2021b). A pronounced depth discrepancy between seismic activity and mining operations is evident from field observations. In the Polysayevo area (Kuzbass), seismic events were recorded at 2–3 km depth, while mining was conducted at 500–600 m (Emanov et al., 2009). A comparable pattern was documented at the Laohutai coal mine (China), where the zone of seismic activity reached 2 km in extent during the development of the 83001 and 63001 sites at depths of less than 1 km (Li et al., 2007). Similar phenomena have been observed in other countries in mining areas, for example, in Poland (Marcak and Mutke, 2013), and during the implementation of other subsoil development projects (Foulger et al., 2018). Moreover, a trend of a gradual increase in the depths of seismic event hypocentres over time can be traced in mining areas. In the work of I.M. Petukhov and I.M. Batugina, attention is drawn to the possibility of such a process developing at the bauxite deposit in the Urals (Petukhov and Batugina, 1999). The works of A.F. Emanov and co-authors show that in the period up to 2012, the depths of the hypocentres of seismic events under the Bachat coal mine were in the range of 1-3 km. In 2013, the Bachat earthquake occurred under the mine with a hypocenter depth of 4 km. By 2020, seismic events were already being recorded at depths of up to 6 km (Emanov et al., 2020). As already noted, seismicity is considered an indicator of the transition of a massif to a critically stressed state. This gives us reason to interpret the process of gradual development of seismicity at ever greater depths beneath the mine or open pit as a process of gradual transition of the massif to a critically stressed state at ever greater depths.

Thus, both theoretical studies and experimental data indicate the existence of rock massif segments in the upper part of the Earth's crust that are in a critically stressed state or close to it. For the purposes of further discussion, we adopt a phenomenological model wherein the progressive intensification of mining operations — i.e., the increasing magnitude of geomechanical impact on the subsurface — leads to a gradual increase in the depth of activation of these zones. Consequently, the rock massif beneath the mining site transitions to a critically stressed state at ever greater depths. This process is accompanied by the activation of pre-existing fractures and the formation of new technogenic fractures, promoting the degassing of progressively deeper horizons. Gas migration toward the surface is facilitated by the network of pre-formed fractures

3. Computer modelling

3.1 Computer model.

In this section, we consider a computer model that simulates the sequential transition of parts of the rock mass to a critically stressed state at ever greater depths beneath the mining enterprise. The structure of the critically stressed area is not addressed in this study. It is possible that this area comprises multiple regions that are either in or close to the critical state, featuring simple or complex shapes that can be described using methods of applied mathematics (Bak et al., 1988; Qiao et al., 2025). For the sake of simplicity, we assume a simple ellipsoidal shape for the zone of the critically stressed state, which is consistent with the classical

concepts of the shape of an earthquake focus (Sadovsky et al., 1983). We define the transition of the rock mass to this state as an increase in its permeability. A total of 11 zones, Z1-Z11, are identified in the model, Fig. 4. Each zone is a separate domain in which the rock mass is described as a porous-permeable medium. The characteristics of the mass (porosity and permeability) change over time within a specific area marked with the letter B (pink area in Fig. 4). For example, for zone Z1, this is section Z1B (critically stressed area), whose permeability increases over time from $1 \times 10^{-12} \text{m}^2$ to $1 \times 10^{-6} \text{m}^2$. The coal seam is shown schematically in area Z1. The methane reservoir (coal seam) is located in zone Z9.

