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Study of the Migrating Mine Gas Piston Effect during Reactivation of Tectonic Faults

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Abstract: The hypothesis of the piston effect during mine gas migration caused by fault reactivation was studied, with the use of computer modeling, to explain cases of a sudden appearance of mine gases on the earth surface in coal mining areas. The study is based on the factual data of the mode and amplitudes of subsidence along faults during mining, the morphology of the fault planes, and the theoretical ideas about the discrete nature of the fault wall displacement along uneven contact surfaces. It is taken into account that the walls of the fault, due to the asperity types "ridge" and "sag", form contacts of the "ridge–ridge" and "ridge–sag" patterns. This study examines the situation where gas pressure in the fracture space can sharply increase due to the jerky displacement of reactivated tectonic fault walls with a rough fault plane. It is assumed that, in the first phase of reactivation, the fracture space expands as a result of the displacer opening and the fact that fault plane asperities engage in the "ridge–ridge" type of contact. With the subsequent relative displacement of the fault walls in the second phase of reactivation, the contact changes into the "ridge–sag" type and a sharp reduction in the fracture space volume occurs. It is shown that a "piston effect" emerges due to the reduction in fracture space and that it promotes an increase in gas pressure and stimulates gas movement to the surface through the available channels. The resulting "piston effects" may also be responsible for the suddenly raised gas content recorded in the air of surface structures and recurrent mine gas migration onto the surface. The findings expand our understanding of the sudden gasification of the earth surface and living spaces in coal mining areas and contribute to the understanding of the gas migration process, thereby helping to monitor hazards.

Keywords: mining; subsidence; fault reactivation; asperities; piston effect; gas migration; disaster control

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Citation: Batugin, A.; Kobylkin, A.; Kolikov, K.; Ivannikov, A.; Musina, V.; Khotchenkov, E.; Zunduijamts, B.; Ertuganova, E.; Krasnoshtanov, D. Study of the Migrating Mine Gas Piston Effect during Reactivation of Tectonic Faults. *Appl. Sci.* **2023**, *13*, 12041. https://doi.org/10.3390/app132112041

Academic Editor: Tiago Miranda

Received: 7 September 2023
Revised: 12 October 2023
Accepted: 16 October 2023
Published: 4 November 2023

1. Introduction

The dangerous phenomenon in coal mining areas that causes environmental and societal damage is the sudden release of mine gases to the surface through tectonic fault zones [1]. Despite the degassing of coal seams during mining [2,3], methane and other colliery gases inevitably migrate to the surface, even after mine closure [4]. The gas emissions into the atmosphere contribute to the greenhouse effect [5,6] and, along with other mining hazards [7–10], create dangerous situations in mining areas. A number of studies provide a long-term history of cases associated with gas emissions [11,12]. Important features of mine gas migration to the surface include the spontaneity of the process and its irregular timing, which make it difficult to predict it. Gas may be released to the surface many years after the mine closure or between monitoring activities. For example, according to the data from [13], methane exploded in the basement of a residential building located at the outskirts of a closed Ordzhonikidze mine three years after the mine ventilation system was cut off. At the abandoned 7/8 Kalinin mine in Donetsk, the released gas exploded 23 years after the mine shafts were backfilled. The permeable zones of tectonic faults constitute a natural way for gas to migrate [14–16]. The presence of highly permeable zones, in turn, creates the conditions for the activation of one of the gas migration mechanisms, namely, hydraulic flow [17]. In mining areas, work is regularly carried out to monitor the gas hazard on the surface, but there is always the risk of a sudden release of gases to the surface in a period between regular observations, which indicates the need to continue studying the mechanisms that control the migration of mine gases to the surface.

As it were, tectonic processes and the presence of tectonic faults are considered to be important factors that act upon the migration of underground gases towards the earth's surface, as these conditions increase rock permeability during its deformation; however, the observed sudden gas manifestations are not explained. The specific objective of this paper is to form a hypothesis about the piston effect explaining the mechanism of occurrence of dangerous situations associated with sudden gas movements towards the surface in mining areas and to verify it by using the method of computer simulation.

2. Theoretical Background

Let us consider the factors that contribute to the emergence of the piston effect during the migration of mine gases to the surface.

2.1. Reactivation of Faults at Their Displacement

The reactivation of faults imposed via mining operations is a well-known phenomenon [18,19]. There are not only theoretical overviews of this problem [20] but also the results of many experimental and theoretical studies [21,22]. Studies on coal deposits revealed that a more intensive displacement in the coal seam roof and floor is observed near a fault plane [22]. Studies at the Vysokogorskoye ore deposit found that major deformations coincide with tectonic faults [23]. The way in which faults influence the non-uniformity of displacement depending on the distance to the mining area and its depth was shown via a computer simulation technique [24]. A.G. Akimov believed that a shift along tectonic faults (fault reactivation) is possible in the following cases: the fault plane dips towards the goaf; the angle of the dip is greater than the angle of the internal friction along the weakness planes; and the dip azimuth differs from the direction of the cut plane by no more than 30 degrees [25]. The activation of displacement processes and fault reactivation are also observed after mine closure and are manifested in the formation of hillocks on the surface, linear subsidence [26], and dynamic movements along faults [27,28]. The reactivation of faults was also registered during hydrocarbon production [29] and other types of human impact in places of tectonic movement activation [30–32]. Consequently, the reactivation of faults is viewed as a common process involved in mining.

2.2. The Amplitudes of Fault Displacement during Their Reactivation by Subsidence Processes

From available public data, it is known that the displacements along reactivated faults can be dozens of centimeters per increment and can total up to several meters [33,34]. Cases of fault reactivation in areas stretching over 15 km or more have been described. The formation of scarps and the subsidence of the earth surface in fault reactivation areas are observed even when the mining operations are located at greater depths. L. J. Donnely describes the case of a steeply dipping fault plane reactivation when a coal seam was worked out at a depth of 600 m [33]. The subsequent overall surface subsidence was almost 4 m. In the period between November 1978 and September 1979 (10 months), the displacement amplitude amounted to more than 2 m.

2.3. Uneven Timing of Fault Reactivation Process

On average, it takes 2 to 5 years for the displacement process to last depending on the mining conditions and residual movements are estimated to be up to 10% of the maximum subsidence, sometimes more [35]. The displacement process develops unevenly over time, the periods of activation can occur many years after mining operations have been stopped [1,36]. The fault reactivation in these periods can manifest itself in a dynamic mode in the form of fault-slip rock bursts [34,37,38] or as seismic events [29,39,40], as a cycle of short-term rock deformations [41] or as a process lasting from 1 h to several weeks or even several years [33]. In the latter case, a lengthy process of massif deformation can also be represented as a pulsating one consisting of multitude of micro-shock-like displacements [31].

