Atypical evolution of seismicity patterns resulting from the coupled natural, human-induced and coseismic stresses in a longwall coal mining environment

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ABSTRACT

A very unusual time-space distribution of seismicity accompanying coal exploitation has been observed in a Polish mine. The earthquakes did not follow the depth of mining but exhibited changing depths from far below to close to the mined seam. One of the deep events which occurred at close epicentral distance to the active mining front was Ml 3.7 event. This paper presents the study of possible coupling of natural, human-induced and coseismic stresses in a longwall coal mining environment. The full moment tensor solution showed that the strong earthquake occurred on an almost vertical plane consistent with approximate strike of local tectonic structure. The signal correlation analysis revealed some highly correlated pairs within both deep and shallow event groups. To evaluate inducing factor of ongoing and past exploitation, geomechanical modelling of its influence on strain and stress at the target depth has been performed. The results exhibited a changing vertical stress regime, which might have promoted failure on preexisting, almost vertical planes of weakness. The earthquakes’ rate variation in time showed no increase in activity right after the occurrence of Ml 3.7 event. The P-S-wave spectra corner frequency ratio had an average of 1.0, suggesting slow rupture. However, the Coulomb stress change analysis showed that the magnitude of stress changes due to coseismic slip of Ml 3.7 event at the hypocentral depth is of the same order as the stress changes caused by mining. Thus, the distribution of seismicity at this level could have been driven by both exploitation and coseismic stresses. Moreover, the seismicity which occurred within first few weeks after Ml 3.7 event, followed positive stress changes. All the obtained results let us prove that the Ml 3.7 event was a tectonic earthquake triggered by ongoing exploitation and that the distribution of following seismicity was affected by coupled natural, exploitation-induced and coseismic stresses.

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1. Introduction

Seismicity accompanies different methods of mining and occurs as failures of the strata, collapses or rock bursts (e.g. Ref. 1, and the reference therein). The distribution of mining seismicity is strictly related to the exploitation progress of mining works and, consequently, to the local stress field (e.g. Ref. 2, and the reference therein). The longwall mining system changes the stress field across the panel, ahead of the face, but also along the sides of the panels within headgate and tailgate.3-7 All these areas are highly probable for seismic events occurrence. According to many analyses, the maximum number of tremors occurs at a distance of tens of meters ahead of the face, above and below the panel.7-10 There are also local extremes in a goaf at a longer distance from the face.11 However, analyzing the seismicity from one of the coal mines of Upper Silesia Coal Basin (USCB), Poland, we observed very interesting and unusual time-space behavior of seismicity pattern – the seismicity typically accompanying exploitation exhibited changing depths from great below to close to mined seam. What is more, one of the events which occurred at great depth below, but at close epicentral distance to active mining front, was a strong event of Ml = 3.7. Such rather unusual seismicity pattern made this case worth studying in the context of possible natural, induced and coseismic stresses governing seismicity distribution in mining environment.

In this paper we present the results of investigation of possible factors, both natural and induced by mining, causing this strong seismic event. Using various methods for studying the event, we
try to find out whether mining exploitation in this region can activate underlying tectonic structures and trigger earthquakes. Also, we investigate whether strong events in mining and geological settings of Upper Silesia can influence the number and distribution of following weaker seismicity. This study is the continuation and extension of earlier work done by Marcak and Mutke, where the seismicity of the same mine was analyzed. Authors were investigating the tectonic activation of rock masses as a result of mining.

We start our analysis from relocation of strong events to verify results obtained by the mine’s routine. In the second step, we perform signal correlation to investigate whether deep and more shallow events have significantly different recorded signals. In order to carefully investigate the $M_L$ 3.7 event, we determined its moment tensor and source parameters. To evaluate inducing factor of ongoing and past exploitation we performed geomechanical modelling of its influence on strain and stress in the rock mass at the target depth. The last part of the analysis is focused on investigating the effect of the coseismic stress changes due to strong event on following seismicity. Static stress transfer phenomenon has been studied in natural earthquakes and was proven to influence the distribution of aftershocks. Recently, few studies have analyzed the influence of static stress transfer on mining seismicity, showing that strong mining events are capable of producing stress changes big enough to influence the spatial and temporal distribution of following seismicity. In our study, we want to investigate whether similar effect was observed after $M_L$ 3.7 event.

