Geology

IDENTIFICATION OF GAS-GEO DYNAMIC ZONES IN THE STRUCTURE OF COPPER ORE DEPOSITS USING GEOPHYSICAL METHODS

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ABSTRACT

This work concerns the identification of weak zones in the structure of a rock mass endangered by outbursts of gases and rocks at approximately 1,200 m depth in the Rudna copper ore mine, Poland. Geophysical recognition with the aid of seismic tomography and borehole ground penetrating radar was applied, along with geological engineering tests. Results showed a very strong correlation between the location of the zone containing gases and water and the anomalous S-wave velocity and field of dynamic Poisson’s ratio, and to a lesser extent, other seismic parameters under the considered geological and mining conditions.

KEYWORDS
Copper ore mining, Gases and rocks outburst, Seismic tomography, Borehole ground penetrating radar (BGPR), Rock quality designation (RQD) index

INTRODUCTION

In Poland since the 1990s, the threat of gas and rock outbursts has significantly diminished, owing to the limitation of the mining industry and the closing down of numerous mines, in particular the hard coal mines in Lower Silesia. Presently, only the hard coal mines operated by the Jastrzębie Mining Company and the Kłodawa salt mine are exposed to the threat of the gas and rock outbursts. Lately, that threat occurred in the Rudna copper ore mine, which is part of KGHM Polska Miedź SA.

In the past, the highest level of the threat of outburst was observed in the hard coal mines of the Lower Silesian Coal Basin, where about 1,730 outbursts were reported (Kosiór & Podolski, 2009). The amount of material released to the excavation ranged from 50–5,000 tonnes of rocks and from 10,000–800,000 m³ of gases, mainly carbon dioxide (CO₂) and methane (CH₄). In the salt mines, the gases released in the outbursts included mainly methane, nitrogen, and hydrogen sulphide (H₂S). The outbursts occurred mostly (82% of incidents) during the drilling of preparatory excavations. The threat of gas and rock outburst in the hard coal mines was related to the tectonic disturbance zones, as well as to the low compactness of coal in the outburst zone, accompanied by a high level of CH₄ emission from the coal bed.
In September 2009, outbursts of gases and rocks were recorded in the Rudna copper ore mine while drilling a preparatory drift by means of explosives at a depth of approximately 1,200 m. As a result of the outburst, about 1,200 m³ of crushed rock material filled the excavation for a length of about 70 m. The mixture of gases released contained > 80% nitrogen, and only a few percent CH₄. Further geochemical examination of gases from that area showed that the released gases were genetically most similar to natural gas exploited in the deposits located in the reservoir rocks of basal limestone and Rotliegendes on the Polish Lowland, at a distance of 30–40 km from the mining zone of the Rudna mine (Dec, Pietsch, & Marzec, 2011). The aforementioned gas originated from an organic substance present in Carboniferous, and partially in Devonian formations. The main reason behind the gas and rock outburst in the Rudna mine was the disturbance of the balance between gas pressure and rock mass strength (the “gaso-geodynamic balance”). We assumed that the balance was disturbed in the layer of highly porous and fissured dolomite filled with gases under high pressure, as a consequence of drilling a preparatory drift by blasting. The Rudna mine engineering staff were carrying out systematic seismic observations and at that time, no tremor was recorded. It must be stressed that until then, no similar phenomenon had been observed in the copper ore mines of KGHM Polska Miedź SA.

In light of the newly identified outburst threat, it was necessary to modify the technology of drilling preparatory workings as the depth of mining increased. Diverse research studies were undertaken, which included geological, geophysical, and geomechanical investigations, in order to assess the threat of an outburst in the parts of the deposit that were planned to be mined. The geophysical and geological tests presented in this paper are components of one of the elements of that examination.

In this paper, we discuss the experimental results of geophysical tests—seismic tomography and borehole ground penetrating radar (BGPR)—employed to identify the zones exposed to the threat of gas and rock outburst in the part of the deposit prepared for exploitation in the Rudna mine. We describe the methodology, analysis of the geophysical and geological engineering test results, and the most significant findings. This study also presents a wider description of geological conditions, with particular focus on the circumstances behind the origin of gas traps in the rock mass of the Rudna mine. The summary section highlights the most important conclusions, which point to the advantages and limitations of the applied geophysical methods when used for the identification of the gaso-geodynamic zones.