Tectonic faults, therefore, provide a discrete nature of the displacement process development both in space and in time. The displacement amplitudes along reactivated faults can reach several meters. Fault reactivation can be repetitive, even many years after mining operations have been stopped.

2.4. The Morphology of Fault Planes

The surfaces of the fault planes have heterogeneity of various orders, from microscopic roughness to large asperities, whereby the fault walls contact only parts of their surfaces. The specific area of fault walls' contact patch is estimated as a few percent of the total area of the fault contact walls by using special tools in natural conditions [42], in laboratory tests, and theoretically [43,44]. In the study [45], the amplitude and wavelength of bumps, or asperities, of a number of faults were empirically studied. The asperity amplitude ranges between 3.5 mm and 6.5 mm for 1 m profiles parallel to slip (along the axis of striations) to 2 m on a 35 m long profile. In the k study [43], a brief review of the main recent results obtained by studying geometry of sliding surfaces in rocks was presented. As it follows from the study, for cracks in the length range from 1 to 1500 m, the roughness measurements are described adequately by the equation:

$$A_{aV} = 7.5 \times 10^{-3} \times L^{0.8} \tag{1}$$

where A_{aV}—average amplitude of profile deviation from a straight line (m); L—block length (m).

According to Formula (1) for a 10-m-long fault, A_{aV} = 4.72 cm, whereas, for a 100 m long fault, A_{aV} = 29 cm.

It has also been observed that there is a certain critical angle θ_{cr} (7–20° for strong rocks) of the local slant of roughness, so that protrusions with $\theta < \theta_{\mathrm{cr}}$ do not collapse during the shear but deform elastically [43,46].

Two extreme states of displacer inhomogeneities' contacts are distinguished in simple models: ridge–ridge state and ridge–sag pattern (Figure 1) [47,48]. The "ridge-ridge" type contact ensures maximum permeability of the fault plane and maximum volume of the fracture space adjacent to the fault plane, while the "ridge-sag" type of contact provides the opposite (Figure 2). We assume that, in the first phase of reactivation, the fracture space expands, resulting from displacer opening and the fact that fault plane asperities are engaged in "ridge-ridge" type of contact. With subsequent relative displacement of the fault walls, i.e., in the second phase of reactivation, the contact changes to "ridge-sag" type and a sharp reduction in the fracture space volume occurs. Thus, when the fault is reactivated and the type of contacts is changed, the volume of the void space also changes and the effect of piston extrusion of gas occurs in the direction of the pressure gradient, i.e., towards the earth's surface. A computer-generated model and the results of such modeling are considered below.

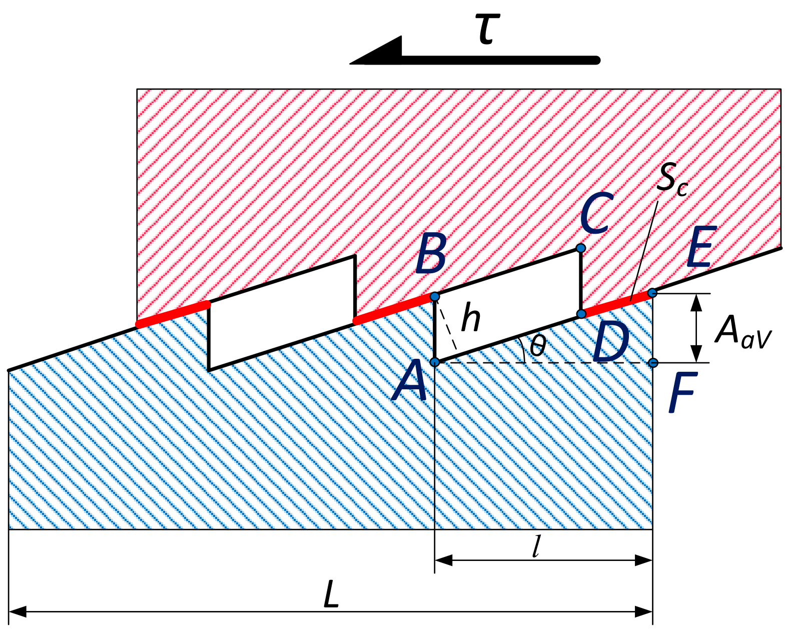

Figure 1. Fault wall contact schematic representation. A_{aV}—average height of surface asperities; θ—angle of local inclination of surface asperities; l—average length of surface asperities; Sc—wall contact area, L—size of fault reactivation area; red and blue colors—the hanging-wall block and footwall block of a fault accordingly; A–F—vertexes of the asperities; h, θ—parameters of the asperities; τ—displacement direction of the hanging-wall block, explanation is below in the text.

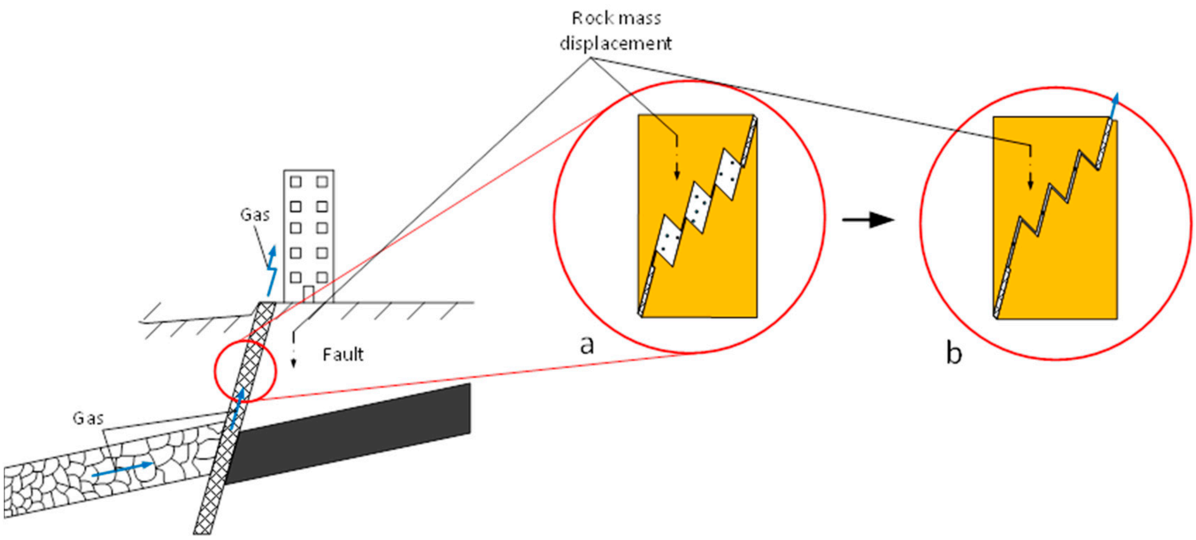

Figure 2. Schematic representation of pathways: mine gases migrating to the surface due to piston effect created by the relative displacement of the tectonic fault walls; (**a**)—"ridge-ridge" type of contact; (**b**)—"ridge-sag" type of contact.