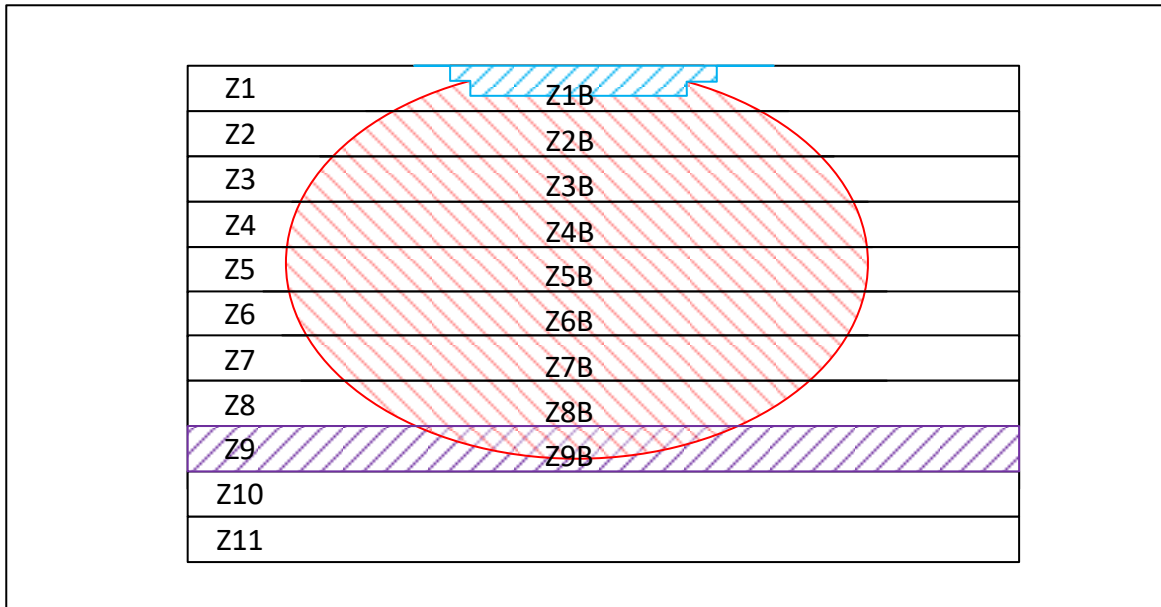


Figure 4 - Computer model diagram. (The open coal mine is shown in blue, the critically stressed area is shown in red, and the methane reservoir (coal seam) is shown in purple).

The ANSYS CFD software package was used for the calculations, which allows modelling with time-varying parameters (transient). Figure 5 shows the computer model.