GEOLOGICAL CONDITIONS ASSOCIATED WITH THE OCCURRENCE OF GAS TRAPS

The copper ore deposit in the Rudna mine falls under the category of bedded deposits. It occurs in three lithological types: in the sandstone of the Weissliegendes formation (top part of the Rotliegend formation), cupriferous clay slates, and dolomites of basal limestone (top part of the Zechstein dolomite series). The lithological series is marked by non-uniform lithological structure and diverse mineralization; hence the level of drilling exploratory excavations varies. Changes in the lithological structure of rock types are clearly related to the varying morphology of the topmost sandstone (Błaszczyk, 1981).

Over the entire area of the copper ore deposit, morphological elevations and depressions occur on the topmost limestone. Those forms 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 (Kaczmarek, 2006). To date, in the mining zone of the Rudna mine, five elevations have been detected. They are 15–35 m high forms, with a maximum length of 25 km and width of approximately 1 km; the distance between the subsequent axes of elevations ranges from 1.5–3.5 km. The northeast slopes of the elevations are very steep, and the southwest slopes are weakly inclined, largely due to the inclination of the main tectonic unit of the Fore-Sudetian Monocline. The morphology of the upper part of carbonic formations and slates is not strictly bound up with the structure of the elevations. The older formations of the Zechstein dolomite series exhibit lesser tectonic discontinuity than the incumbent formations of that series. The Zechstein dolomite series was subject to tension and compression during the period of the formation of folded structures, overthrusts and faults (Jerzykiewicz, Kijewski, Mroczkowski, & Teisseyre, 1976). The fissures thus created were filled with material 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. Both fissures, as well as the porous spaces of folded structures, may serve as gas collectors. Most probably, during the formation of the Fore-Sudetian Monocline, the gases...
flowed in from the Carboniferous period strata, and afterwards they accumulated in the layers of the dolomite series (Błaszczyk, 1981). The characteristics of the gas traps indicate that they are most likely to occur in the slopes of morphological elevations in the 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 (Błaszczyk, 1981). The phenomena observed in the fissuring zone often include water outflow and sometimes fine crystalline white salt (Suchan in Pilecki, Czarny, Łątka, Krawiec, Pilecka, & Pszonka (2012)). It was assumed that the gas traps exist along the direction of major tectonic structures (Dec et al., 2011).

METHODOLOGY TO DETECT ZONES OF GASO-GEODYNAMIC THREAT

The gaso-geodynamic threat in the Rudna mine is related to the accumulation of gases, presumably in the porous and fissured spaces of the formations of the dolomite series, in the area of slopes of morphological elevations of Weissliegendes limestone. Bearing that in mind, the aim of geophysical, and geological engineering examination was to identify the weak zones associated with the fracturing of the dolomite layer in the area of morphological zones, in the immediate roof of the excavations.

In the cross-section of the excavations where the geophysical tests were performed, limestone was present in the top part, and above—a clay slate of a minor thickness (amounting to several dozen centimeters), which locally disappeared, and a layer of dolomite with the thickness up to approximately 12 m (Figure 1). It must be stressed that the dolomite layer possessed the most favorable seismic properties in comparison with the adjacent rock types: sandstone, clay slate and anhydrite (Figure 1). Therefore, the identification of the waves in the dolomite layer presented no considerable difficulties.

![Diagram](image)

Figure 1. a) General geological profile from the area under investigation; b) uniaxial compressive strength $R_c$; c) rock burst liability indicator Wet; and d) the rock’s volumetric density on the basis of KGHM Cuprum data (Pilecki et al., 2012)