3. Computer-Generated Model and Its Parameters

3.1. Parameters of Fault Wall Displacement on Rough-Surfaced Plane when Fault Reactivation Is Triggered by Shift Processes

In a computer-generated model, it is required to set the values of fluid pressure in voids at the fault plane that change during fault reactivation and of rock permeability in the faulted zone. In the case when the void-filling fluid is gas, we can assume that, at a constant temperature, its behavior obeys the Boyle–Mariotte law:

$$PV = \text{const} \tag{2}$$

where P is pressure and V is gas volume.

Let us assume that the gas volume is equal to the volume of void space adjacent to the fault plane. Then, with a relative displacement of the fault limbs and changing space volume, a smooth or pulsating change in pressure can occur in gas filling the space.

3.1.1. Estimation of Void Space Volume Change

We offer an estimate of the change in the volume of the void space adjacent to the fault plane based on the value of a single-step displacement along the fault plane. The magnitude of such shift can be estimated from the results of in-mine observations and on the basis of theoretical concepts describing pulsating mode of fault wall displacement. When fault walls are displaced, seismic energy is released in a dynamic form, and the magnitude of such displacement in the source zone can be estimated by the amount of seismic energy. C. Tsuboi explained the relationship between the earthquake energy E and volume of the source zone V_{sz} [49]:

$$E(erg) = 1000\ Vsz\ (\mathrm{cm}^3) \tag{3}$$

From this and similar empirical equations [50,51], it can be calculated that the size of the fault source zone during an earthquake with up to K = 5 energy class does not exceed 10 m. It is proposed to estimate the lower limit of the displacement amplitude A (m) for brittle-plastic deformations under triaxial compression in the source zone L_{sz} (km) by the following formula [52]:

$$lgA = 0.5lgL_{sz} \tag{4}$$

Based on Equation (4), it can be found that the displacement amplitude for K = 5 energy class earthquake is just a few millimeters. In-field observations of the rock burst manifestations with the fault-slip mechanism also show that the amplitude of displacements along fault planes during seismic events of class K < 5 does not exceed 1 cm [37].

To estimate the volume of the void space V_{vs} and its change ΔV during the fault reactivation, we use the simplest model of the fault walls' contact shown in Figure 1. The $ABCD$ figure with the indicated parameters h, θ depicts the void space (cavity) here, and the segment $DE = Sc$ depicts the contact patch of the walls of the fault, $A_{aV} = EF$. From geometric considerations, we can conclude that the volume of voids V_{vs} shown in Figure 1 in a fault plane section with length L and width W will be:

$$V_{vs} = A_{aV} \cdot L \cdot W \cdot (1-n) \tag{5}$$

where n—is a parameter characterizing the total wall contact area and $n = \mathrm{DE}/\mathrm{AE}$, Figure 1.

When the walls are displaced along the arrow (Figure 1), the volume of the void space decreases by ΔV and parameter n changes from n_1 to n_2.

$$\frac{\Delta V}{V} = \frac{n_2 - n_1}{1 - n_1} \tag{6}$$

Assuming that A_{aV} = 4 cm and θ = 10–15°, then we can obtain that, with a wall displacement of 1 cm, ΔV equals fractions of a percent.

This certainly is a very rough estimate. The volume between asperities can be filled with fault plane contact disintegration products (debris) or secondary minerals, and the single-step displacement amplitude can be an order of magnitude less. Nevertheless, the estimates made allow us to assume that, in case of a single-step fault wall displacement, the volume of free space along the fault plane will decrease by hundredths or tenths of a percent. Taking into account Equation (2), the pressure increment during displacement along the fault should be estimated as 250 Pa and more.

3.1.2. Description of the Computer-Generated Model

The graphic showing mine gas migration associated with fault reactivation is provided in Figure 2.

Gas flow model for migrating gas by piston effect is solved by CFD ANSYS 16-CFX software. The simulation is carried out in a transient setting. Air ideal gas and methane CH4 are used as the fluids. Turbulence model is the k-Epsilon. The gravitational force g is directed along the y axis. "Rock" and "Excessive fissuring zone" are presented in the form of porous domains. "Cavity" and "Air" are represented as fluid domains. Some parameters of the simulation are shown in Table 1.

Table 1. Parameters of the simulation.

Parameters	Value	Notes
Analysis type	Transient	
Total time	3 (s)	
Timesteps	0.01 (s)	
Fluid	Air ideal gas, CH_4	Material Library
Gravity Y Dirn.	$-g$	
Turbulence model	k-Epsilon	
Turbulence	Intensity 5%	
Multiphase	Homogeneous model	
Fluid buoyancy model	Density difference	
"Excessive fissuring zone" Permeability	1×10^{-5}, 1×10^{-4} (m^2)	
"Rock" Permeability	1×10^{-14} (m^2)	
"Air" Volume fraction	100%	Air ideal gas
"Cavity" Volume fraction	100%	CH_4
Pressure increased	250, 1000 (Pa)	Cavity inner surface

The process of gas release into a cavity (void space) located in a rock mass was simulated (Figure 3). The cavity represents a domain filled with mine gas. This cavity has inner and outer surfaces. The inner surface is used as a zone whereupon the pressure surge is set. The outer surfaces border on rock mass and on the zone of excessive fissuring. The simulated process is proposed as an analogue of sharp rock displacement process and increasing fluctuating pressure. There is a surface of excessive fissuring zone that is adjacent to an object on the surface, represented by the "air" domain. The simulation parameters (creation of a computational mesh, selection of initial and boundary conditions, turbulence models, etc.) were selected, being based on a previously performed study [53].