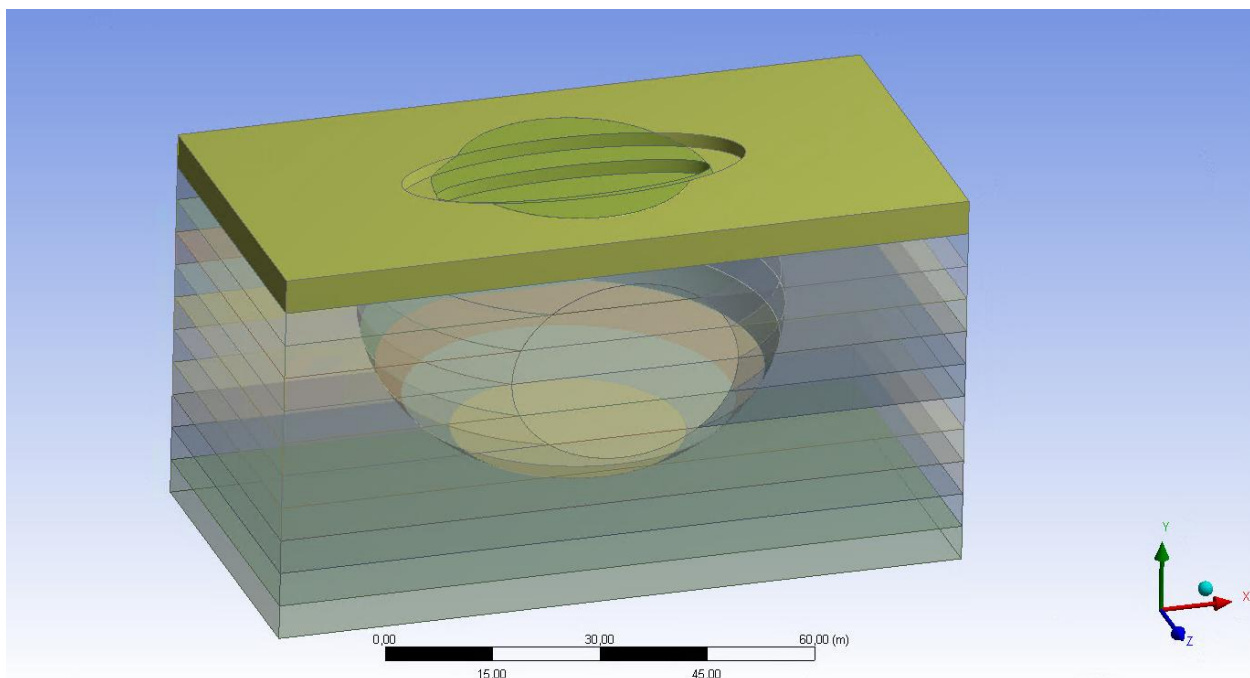


Figure 5 – General view of the computer model

To simplify the simulation of the process under study, the dimensions of the coal cut were not changed, and the development of mining operations (deepening/expansion of the cut or dumps) was specified by a sequential increase in the permeability of the rock mass in subzones Z1B-Z9B falling within the zone of influence of mining operations. For example, for domain Z1B, the permeability was set as follows:

$$k_{1B}(t) = 10^{-12} + 10^{-11} \text{step}(t - 5) + 10^{-10} \text{step}(t - 10) + 10^{-9} \text{step}(t - 15) + 10^{-8} \text{step}(t - 20) + 10^{-7} \text{step}(t - 25) + 10^{-6} \text{step}(t - 30), \quad (2)$$

Where:

- $1 \times 10^{-12} \text{ m}^2$ — rock massif permeability;

- $\text{Step}(t/(1 \text{ s}) - 5)$ — dimensionless step function with a nominal activation time of $t=5\text{s}$.

For subzones Z2B-Z9B, the corresponding formulas were also specified.

In domain Z9 (coal seam), methane CH_4 was specified as the gas component, under an excess pressure of 10,000 Pa and a concentration of 100%. The range of permeability variation from 1×10^{-12} to $1 \times 10^{-6} \text{ m}^2$ was chosen by the authors for clarity and may not coincide with actual values.

3.2 Modelling results

The simulation results show the methane concentration fields shown in Figures 6-9 in the secant plane through the centre of the model. The permeability of the rocks is indicated on the left for each zone both as a colour indication and numerically. At the initial stage of mining operations, the permeability of the rocks is $1 \times 10^{-12} \text{ m}^2$. The methane trapped in the coal seam is in a stable state, and its concentration is indicated by colours ranging from red (100%) to blue (0%). The top of the figure shows a schematic representation of the quarry and its stages of development (brown).

The movement of the critically stressed area deep into the earth is recorded by seismic events, which in this model are a visual indication of theoretical positions and are not the result of computer modelling.