The methodology for detecting zones of gaso-geodynamic threat consisted of three stages. In the first stage, a part of the deposit presumed to be threatened by outbursts of gases and rocks was identified on the basis of geological investigation carried out with the use of preparatory drifts. It was assumed that the fundamental and possibly useful information will be offered in the assessment of the alterations of elastic properties of a rock mass, obtained by means of seismic tomography.
The measurements were taken from two perpendicular drifts, due to the way in which the deposit had been cut (Figure 2a). The waves were generated by setting off a small explosive of 150–300 g and they were detected by 40 Hz geophones. Approximately 410 seismic rays were obtained (Figure 2). The poorly constrained zones are located mostly in the edges of the area under investigation, in the neighbourhood of sources and receivers. The smallest number of rays that covered the mesh of the grid (25 × 25 m) was 12 for the P-wave and 17 for the S-wave. A simultaneous iterative reconstruction technique algorithm (Gilbert, 1972) was applied in the calculations, with the curvilinear reconstruction of the seismic rays. The maximum mismatch between calculated and measured times for the resulting model for a single seismic ray equaled 2.08 ms for the P-wave, and 2.24 ms for the S-wave; therefore, the errors in wave velocity calculations are approximately 110 m/s and 50 m/s for the P-wave and S-wave, respectively. The results are presented in the form of the map of velocity field changes of the P-wave and the S-wave, the ratio of the P-wave velocity to the S-wave velocity (Vp/Vs), the dynamic Poisson’s ratio and the dynamic Young’s modulus of elasticity. For the purpose of calculating the dynamic Young’s modulus in the dolomite layer, we assumed the volumetric density equalled 2,800 kg/m³.

Figure 2. a) Map of P-wave rays path in local coordinates from the area under investigation; b) an example of seismic recording in section A-B; c) an example of trace in point S1

In the second stage, the results of the seismic tomography were used to design and make a control borehole in the zone of the seismic anomalies, for the purpose of a detailed investigation of the structure and properties of the rock mass. The control borehole was approximately 156 m in length and 0.075 m in diameter, and was inclined at an angle of about 7º in the direction of the dolomite layer in the excavation roof. The borehole was drilled up to the bottom part of the anhydrite layer located above the dolomite layer. In the process of drilling, special attention was devoted to recording the outflow of gases and water, as well as to the fracturing of the rocks and other effects related with drilling. On the basis of the core, the lithological description was verified, and the rock quality designation (RQD) index (Deere, 1964; Deere & Deere, 1988) was calculated.

In the third stage, the BGPR was used to obtain detailed geological engineering information. It needs to be emphasized that first experimental borehole radar measurements in underground excavations in coal mine were reported by Cook (1973). In-mine use of a BGPR system was significantly developed within the framework of the International Stripa Project (Olsson, Falk, Forslund, Lundmark & Sandberg,
In the mine conditions under consideration, a BGPR with antennas at a frequency of 100 MHz made it possible to collect information about the rock mass around the borehole at a distance of approximately 12 m. The specific BGPR measurement methodology applied is presented in Łątka, Czarny, Krawiec, Kudyk, and Pilecki (2010). The radar data recorded were further processed in accordance with standard procedures (Łątka et al., 2010). As a result, the final radargram was obtained, which was correlated with the lithology, changes in the RQD index and information on the water and gases presence gathered during drilling.

RESULTS AND DISCUSSION

Seismic tomography

The seismic tomography results comprise maps of the P-wave and the S-wave velocity changes (Figures 3b, c). In addition, maps of changes of the following parameters were made: the ratio of the P-wave to the S-wave Vp/Vs (Figure 3d), the dynamic Poisson’s ratio (Figure 3e), and dynamic Young’s modulus of elasticity (Figure 3f).

The changes in the P-wave and S-wave velocities and other properties are complex, which point to the fact that the elastic properties of the dolomite layer vary locally. No greater structural and tectonic disturbances were detected. The average velocities were 6,315 m/s for the P-wave, and about 3,060 m/s for the S-wave. Major anomalies are marked on the maps of the P and the S-wave velocities (Figure 3b, c). The zones of negative anomalies are marked with a white dotted line, and the zones of positive anomalies, with greater velocity values, are marked with a black dotted line. The negative anomalies of the P-wave (1 and 2), similarly to the negative anomalies of the S-wave (1–5), may be associated with considerable fracturing and an increased presence of water in the rock mass. The anomalies of the velocity of the S-wave (1, 5–7) coincide with the anomalies of the P-wave (1–4).