In computer simulation, pressure build-up as a result of rock displacement was set as a pressure surge on the inner surface of the cavity (Figure 3b). The rock properties were set as a porous medium with 1×10^{-14} m^2 permeability (Figure 4a). The permeability of the fault zone (Figure 4b) was assumed to be 1×10^{-5} m^2 and 1×10^{-7} m^2. The pressure surge on the inner surfaces of the void is assumed to be 250 Pa and 1000 Pa. Three stages of the process were simulated, each lasting 1 s. In the period between 0 and 1 s (stage 1), the pressure in the fault zone did not change; in the period between 1 and 2 s (stage 2), the pressure increased stepwise to 250 Pa or 1000 Pa; in the period between 2 and 3 s (stage 3), the pressure decreased (gas outflow from area of high pressure).

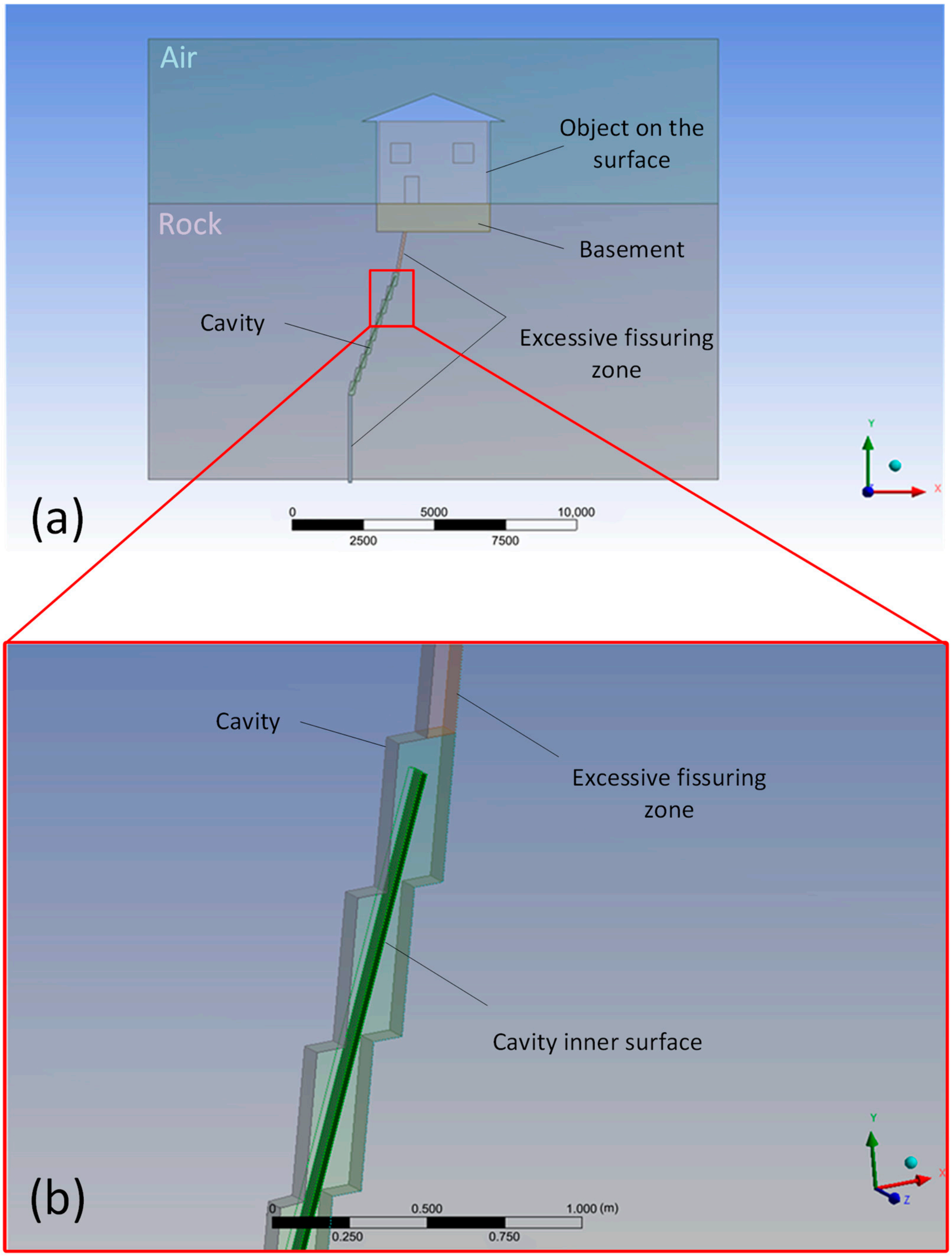

Figure 3. Computer-generated model of the subject of research: (**a**)—general view, (**b**)—close-up view of area with cavity.