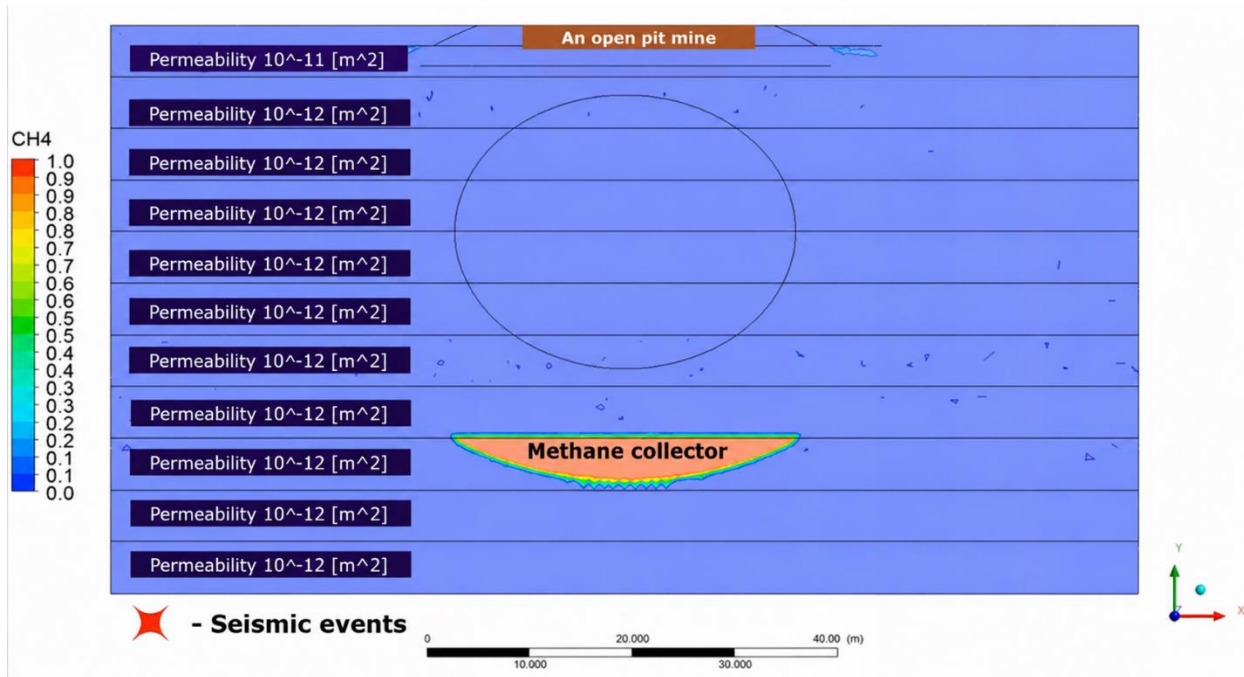


Figure 6 – Methane concentration field at the initial moment in time, in a section through the centre of the model. Seismic-event symbols are schematic illustrations of the proposed conceptual mechanism and are not outputs of the numerical simulation.

As mining operations progress, the permeability of the rock increases (Figs. 7-9). Figs. 7 a-d show the stages of change in rock permeability in zones Z1-Z5. As can be seen from the figure, methane does not move towards the earth's surface.

Figure 8 a-d shows the stages of change in rock permeability in zones Z1-Z9. The change in permeability in zone Z8, located directly above the methane reservoir, to values of $1 \times 10^{-10} \text{ m}^2$ (initial value $1 \times 10^{-12} \text{ m}^2$) leads to the start of methane movement upwards. A further increase in the permeability of zone Z8 to 1×10^{-9} ($1 \times 10^{-6} \text{ m}^2$) intensifies the process of methane escaping from the reservoir (Fig. 9, a-d).

