Recognition of gasogeodynamic zones in the rock mass using seismic tomography in Rudna copper ore mine

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Abstract. In this work, the results of four seismic tomography surveys are presented. The research was conducted to identify the zones exposed to the threat of gas and rock outburst. The changes to the dolomite layer stiffness in the mining excavation roofs were analyzed. The surveys were conducted in the Rudna copper ore mine in the field of XXVIII/1. The research area was about 0.21 km2. The seismic waves were generated by a small amount of explosive material (100 – 300 g) located and installed in short blast holes (1.5 – 2.0 m). The processing and the interpretation of the measurement data did not cause serious problems due to the more favourable elastic properties of the dolomite layer compared to the adjacent anhydrite and sandstone layers. As a result, the maps of parameters like the longitudinal wave velocity (P-wave), the shear wave velocity (S-wave), and the ratio of the P-wave velocity to S-wave velocity and the dynamic Young modulus were estimated. The results showed that the changes in the seismic parameters were relatively small over most of the research area. This may be evidence of the minor effects of gas and rock outbursts.

Keywords: copper ore mine, gasogeodynamic phenomena, seismic tomography, seismic parameters

1 Introduction

The gasogeodynamic threat in the Rudna copper ore mine is related to the accumulation of gas and water under high pressure in the highly fissured and porous areas of the dolomite layer [1–3]. A unique technology based on seismic tomography, drilling of control boreholes and borehole ground penetrating radar (BGPR) surveys was developed for the identification of these areas [4–6]. In the first stage of this technology a seismic tomography survey in the dolomite layer is conducted. The second stage consists of drilling control boreholes in the locations of anomaly indicated by the seismic tomography results. The drillings are conducted with special care, this is accomplished by registering all signs of fissuring and gas or water outflows. The rock quality design coefficient (RQD) is also calculated. In the last

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stage the BGPR surveys are conducted in the drilled control boreholes in order to obtain more detailed results [7–9].

In this work the results of four series of surveys using the seismic tomography method are gathered. The surveys were conducted in the XXVIII/1 field in the geological and mining conditions of Rudna copper ore mine in the years 2013 – 2017.

2 Geological conditions

The copper ore deposits in the Rudna mine occur in three lithological types: the sandstone of the Weissliegendes formation, cupriferous clay slates and the dolomites of the Zechstein series. A characteristic feature of the deposit area is the non-uniform formation of the lithological structure and diverse mineralization [10]. The variability in the lithological structure of rock types is related to the diverse morphology of the topmost sandstone layer [10–12].

Over the entire area of the copper ore deposit, morphological elevations and depressions occur [13–14]. The elevations are the relics of sand dunes, which originated in desert conditions during the period of the Rotliegend. The marine transgression in the Zechstein period brought about the flattening of the dune elevations and the resedimentation of sand in the lowering of the interdune areas. During the current operation of the Rudna mine 5 elevations have been identified. They are 15–35 m high forms, with a maximum length of 25 km and a width of approximately 1 km. The northeast slopes of the elevations are very steep, and the southwest slopes are slightly inclined, largely due to the inclination of the main tectonic unit of the Fore-Sudetian Monocline.

However, the morphology of the slates and the lower part of the dolomite series is not strictly bound up with the structure of the elevations. The localization of the dolomite series between the more plastic series of sandstone and anhydrite has a significant impact on the tectonic processes occurring in the dolomites. The Zechstein dolomite series was subjected to tension and compression during the period of the formation of folded structures, overthrusts, and faults [15]. The fissures thus created were filled with material that had been transported in water.

Within the Zechstein dolomite series, in the areas of fissuring isolated from above by the layers of anhydrite, gas traps are observed. In all probability the gases could flow into the dolomite series through a system of fissures from the Carboniferous strata during the formation of the Fore-Sudetian Monocline [1–3, 11] (Fig. 1). The characteristics of the gas traps indicate that they are most likely to occur in the slopes of morphological elevations in zones of tensile stress. They may also be present in the weakly inclined top portion of the Zechstein formations, if in the dolomite series, some larger zones of fissures and faults were formed in the area of a drag fold structure or an overthrust [11]. It was assumed that the gas traps could also exist along the direction of major tectonic structures [2–3].