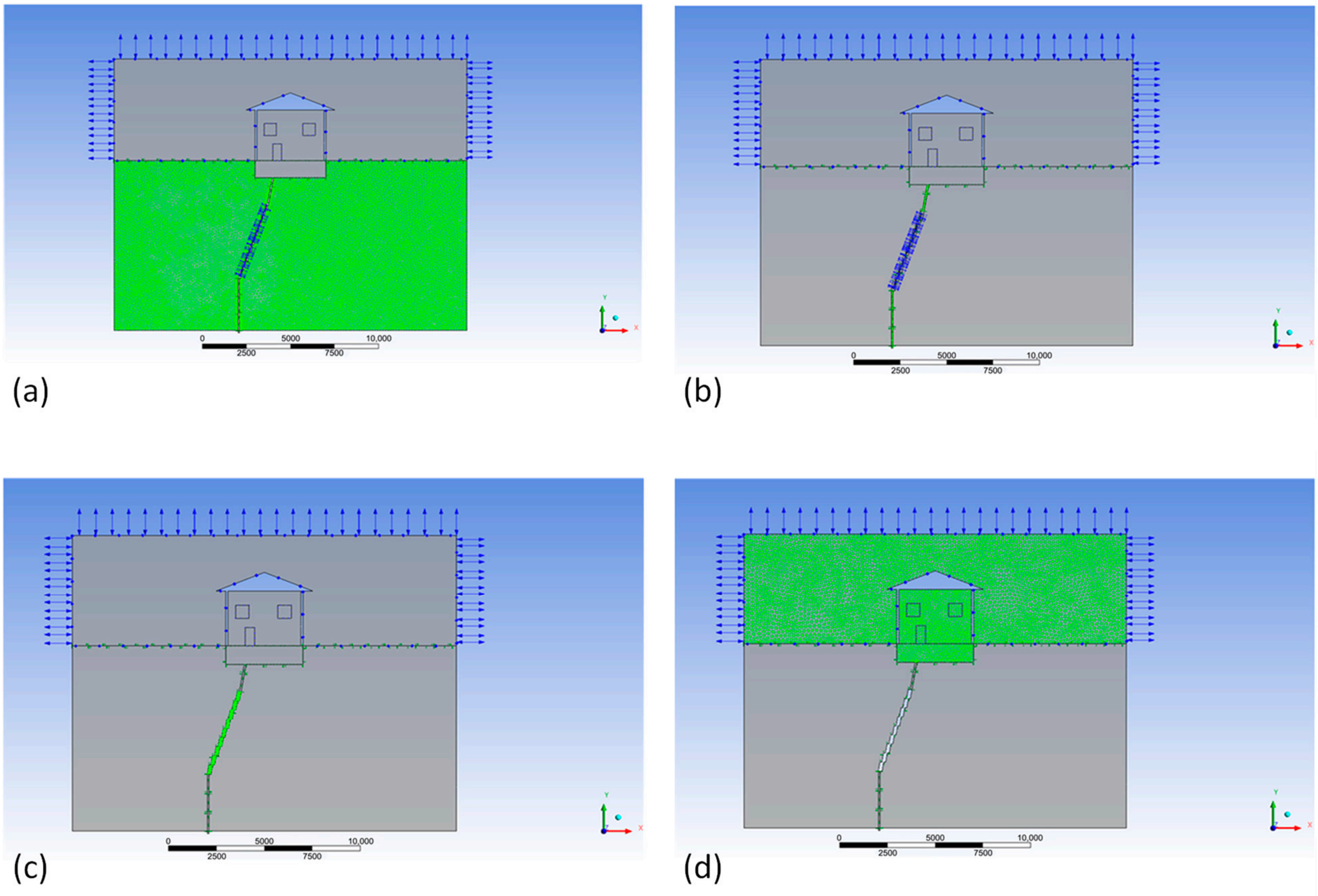

Figure 4. Entry conditions: (**a**)—ground area/district is selected, (**b**)—fragment of a crack is selected, (**c**)—part of cavity (void space) is selected, (**d**)—surface area is selected.

4. Simulation Results and Discussion

The simulation results are presented in Figures 5–7. From Figure 5, it can be seen that, at the initial moment (0–1 s, stage 1), the process of gas migration through the permeable zone is mildly expressed. When pressure increases (1–2 s, stage 2), intensive gas migration to the surface begins and, at the third stage (2–3 s), the process of gas migration continues. Therefore, even a one-off increase in pressure up to 250 Pa is capable of triggering mass transport of gases along the tectonic fault plane to the surface in a short span of time.

Piston effect is still more explicitly expressed when the pressure rises to 1000 Pa (Figure 7), even when fault permeability is lower (1×10^{-7} m^2). It can be seen from the figure that, during the period of a constant pressure (stage 1, 0–1 s), gas migration along the permeable zone is insignificant. After the pressure is increased (stage 2, 1–2 s) to 1000 Pa, the migration process intensifies and develops at stage 3 (2–3 s) even when the pressure drops to the initial value.

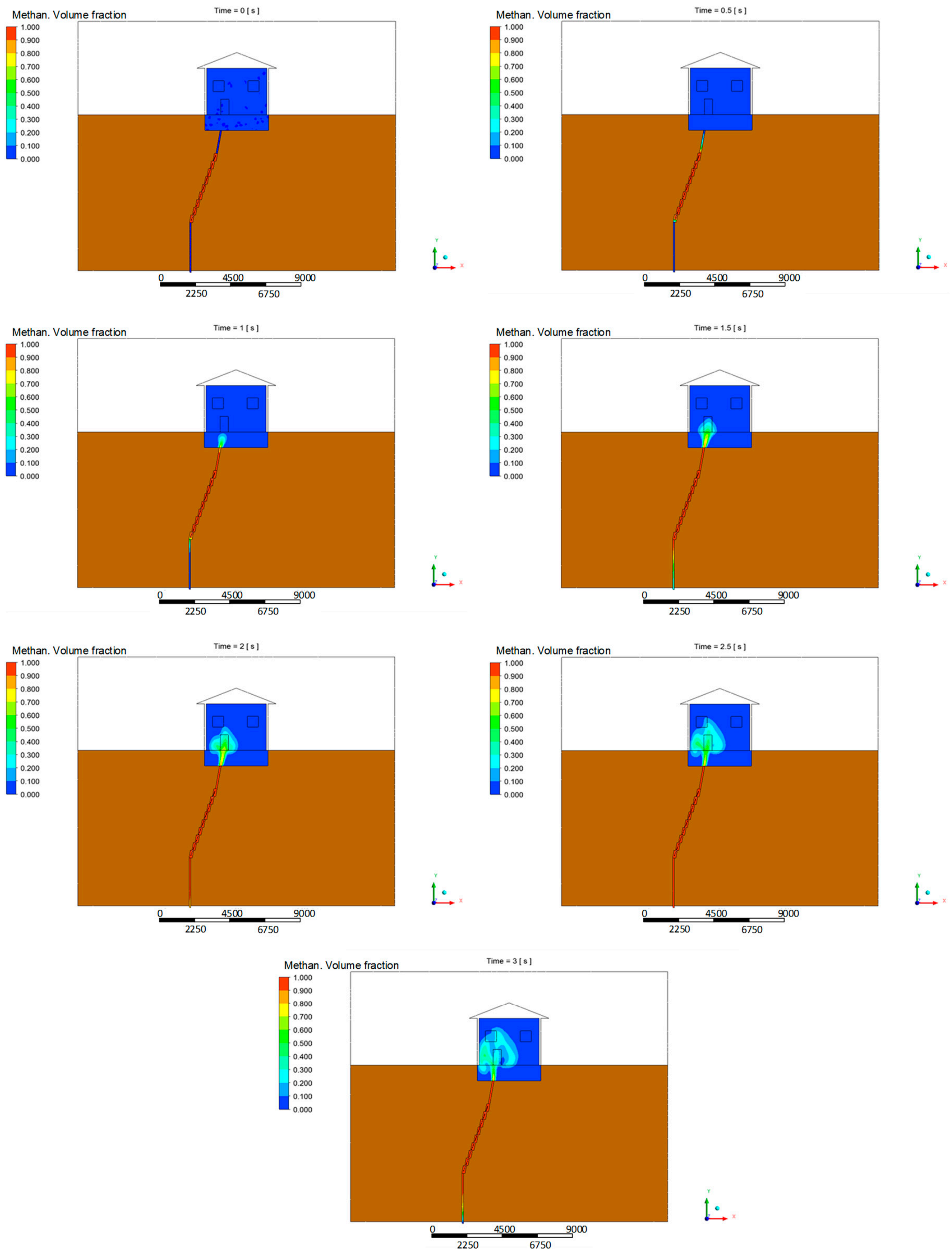

Figure 5. Simulated result: migration of mine gases to the object on the surface in the time span (0–3 s) with a fault zone permeability of 1×10^{-5} m^2 and pressure surge to 250 Pa.