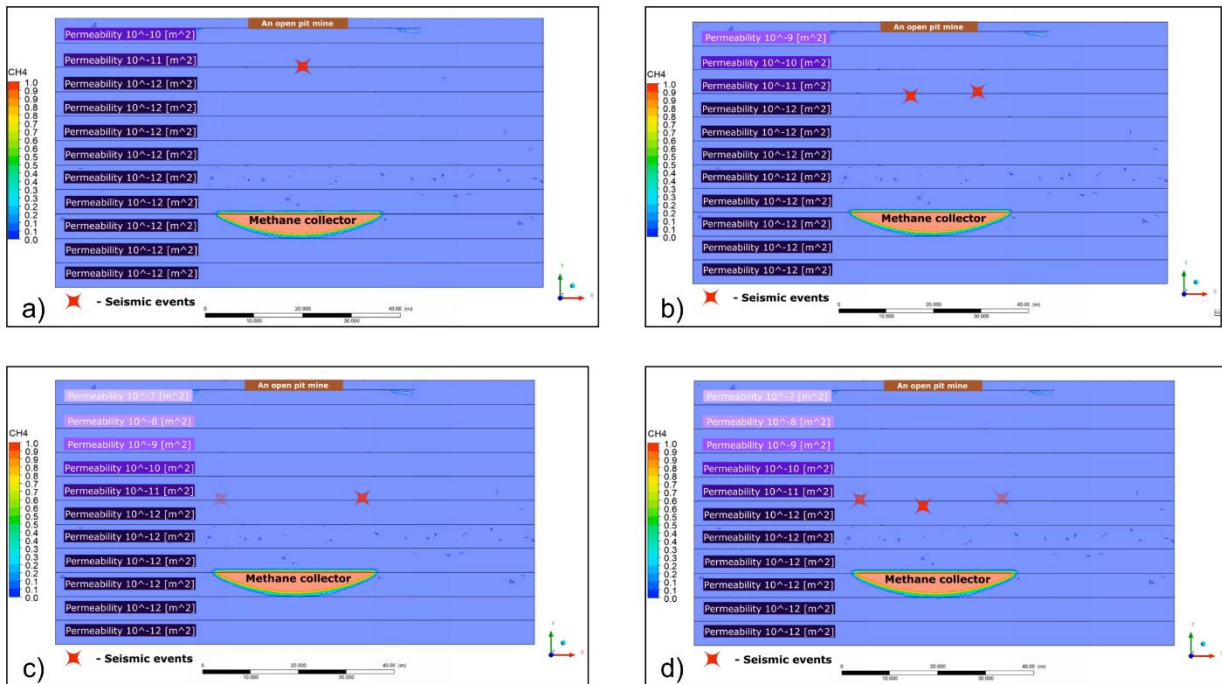


Figure 7 – Methane concentration field with changing permeability in zones Z1-Z5. Seismic-event symbols are schematic illustrations of the proposed conceptual mechanism and are not outputs of the numerical simulation.