In the research area three lithological layers were analyzed: the sandstone layer in the lower part of the roadway, the layer of dolomite and the anhydrite layer in the roof. Figure 2 shows an example of a cross-section obtained on the basis of the core of a borehole drilled in the roof underneath the sidewalk. Based on the borehole data it was observed that the dolomite layer has a thickness of up to 12 m. The dolomite layer has the most favorable elastic properties compared to adjacent layers. For this reason, the identification of seismic waves in a wave image does not pose major difficulties. Based on the modeling results [6], it was found that the first arrivals of the P and S waves are related to the direct wave in the dolomite.

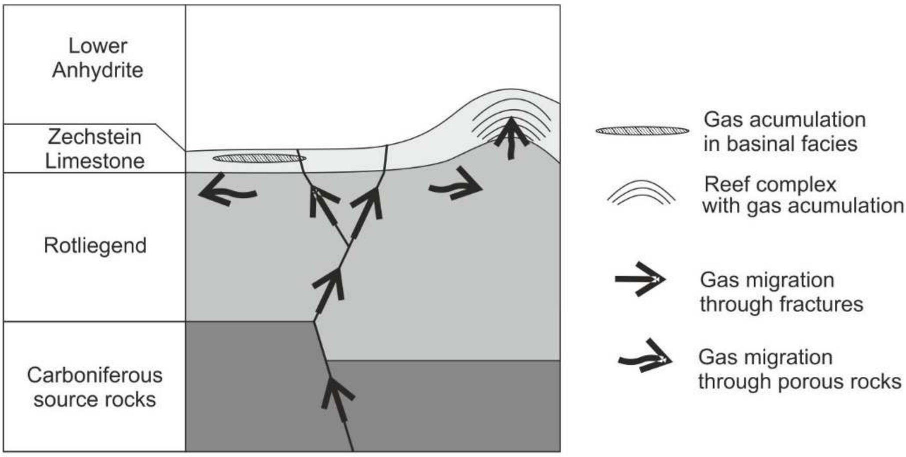

Fig.1. Schematic diagrams showing possible sources of the gas accumulation in basinal facies in the Zechstein Limestones in the Rudna Copper Mine [1].

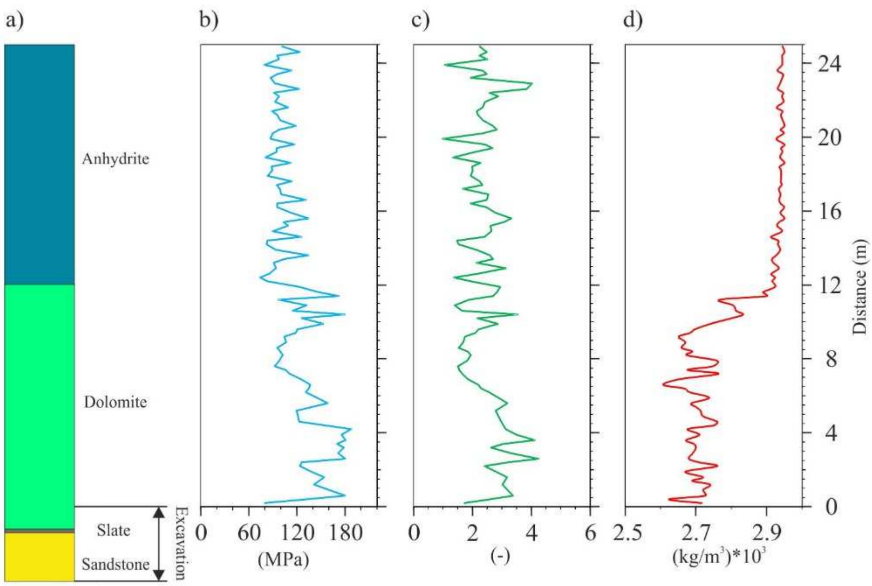

Fig. 2. Geological profile from the borehole Km01 H-23 from research area (a) together with the profiling of the uniaxial compressive strength R_c (b) rock burst liability indicator W_{et} (c) and the rock's volumetric density ρ (d) (on the basis of KGHM Cuprum Research and Development Center data).

3 Methodology

Measurement methodology

The most important factor from the point of view of measurements in the seismic tomography method is the appropriate location of geophones and wave excitation points. The measurement scheme is being developed in order to obtain the best possible coverage with the seismic rays of the analyzed area. A significant influence on the geometry of the seismic tomography was the development of mining works and excavation availability.