The mean Vp/Vs ratio is 1.98. The reasons behind the anomalous values (Figure 3d) may be similar to those for other seismic parameters. The mean dynamic Poisson’s ratio is 0.33. The arrangement of the isolines for the dynamic Poisson’s ratio (Figure 3e) is similar to the arrangement for the Vp/Vs ratio (Figure 3d), as in both cases the only variables assumed for calculations were the velocities of the P-wave and S-wave. The larger values, particularly in anomalies 1–4, may have been caused by a considerable fracturing of the rock mass and an increased presence of water. On the map (Figure 3e), two other anomalies are marked (5 and 6), both with a value of approximately 0.25. These anomalies may be related to the greater compactness of the rock mass. The dynamic Young’s modulus is 74 GPa. The negative anomalies of modulus 1 and 2 are characterized by lower elasticity, whereas the positive anomalies 3 and 4 are characterized by a significantly greater elasticity, which is consistent with the distribution of the other seismic parameters.

The identification of the location of seismic anomalies made it possible to design a control borehole (Figure 3a) to find the explanation for the anomalies described above. The core obtained from the control borehole (Figure 4) showed that the zone of intense fracturing had been properly identified. The zone coincided to the greatest extent with the seismic anomalies on the maps of the S-wave velocity changes (Figure 3c), and dynamic Young’s modulus (Figure 3f). It should be assumed that the remaining negative and positive anomalies have the same nature, that is, they mark the zones of an intense fracturing and an increased presence of water, or the rock mass in those zones is more compact. The correlations of the anomalous seismic parameters were verified by the BGPR test to confirm the above observations with greater certainty; further geochemical tests are planned.
Figure 3. Locations of the sources and receivers used in the seismic surveys: a) control borehole location; b) maps of the P-wave velocity changes; c) S-wave velocity; d) P-wave to S-wave velocity ratio; e) dynamic Poisson’s ratio; and f) dynamic Young’s modulus of elasticity. The blue line denotes the location of control borehole. Dashed black and white lines denote seismic anomalies. The dotted blue line is the border of elevation zone and the red line is the border of sandstone cemented by anhydrite.
Figure 4. The core from the control borehole

**BGPR**

By way of BGPR tests, a radargram was made (Figure 5), which includes additional information on the following features: lithology (obtained on the basis of the core investigation); location of major discontinuities; zones of signal attenuation; and values of the RQD index. On the basis of the radargram, it is possible to identify the maximum ranges of exploration for the 100 MHz antennas. They vary from approximately 6 m in the dolomite with the presence of water to about 18 m in the anhydrite.

Figure 5. Radargram from control borehole with markings for the RQD changes and lithology on the basis of the core investigation
The information obtained from the radargram correlates to a large extent with the geological engineering data concerning lithology, changes in the RQD index, and phenomena observed in the process of drilling the borehole. On the radargram, at a distance of about 6 m from the mouth of the borehole, no useful signal was recorded due to the screening of a steel casing pipe. At the section of 6–94 m, approximately 12 larger fractures were recorded; however, there were the sections with a greater compactness of rock mass (e.g., from about 6–11 m), and the sections where the fracturing was more significant (e.g., starting with 74 m away from the mouth of the borehole (Figure 4)). This is also visible on the changes of the RQD index shown in Figure 5.

In the zones of more predominant fracturing, chocking of the drilling head was observed. At the final part of the section starting from approximately the 78th m of the borehole, the radar image shows a greater attenuation of the signal, whereas from 94–108 m, it decays completely (Figure 5). Most likely the main reason behind the attenuation of the signal is the intense fracturing of the dolomite layer and the dense interbeddings of clayey material. This is also seen on the RQD diagram, and the zone from 80–86 m is particularly fractured (RQD = 0%). The intensity of fracturing at this section of the borehole is clearly visible on the photographs of the core (Figure 4).

The simultaneous outflow of water and gases was recorded in the zone around the 94th m. The measurement was taken by means of a gas analyzer at the casing pipe before the drilling and while the core barrel was being sunk. The gas analyzer detected the presence of varying amounts of CH₄, CO₂ and H₂S. A minor outflow of water (approximately 0.001 m³/min) was observed in the same location. While flowing through the borehole, the water caused the radar signal to attenuate. At the farther section of the borehole, CH₄ and CO₂ concentrations increased, which points to the gas presence in a longer section of the borehole—up to the boundary with the anhydrite layer. At the part of the radargram depicting the section between 108 and 139 m, one can see a reflection at the lithological boundary between dolomite and anhydrite. According to the radargram, the boundary is situated at 139–140 m. The location of that boundary is also visible in a sudden drop of RQD to 0% at 139–140 m of the borehole. In that zone (from 131–143 m), the highest concentration of gases was also detected. The radargram shows the greatest density of fractures in the area adjacent to the anhydrite-dolomite lithological boundary. At the length between 108 and 139 m of the borehole, some inclusions of anhydrite occur in the layer of dolomite. At the farther section, the range of the radar’s signal improves to approximately 12 m. Also RQD increases to about 90%. At the end of section, from 140–154 m, the signal propagated in the very good quality anhydrite layer (Figure 4). The signal range radically improved to about 20 m. The RQD index in that zone also reached high values (approximately 90%).