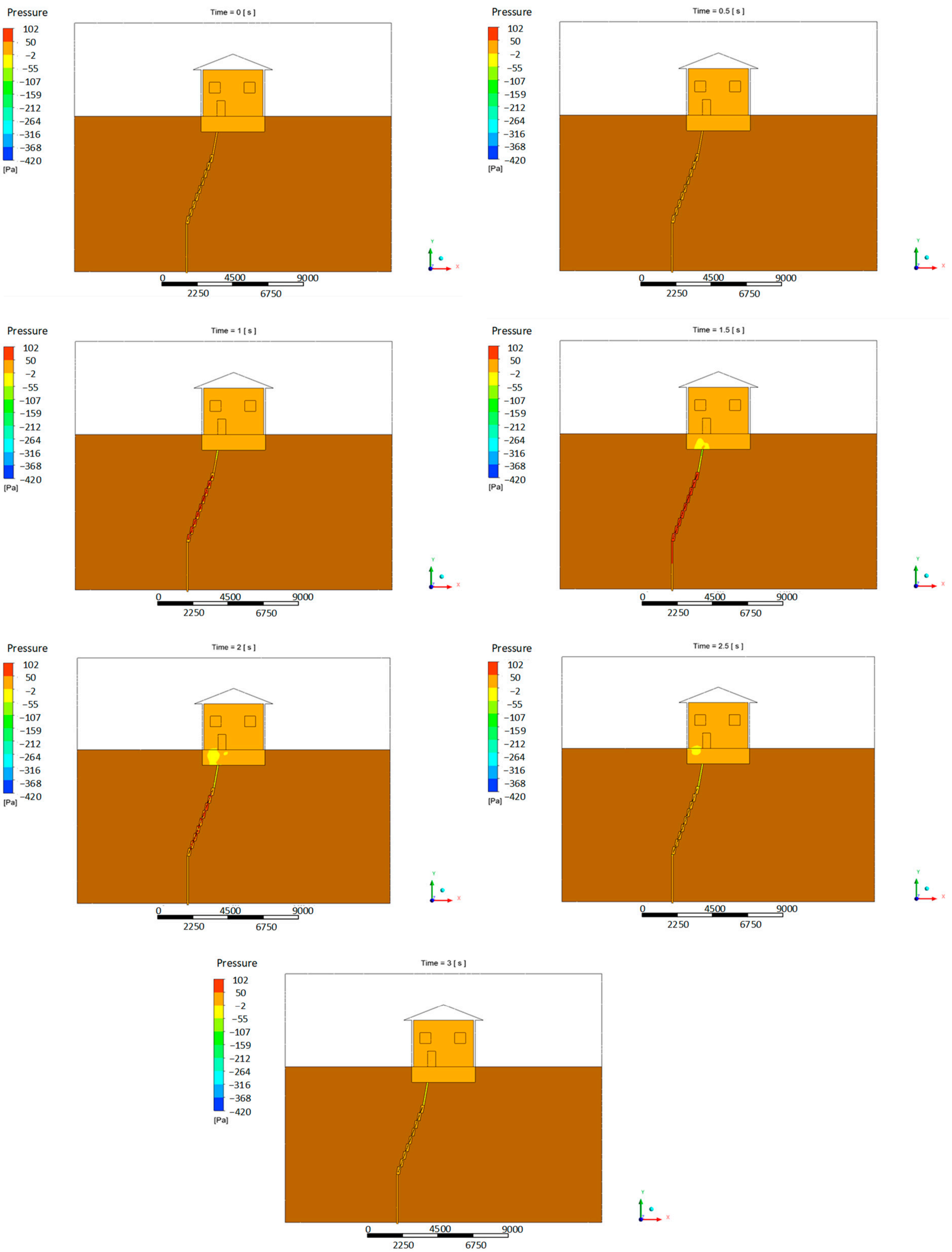

Figure 6. Simulated result: pressure change.