In the mining conditions of the field XXVIII/1 in the Rudna mine in each of the four series of tests, the measurement profiles were located in two perpendicular drifts (Fig. 3). The drifts were about 500 m apart. The profile located on the NE side of the examined area consisted of 24 geophones. The profile installed on the SW side of the test area consisted of 72 geophones. The sensors were installed with an interval of 5 m in the roof section of the drifts in the dolomite layer.

A seismic wave was excited in blasting holes using explosives of 0.3 kg. The number of blast holes as well as the distance between holes for individual measurement series were variable. Typically, at least 19 blasting holes were used at intervals not exceeding 30 m. The length of the blast hole was 1.5 - 2 m.

The measurements were carried out using four sets of 24-channel Geode seismic apparatus. Geophones of 100 Hz natural frequency were used. For all registrations, the signal sampling rate was 0.125 ms, and the registration time was 2 s. The transmission of the signal with information concerning the timing of blasting was carried out using a two-core cable by breaking their loop on the explosive. The cable length was up to 1200 m.

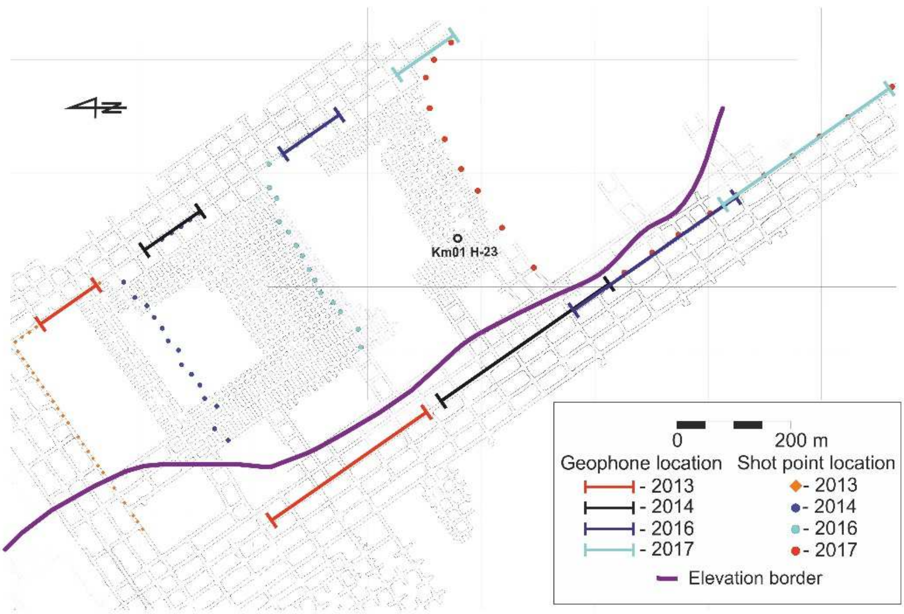

Fig. 3. Measurements scheme.

Processing and interpretation methodology

To determine the field of transverse and longitudinal wave velocity in the rock mass in the Rudna mine, the SIRT (Simultaneous Iterative Reconstruction Technique) algorithm was used [16]. Data processing consisted of [17]:

- frequency filtration and traces analysis for the identification of various types of seismic waves (Fig. 4),
- determining the times of the first brakes in the longitudinal and transverse wave,
- implementation of measurement geometry,
- proposal of the initial velocity model and discretization of the studied area to a finite number of cells.