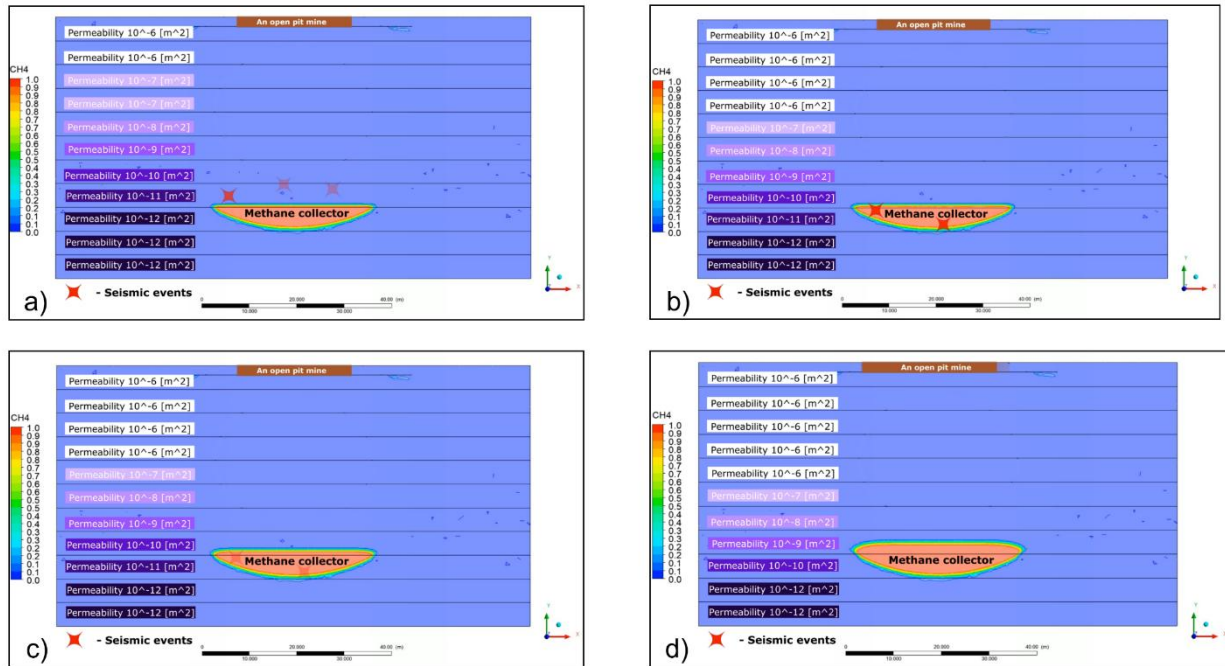


Figure 8 – Methane concentration field with changing permeability in zones Z1-Z9. Seismic-event symbols are schematic illustrations of the proposed conceptual mechanism and are not outputs of the numerical simulation.

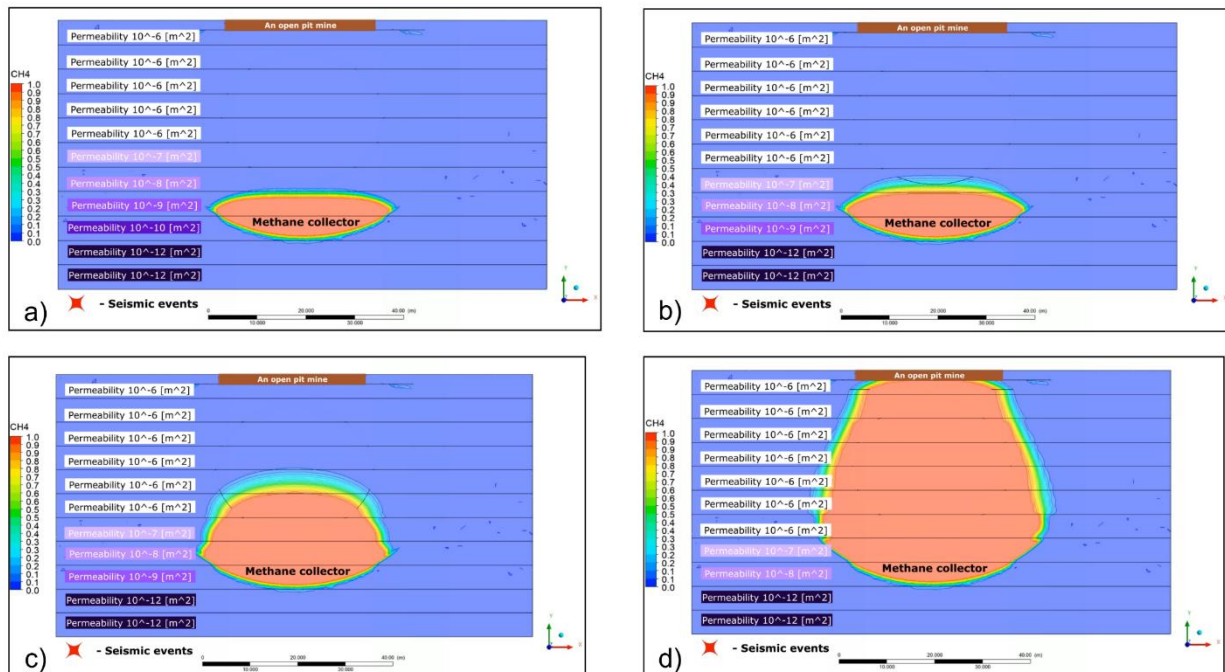


Figure 9. – Process of methane emission from the reservoir with a further increase in permeability.

4. Discussion of results

We assume interaction between global geodynamic processes and local geomechanical processes arising during mining operations. Global geodynamic processes form tectonic stress fields and create conditions for the emergence of areas of the rock mass that are in a state close to (or at) the critical. Technogenic stress fields formed by mining operations change the stress state of the rock mass in local areas deeper than the mining area, which leads to the effect of "pushing through" the critically stressed state to greater depths.