CONCLUSIONS

This work presents the results of geophysical, and geological engineering tests, carried out to identify the structure and properties of the rock mass in the part of the copper ore deposit in the Rudna mine, Poland, with particular focus on the weak zones related to gaso-geodynamic phenomena. Geophysical tests concentrated on the recognition of the structure and properties of the dolomite layer located in the immediate roof of the excavations.

The first stage of the investigation consisted of tests based on seismic tomography, to identify anomalous changes in the elastic properties of the rock mass in the dolomite layer. Results served as the data necessary to design a control borehole to verify the seismic information. Subsequently, BGPR was used, equipped with 100 MHz antennas. The data were correlated with information on lithology and the degree of fracturing of the rock mass, including the RQD index, as well as additional information on the presence of water and gases, mechanic symptoms and other phenomena observed in the process of drilling.

The performed tests made it possible to formulate the following conclusions:

- The recorded anomalies in the P-wave and S-wave velocity changes (and other seismic parameters) were mainly related to the varied fracturing of the dolomite layer and presence of water in the rock mass. As a result of the verification of the anomalies by means of the borehole tests, the strongest
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 reasons as the anomalies that were verified.

- The zone of the outflow of water and gases detected in the process of drilling at 94 m of the control borehole in the dolomite layer correlates with the zone of strong attenuation of the radar’s signal at the section from 78–108 m. Most likely, the main reason behind the signal attenuation is the intense fracturing, and more significant presence of water and clayey interbeddings in the dolomite.
- The BGPR tests made it possible to identify more precisely the lithological boundary between dolomite and anhydrite. It was difficult to make a geological interpretation of that boundary in condition the top part of porous and fissured dolomite is cemented by anhydrite.
- The limitations encountered in carrying out geophysical measurements were methodological in nature and associated with the underground conditions at the mine.

Taking into consideration the advantages and limitations of the geophysical methods (seismic tomography and BGPR) applied in this study, it must be stressed that the results supplement the geological engineering investigation in an interesting and revealing way. They do not solve the major problems related to the threat of an outburst, but they may be useful for monitoring the rock mass in the course of preparatory works preceding mining operations. However, the results presented in this study need further investigation as to their usefulness in varying conditions of an outburst hazard.

ACKNOWLEDGMENTS

Special thanks are extended to Jarosław Suchan, mining geologist, and the workers of Rock Burst and Mining Technology Department at KGHM Polska Miedź SA Oddział Zakłady Górnicze "Rudna" for their comprehensive support for investigations. We also thank peer reviewers, and Janice M. Burke, Technical Paper Coordinator of CIM Journal for valuable comments and enormous assistance.

An earlier draft of this paper was published in the CIM World Mining Congress 2013 Conference Proceedings, prior to undergoing the CIM Journal peer-review process.

Paper reviewed and approved for publication by the Geological Society of CIM.

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REFERENCES


Łątka T., Czarny R., Krawiec K., Kudyk M., & Pilecki, Z. (2010). Eksperymentalne badania położenia nieciągłości, pustek i stref rozluźnień w górotworze za pomocą georadara otworowego [Experimental research of discontinuous, empty and fracture zones location in rock mass with...


Pilecki, Z., Czarny, R., Łątka, T., Krawiec, K., Pilecka, E. & Pszonka, J. (2012). Rozpoznanie struktury górotworu z wyrobisk udostępniających metodą prześwietlania sejsmicznego wraz z zastosowaniem georadaru otworowego [Recognition of rock mass structure by seismic tomography and borehole georadar from preparatory drifts] (Research Report), Kraków, Location: MEERI PAS.