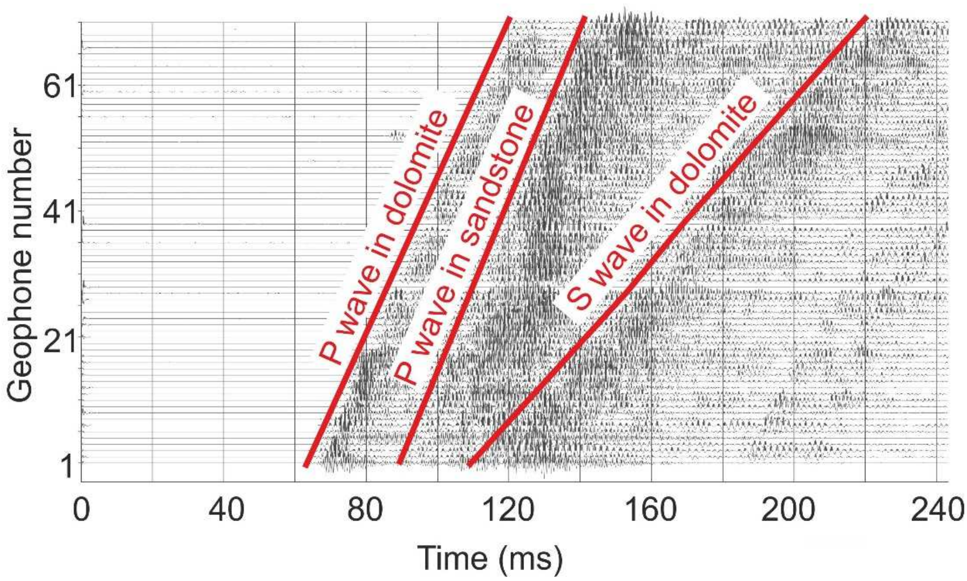

Fig. 4. Example of the seismic record from one of the blast point on the profile.

Next, an interpretation was carried out, which consisted of:

- inversion calculations for the curvilinear reconstruction of the seismic rays,
- calculations of matching errors between calculated and measured times for the resulting model,
- subsequent inversion calculations for improved data,
- developing a map of the variability of seismic parameters using interpolation procedures.

An example of the computational parameters of tomography for the longitudinal and transverse wave for the fourth measurement series is summarized in Table 1.

Table 1. Seismic tomography parameters used in the fourth measurement series in the Rudna mine.

Parameter	P-wave	S-wave
Number of seismic rays	914	921
Mesh dimensions	20x20m	20x20m
The amount of iteration required to stabilize the final model	20	21
The sum of residual deviations	7.8	7.23
RMS error	0.57	1.32
The maximum mismatch between the calculated and measured times for the resulting model for a single seismic ray	1.7 ms	3.8 ms
The average value of the seismic coverage of a single cell	72	46

4 Results and analysis

On the basis of seismic tomography surveys, maps of P-wave (Fig. 5) and S -wave (Fig. 6) velocity were developed for four measurement series in the dolomite layer in the field XXVIII/1 in the years from 2013 to 2017. The map of the dynamic Young's modulus was also developed based on changes in the P and S wave velocity values (Fig. 7). In order to compare the results of measurements, the maps are presented in the same color scale for each series of a given parameter. Larger anomalies are described by numbers.

The comparison of results from subsequent measurement series indicates that it is not possible to obtain the continuity of the isolines of seismic parameters. The secondary stress field associated with the progress of exploitation has a significant influence on the trajectory of the isolines.

On the maps of seismic parameters, two types of anomalies were distinguished: positive anomalies and negative anomalies. It is assumed that the negative anomaly arises in the zone of intense cracks and higher porosity, in which gas and water may also potentially accumulate. The positive anomaly is the effect of the tightening of existing cracks and pores.

On the map of the P-wave (Fig. 5), in the zone of the excavation front, clear positive anomalies marked with number 1 may be observed. The anomalies are associated with the load and deformation of direct roof layers in the exploitation zone. This influence is particularly visible in the north-eastern corners of the research areas due to the greater intensity of mining works. The bending of the roof layers results in the closing of pores and cracks and, as a consequence, an increase in the stiffness of the dolomite layer. These effects increase the velocity of the seismic waves. Negative anomalies are marked with number 2. They were identified on the P-wave velocity map in the results of the first and fourth series of measurements. The anomaly from the fourth series of measurements was located directly at the excavation front and could probably be associated with an excessive load of this fragment of the rock mass. The anomaly identified in the first series of tests, despite being located near the front, covers a much larger area compared to the fourth series. During the drilling of the control borehole, the presence of gas was found to be responsible for this anomaly, but its outflow was small. In addition, the obtained core from the borehole indicated the presence of an intense cracks zone, thus confirming the results of the seismic tomography [4]. In the other series of measurements, negative anomalies were found to be relatively small and the velocities slightly deviated from the values in the undisturbed rock mass. In the control boreholes carried out in this area, no gas outflow was detected, but only a water flow of 3 l/min.