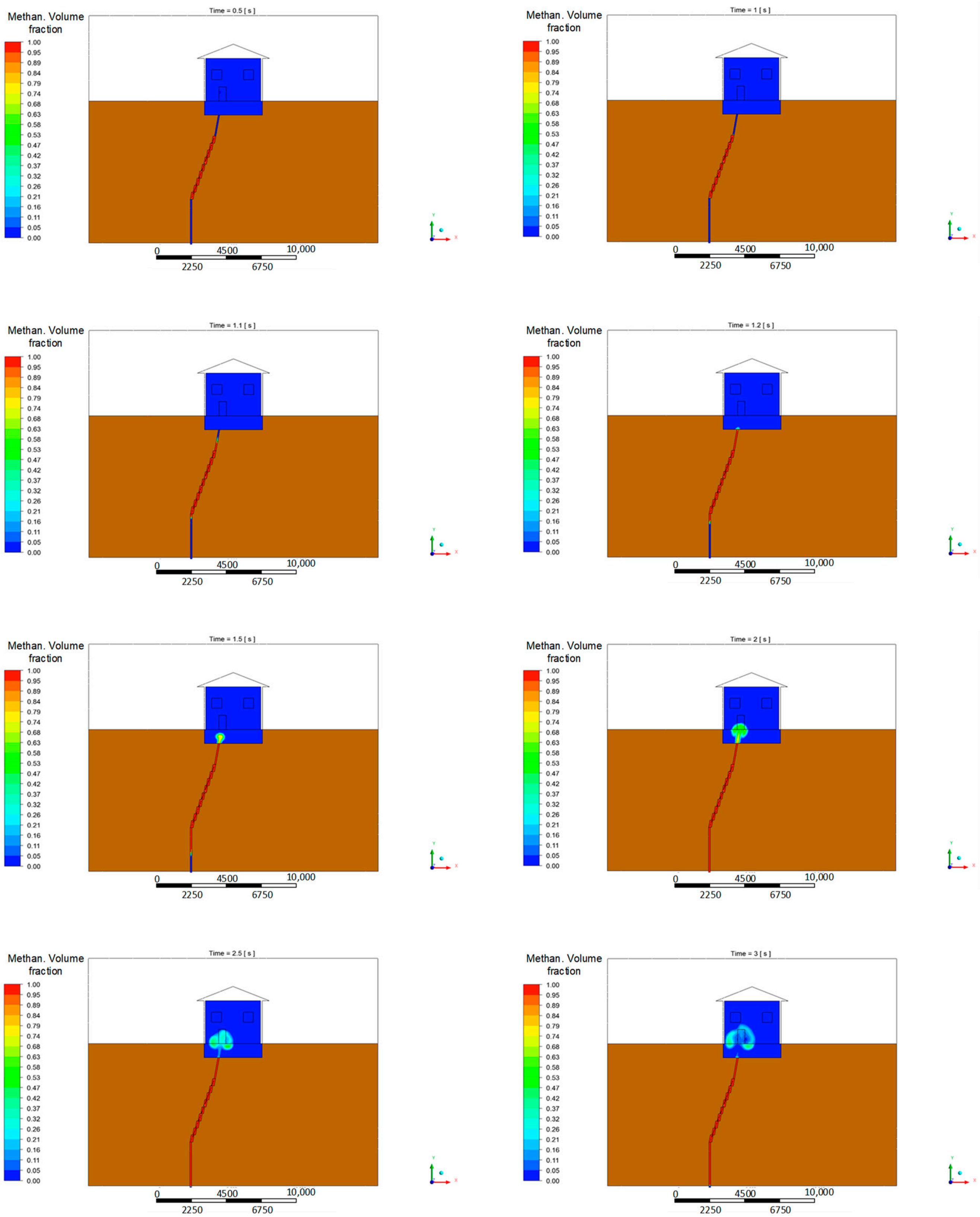

Figure 7. Simulation of gas migration at pressure surge to 1000 Pa and permeability of the fault zone.

5. Discussion

One of the main natural ways of gas seepage is tectonic faults, which has been studied at the global level [54], as well as regional [55,56] and local levels [15,29,57,58]. In the study of S. Scholz et al., the occurrence of gas anomalies in earthquake preparation areas is explained by dilatancy processes [59]. Neotectonic activations in the deposit localization areas result in high permeability of the earth's crust faults and its degassing [60]. Subsidence processes that accompany mining and oil extraction operations maintain high permeability of existing faults and form new highly permeable zones [29,61]. This approach explains why tectonic disturbances are dangerous zones for the release of gases. However, this approach does not explain the spontaneity or the sudden appearance of gas on the surface of even already closed mines. The simulation results show the reality of the phenomenon of sudden release of gas to the surface during reactivation of the fault and displacement of its walls on asperity planes.

Of course, our model has a high level of conjecture. We use a flat model, as shown in Figure 1. Our choice is based on the results of studies that show that the contact area of the fault walls does not exceed 10% [43,44] and, in this case, our choice is quite justified. Secondly, based on the results of field observations [62], we assume that the size of the asperities along the line perpendicular to the displacement vector is much larger than along the displacement line. Therefore, we believe our choice of a flat model is quite justified.

In mine conditions, due to the constant drainage of mine waters, the fault planes are often well washed and have a visible gaping [63]. In such conditions, the entire volume of asperities is filled with mine gas and our model does not require additional assumptions in this part. In another field, there is a situation where the asperities of the fault are filled with crushed material. In this case, when the walls of the fault are shifted and the type of contacts is changed from "ridge-ridge" to "ridge-sag" (Figures 1 and 2), the filler will be compacted under the influence of rock pressure, which, at values up to 30 MPa, can lead to a reduction in the volume of the filler up to 10% or more [64] and, also, give the effect of squeezing gas out of the fault zone, although less pronounced.

As an example, let us consider the following case: activation of subsidence processes in the north of Kuzbass. Kuzbass is a mining–industrial region of Russia with an unfavorable environmental situation [65–68]. Here, the Sudzhenskaya and the Anzherskaya mines were working out Tenth, Andreevsky, and Koksovy seams. The percentage of sandstones in the coal-bearing strata is up to 70–80% in the region There are major tectonic faults in the mine field, traced from the earth's surface to the depth of mining, Figure 8, according to [69]. Gas monitoring at these mine fields in 2012–2013 revealed instability of gas-dynamic processes. For carbon dioxide, concentrations of up to 5.3% were recorded, which is beyond the prescribed limit [70].

Seismic stations recorded seismic events of K = 3–4 energy classes [70] in these mine fields at the time when subsidence processes were activated in 1999–2000, which suggests that amplitudes of single-step dynamic displacements in faults were up to 1 cm. According to the studies [69,71] and personal observations of the authors, fault planes have striations, ridges, and, in some areas, there are shatter zones, Figure 9.

The depth of mining operations reached 600–700 m, which suggests that the dimensions of the reactivated sections of fault planes reached a few hundred meters. Taking into account the assumptions about the fault plane morphology described in Section 3.1.1, the reduction in the void space volume at section L = W = 10 m with 1 cm displacement along the fault plane will be less than 1 m^3, whereas, at 20 cm displacement (complete closure of void space) with the reactivation of the 200 $\times$ 200 m fault plane, V can reach almost 1500 m^3, which is quite sufficient to create a hazardous situation on the surface. Since the subsidence process develops unevenly in time and can be activated as a result of mine flooding or the development of a seismic process in the region, the phenomenon under investigation can manifest itself in mine fields over a long period of time.

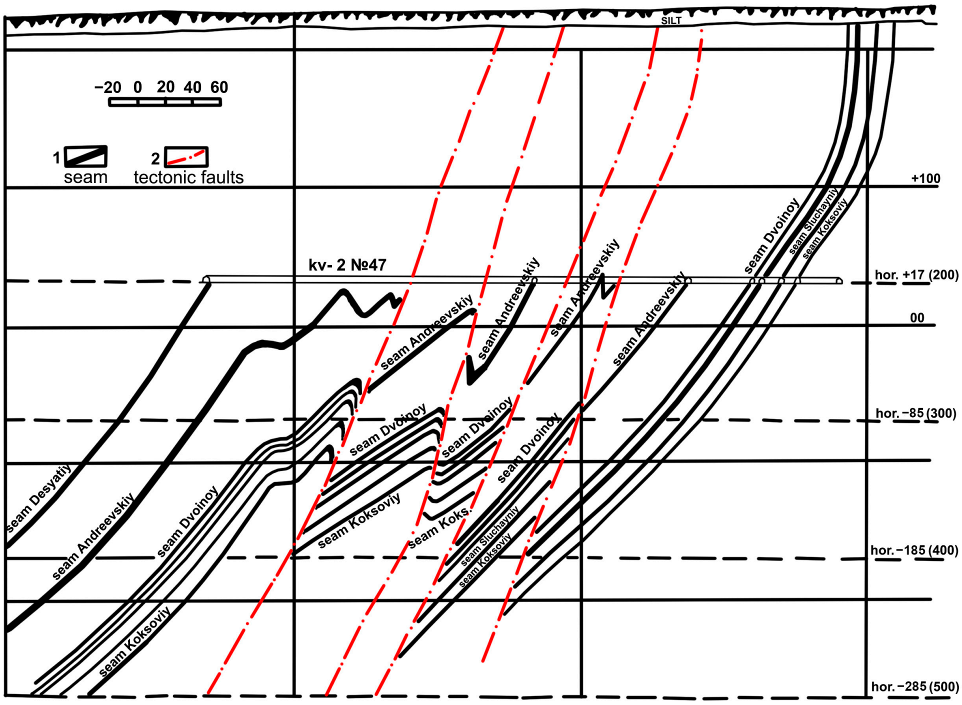

Figure 8. Schematic representation of the tectonic structure of the area occupied by Anzherskaya and Sudzhenskaya mines (according to [69]).