Our proposed hypothesis of gas migration from deep underground to mining workings and further into the environment correlates with known views on the nature of gas anomalies on the surface. In geology, the migration of gases from the subsurface to the Earth's surface is considered part of the geological life of our planet, and tectonic processes are one of the leading mechanisms of this phenomenon (Vernadsky, 1912). It is believed that tectonic faults serve as the main canals for gas migration from the subsurface to the surface, as they have increased permeability (Kasatkin and Obzhirov, 2018; Khilyuk et al., 2000; Korchagina T.V., Efimova N.V., Gabin A.B., 2017). Their high permeability, as well as the formation of new highly permeable areas, is supported by neotectonic activations, the conditions for which exist not only in seismically active areas, but also within lithospheric plates (Batugina and Petukhov, 1990; Gresov et al., 2014; Townend and Zoback, 2000). R.H. Simpson argued that faults originate in the lower part of the seismically active layer and provide movement of fluids from the Earth's interior to the surface (Sibson, 2020). In our model, mining operations lead to the formation of a technogenic seismically active layer, the depth of which gradually increases, creating conditions for the formation of cracks and faults.

There is also other evidence that can be interpreted within the framework of the proposed hypothesis. Radon gas anomalies in soil air and the lower atmosphere are associated with the preparation of seismic events (Riggio and Santulin, 2015). The physical nature of radon anomalies is explained by the processes of deformation of rocks in the Earth's crust. Radon gas and other gases previously trapped in the pore space of rocks are able to migrate through the resulting cracks to the Earth's surface. All of the above phenomena can be explained in terms of changes in the stress state in the subsurface and the transition of a massif section to a critically stressed state with its deformation and emission of gases.

Here we attempt to estimate, for example, the amount of methane that can migrate to the Earth's surface due to the formation of rock mass destruction zones caused by seismic activity at depth, under the conditions of the Bachat open-pit mine, which we have already mentioned. Fragments of the geological cross-section of the Bachat coal mine area are shown in Fig. 10.

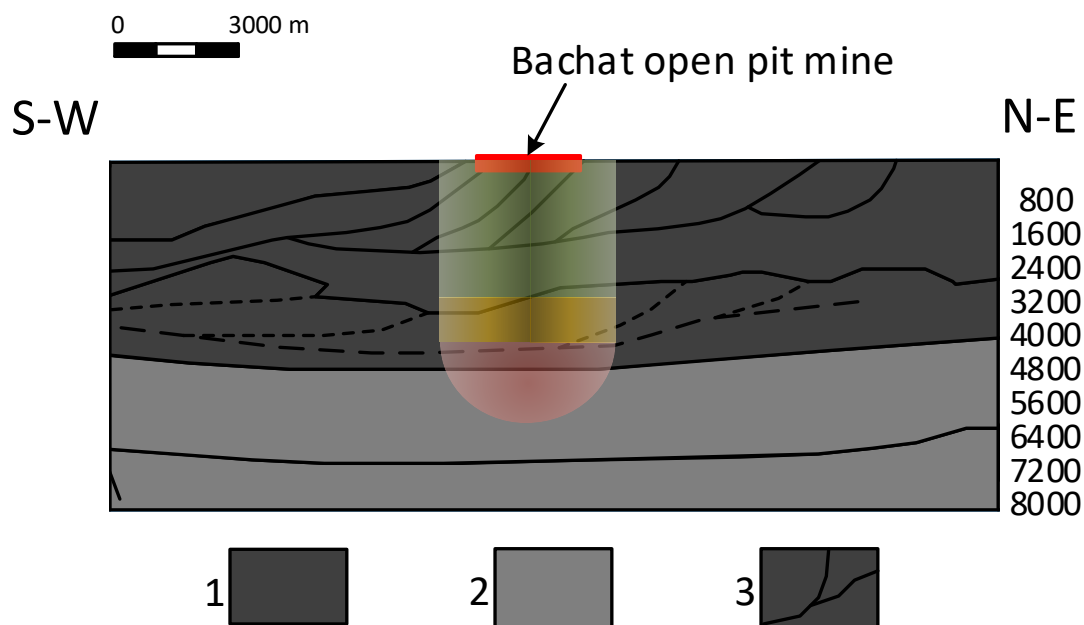


Figure 10 – Fragments of the geological section of the Bachat coal area in Kuzbass.