On the collective map of the field of S-wave velocity changes (Fig. 6) anomalies are marked with numbers ranging from 1 to 4. Anomalies 1 and 2 have a similar range and value compared to anomalies marked on the map of P-wave velocity changes. In the third measurement series a greater negative anomaly marked with number 3 appeared. No gas outflows were recorded in the drilled control borehole as well as during the mining operations. Only on the side walls of the drift there was a slight moisture. A wider negative anomaly has also been identified in the fourth measurement series and marked with the number 4. S-wave velocities changes in this zone are small, however.

Figure 7 shows a cumulative map of the changes in the dynamic modulus of elasticity. The calculated anomalies coincide quite closely with anomalies identified on the map of S wave velocity changes. The elastic modulus values vary in range from approx. 68 - 90 GPa. A dolomite density of 2800 kg/m3 was assumed for the calculation of this parameter.

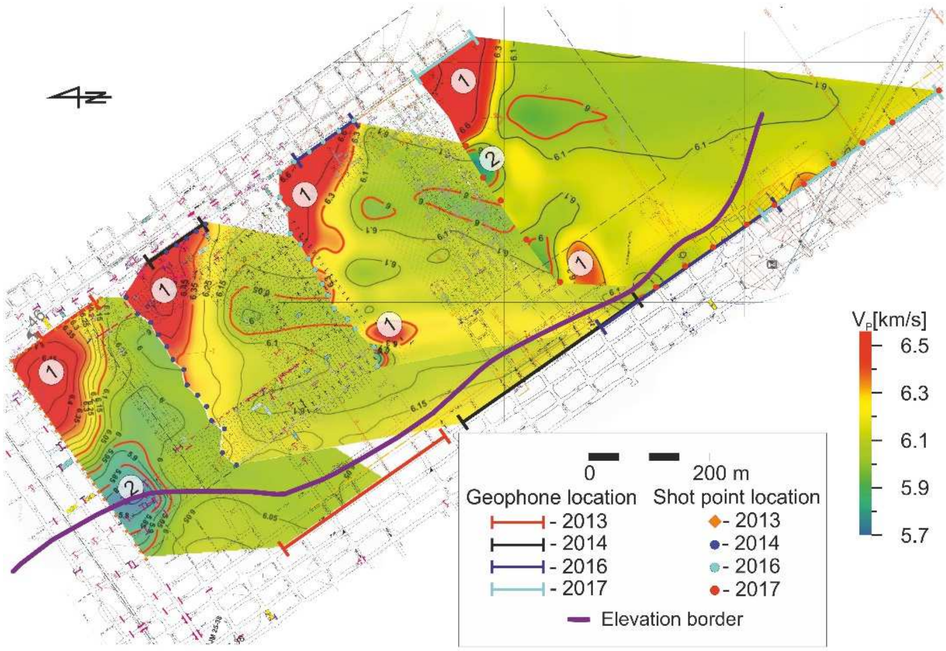

Fig. 5. Map of P-wave velocity changes.

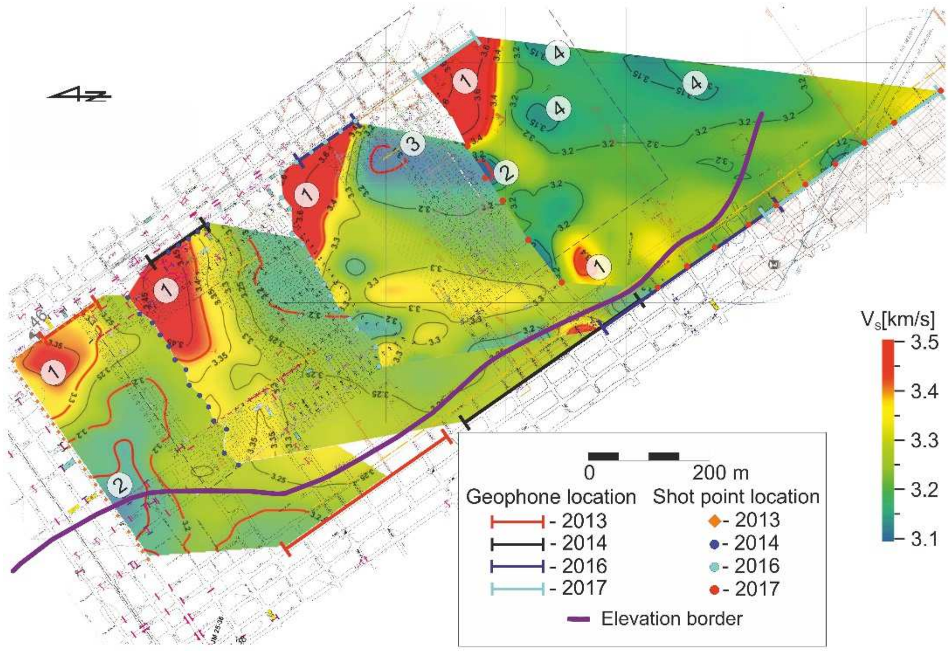

Fig. 6. Map of S-wave velocity changes.