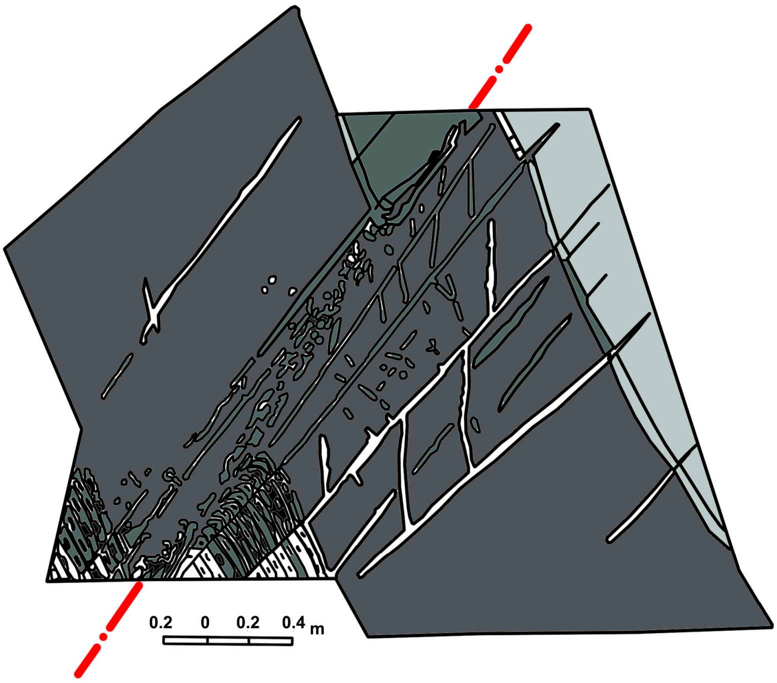

Figure 9. Sketch of a tectonic fault at the Anzherskaya mine (according to [69]). Red line—fault plane, gray color—formation, green, light green—rocks, white—cavity.

The conducted studies show that gas outflows along possible paths of gas migration can occur spontaneously and be associated with a sharp increase in gas fluid pressure in the rock fracture space due to the development of geodynamic processes, creating a piston effect. Therefore, it is quite likely to take no notice of hazardous areas on the earth's surface, where methane and (or) other gases can bleed from coal seams and host rocks, which only becomes evident during assessment monitoring. The results thus obtained correlate with known studies that examine the influence of geodynamic processes on the increase in permeability of tectonic faults and degassing of the earth's interior [72–74]. In this study, however, we showed that one of the mechanisms of degassing earth's interior can be a piston effect arising from fault reactivation.

Based on these findings, it can be recommended to carry out continuous monitoring in potentially dangerous—for gas release—places, regardless of the results of evaluation monitoring.

6. Conclusions

Using computer modeling, the hypothesis of a piston effect during the migration of mine gases caused by the reactivation of faults was investigated to explain the cases of the sudden appearance of mine gases on the surface of the earth in coal mining areas and the main conclusions reached are as follows:

1. In mine conditions, fault planes can be washed with mine water and have a free volume of void space between the asperities, filled with mine gases. The two opposing types of contacts of fault walls are the "ridge-ridge" type (maximum volume of void space along a fault plane) and the "ridge-sag" type (minimum volume of void space). The height of the asperities and their sizes are, on average, such that a void volume of up to 0.05 m^3 can be adjacent to a fault plane area of 1 m^2.
2. Mining causes the reactivation of tectonic faults during subsidence processes. The size of a reactivation part of a fault plane can reach several kilometers in a strike and hundreds of meters in a depth. The displacement along the fault plane can be several meters in total and up to 10 cm and more during a single shock, which commensurate with the magnitude of the asperities. In strong rocks of coal-bearing strata, asperities with a gentle angle of inclination are deformed elastically without destruction of the frame. In this case, wall displacement along an uneven fault plane leads to an alternation of typical contacts of the wall surfaces from the "ridge-ridge" to the "ridge-sag" and a sharp decrease in the volume of the void space surrounding the fault plane, which causes a piston effect of squeezing them towards the earth's surface.
3. According to computer modeling, with a shock-like displacement of the fault walls along an uneven fault plane by 1 cm, and even in the case of filling the void space with crushed material, the gas pressure in the fault plane area can increase by 250–1000 Pa in 1–2 s, which is already sufficient for a gas migration starting in the direction of the earth's surface. With a single-act displacement of the fault walls by 20 cm in an area of 200 $\times$ 200 m, the volume of gas released to the surface can reach 1500 m^3, which poses a real threat to the environment and the safety of the population.
4. As a recommendation, it can be offered to carry out geomechanical monitoring in potentially hazardous—for gas release—places, regardless of the results of traditional gas monitoring.

The findings expand our understanding of the sudden gasification of earth surface and living spaces in coal mining areas and contribute to the understanding of gas migration process, thereby helping to monitor hazards.

Author Contributions: Conceptualization, A.B.; methodology, A.B. and K.K.; validation, A.B., A.K. and A.I.; formal analysis and numerical modeling, A.K., A.B. and V.M.; investigation, A.B., E.K. and B.Z.; resources, K.K.; data curation, A.B., A.K. and D.K.; writing—original draft preparation, A.B. and A.K.; writing—review and editing, A.B. and A.I.; visualization, E.E. and D.K.; supervision, A.B.; project administration, E.E.; funding acquisition, A.B. and A.I. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by a grant № 22-27-00728 from the Russian Science Foundation (RSF), https://rscf.ru/en/project/22-27-00728/ (accessed on 15 October 2023).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful for the help to the staff of the department "Safety and ecology of mining" of NUST MISIS.

Conflicts of Interest: The authors declare no conflict of interest.

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