1 - coal-bearing strata; 2 - coal-free strata; 3 – lithological boundaries (adapted from (Kocharyan et al., 2019);

The areas of technogenic seismicity are shown as follows:

Green — prior to 2012;

Yellow — in 2013;

Red — in 2020.

We will calculate methane emission E, m^3 , using the formula:

$$E = RSk, \quad (4.1)$$

where R is the average areal methane resource density m^3/km^2 ; S is the assumed area of the rock mass considered in the degassing scenario km^2 ; and k is the assumed dimensionless fraction of methane resources released from that rock mass.

The methane resource density R in the Kuzbass region have been estimated down to depths of 1.8 km and amount to 582 million m^3/km^2 for the Bachat area (Trofimova and Cheremisina, 2015). Under the Bachat open pit, the seismic process in 2013 developed over an area of 3×10 km and to depths of 4 km, i.e., across the entire thickness of the coal-bearing strata. Taking into account the practical experience of coal seam degassing (Slastunov et al., 2022), we assume a degassing coefficient k value of 5-10 % ($k=0.05-0.1$).

Using the regional average methane resource density $R=582 \times 10^6 m^3/km^2$, an assumed scenario area $S=30 km^2$, and an assumed degassing coefficient $k=0.05$, Eq. (4.1) gives a potentially releasable methane volume of $E=873 \times 10^6 m^3$. This approximate scenario-based estimate suggests that methane emissions from deep horizons, driven by seismicity, may be comparable to emissions from the seams currently under development. According to available estimates, methane release into the atmosphere during the development of the Bachat open pit mine to a depth of 200 m amounted to $104.8 \times 10^6 m^3$ (Melnikov N. N., 2018). , which is less than could be released during the evolution of mining-induced seismicity.

The aftershock zone of the Bachat earthquake has existed for more than 10 years and spans the space from the Earth's surface to depths of several kilometres, which indicates the continuous reactivation of fractures in this large rock mass and the maintenance of favorable conditions for gas migration into the mine workings.

Furthermore, at high pressures at depths of several kilometer's, displacements along faults during seismic events can lead to temperature anomalies. According to researchers, temperature anomalies and high rock pressure can lead to the synthesis of additional methane through mechanochemical reactions (Feit et al., 2002) and, according to our proposed hypothesis, can cause an increase in the gas content of mine workings during the development of induced seismicity.

Thus, our proposed effect is consistent with the theoretical and phenomenological concepts regarding the conditions for gas emission from zones of critically stressed state of the rock mass. It is supported by the results of computer modelling and explains the experimental observations of increased methane emission into the mine workings.

Conclusions

The results of theoretical assessments and experimental observations indicate that the development of mining-induced seismicity at mining fields is accompanied by a gradual increase in the depths of seismic event hypocenters. Since seismicity is an indicator of the transition of a rock mass into a critically stressed state, its evolution in mining areas manifests as the progressive propagation of a destruction zone into increasingly deeper horizons. This process of fracturing, and the associated increase in permeability, propagates from shallow to deeper levels, promoting the degassing of the rock mass and facilitating the migration of gases from deep geological horizons into mine workings, as demonstrated by numerical modeling.

Using the Bachat open-pit coal mine in Kuzbass as a case study, it was shown that mining-induced seismic degassing of the rock mass may result in methane inflows from deep geological horizons that may be comparable to emissions from the mined coal seams. Consequently, the development of mining-induced seismicity, accompanied by the progressive deepening of hypocenters, may be responsible for episodes of sudden gas accumulation in mine workings and at the Earth's surface.

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