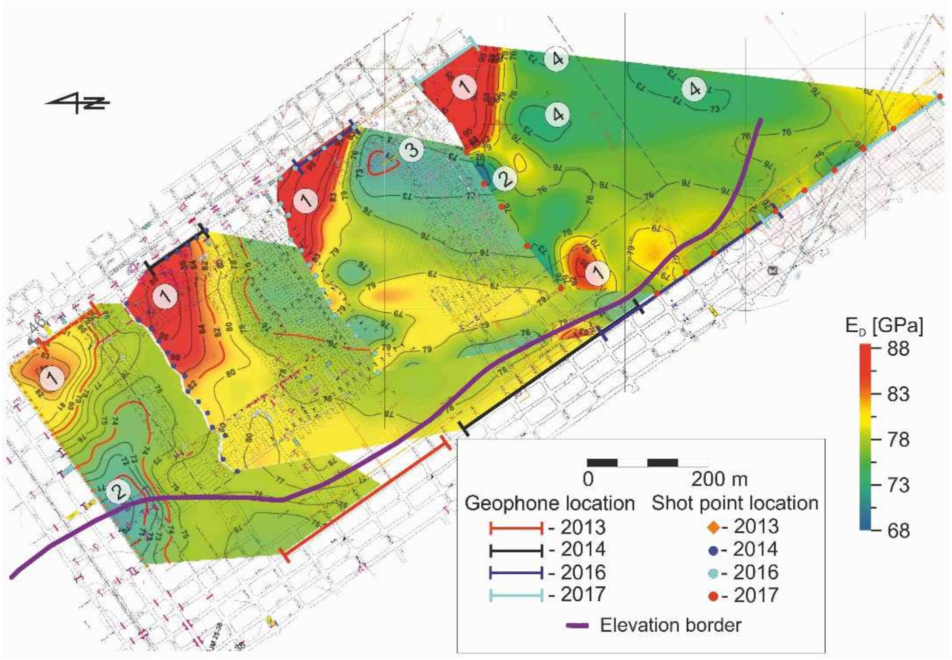

Fig. 7. Map of Young modulus changes.

5 Conclusions

In the study, we present the results of seismic tomography measurements carried out for the purpose of recognizing rock mass properties, in particular, the aspect of the occurrence of gasogeodynic phenomena in Rudna copper mine. The research was aimed at identifying changes in the stiffness of the dolomite layer in the roof of mining excavations due to the location of gas traps. It was carried out over a very large area in a field several hundred meters in length and width. The measurements were carried out using 96 geophones and four sets of seismic apparatus connected to each other. The source of the wave was a small explosive (about 300 g). The processing and interpretation of the measurement data did not cause major problems due to the more favorable elastic properties of the dolomite layer, compared to the adjacent layers of anhydrite and sandstone, high source energy and longer wave propagation time. As a result, maps of changes in seismic parameters such as P-wave velocity, S-wave velocity, Young's modulus of elasticity and others were calculated.

The use of the proposed methodology made it possible to formulate the following conclusions:

- As a result of the verification of seismic anomalies by means of borehole tests, the closest relationship existed for the S-wave velocity and the dynamic Young's modulus changes. It should be assumed that the other negative and positive anomalies, which were not controlled in the borehole tests, have analogical sources to the anomalies that were verified.
- Small changes in seismic parameters indicate the relatively favorable levels of gasogeodynamic risk in the rock mass, characterized by a weak variation in fracture intensity in the dolomite layer.
- In the vicinity of the front line of the exploited field, observed seismic anomalies are related to the influence of mining operations. The nature of the anomalies indicates that

they occur due to the tightening of existing pores and cracks. As a consequence, an increase in the stiffness of the dolomite layer is observed. The main reason for this is the additional load from the bending of the roof strata.

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