2. Seismogenesis conditions of USCB

The USCB in southern Poland is the place of intense coal exploitation carried out since 18th century. Coal seams deposited within Carboniferous sandstones, conglomerates and mudstones are now being exploited in more than thirty mines using the longwall method. Mining induced seismicity in the area has been monitored since 1929 when the first mining-dedicated seismological station was opened in Racibórz city in southern USCB. Since then, with only three years break after World War II, seismic monitoring was constantly improved leading to the present day Upper Silesian Regional Seismological Network (GRSS) conducted by Central Mining Institute (CMI) and a number of local networks conducted by mines themselves. Locations of most seismic mining areas correlate with tectonically complicated parts of the USCB, i.e. the Kłodnicki fault, Main anticline and Bytom syncline regions (Fig. 1). Seismicity in these regions’ mines is not only the most intense in the area but also characterized by the highest magnitudes. The strongest events recorded in the USCB in the last twenty years had local magnitudes ranging from 3.8 to 4.0 and occurred in mines in mentioned areas.

In numerous studies of mining seismicity authors have distinguished several mechanisms of seismic events which correspond to diverse stress state around mining face and exploited voids. Bimodal frequency-magnitude distribution indicates two main types of events and has been observed in several mines: e.g. Polish coal mines, Polish copper ore mines and South African gold mines. Mentioned studies suggest that smaller earthquakes - named type A after Richardson and Jordan, are directly connected with mining operations whereas bigger earthquakes, type B, are associated with local and regional tectonic structures which create weak zones and promote shear failure. The type A seismicity occurs as a result of interaction between mining induced and local tectonic stresses and cluster mainly in close vicinity to mining stope. Such events are characterized by low and medium magnitudes and can have significant non-double-couple component associated with volume change caused by stope closure. Mining tremors associated with local and regional tectonic structures, type B, have usually larger magnitudes, their mechanisms are coupled to pre-existing faults or other zones of weakness and thus are rather of double-couple type. Such events can also occur at greater distances from an active mining front. Such events in USCB are usually associated with well-known geological units intersecting the area mostly in its north part, including well mapped Kłodnicki fault and Main anticline (Fig. 1). Many of these big events have also been assigned to Bytom syncline intersecting numerous mines and striking WNW-ESE, however, no significant faults have been mapped there. One of the mines currently inducing intense seismicity and passing Bytom syncline axis is Bobrek Coal Mine in Bytom city (Fig. 1). In December 2009 strong seismic event of $M_L = 3.7$ occurred during exploitation of longwall panel (LP) 3 of coal seam no. 503. The routine mine location showed that the event occurred when mining front approached the syncline axis. The lack of damage at mining level and the fact that the event was felt on the surface at great distance from its epicenter indicated that its hypocenter was much below mined seam suggesting tectonic character of the event. Its great depth was later confirmed by 3D locations (Fig. 2). Interestingly, distribution of smaller events, typically accompanying exploitation, also exhibited great depths. What is more, the seismicity became more intense when the mining front passed approximately half of planned panel's length.

3. Data

The strong seismic event of $M_L = 3.7$ occurred on December 16th, 2009 during mining of panel 3/503 in Bobrek mine. The mine, located in one of the most seismically active parts of USCB (Fig. 1), has been extracting coal from twelve seams using multilevel method and longwall system. Local magnitudes have been calculated from energy measurements using formula developed for USCB and based on local mine network recordings. A local network was designed to monitor and locate seismicity accompanying exploitation. At the time of the event occurrence it consisted of seven vertical and five three-component short period (1–200 Hz) DLM3D seismometers manufactured by CMI, with sampling rate of 500 sps. In the second half of January 2010 the network was extended with 6 additional vertical sensors with the

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**Fig. 1.** Map of USCB with seismicity recorded by GRSS in 2014, only $M_L>2.5$-black points. Note the location of Bobrek mine. Main seismotectonic units mentioned in the paper are marked with letters: A-Bytom syncline, B-Kłodnicki fault, C-Main anticline.
same parameters. The mining routine location and determination of events’ energy was based on manual picking of P and S waves arrivals and performed only in 2D. Exploitation of seam 503 was held in four longwall panels, advancing from north to south. Since the start of exploitation of panel 1 in 2005, three strong events with local magnitude above 3.0 were observed, two of which are supposed to be associated with underlying Bytom syncline axis. The seismicity accompanying the exploitation of panel 3 became the subject of Laboratory for Monitoring Mining Induced Seismicity project (LMMIS) held by Central Mining Institute, a part of IS-EPOS project (http://is-epos.eu/). It has been relocated by CMI using the same software as the mining geophysical survey, but in 3D mode, using repicked signals. The final catalog comprises of 2996 events with magnitude of completeness $M_c = 1.5$. CMI located $M_c = 3.7$ event at depth of $\approx 700$ m below exploited seam. The depths of smaller events accompanying exploitation exhibit an atypical distribution - the majority of seismic events have also been located much below the seam with only few events typically surrounding the stope level (Fig. 2b). Note that no prior exploitation has been performed at such depth. The depth distribution changed at some point when, according to Marcak and Mutke\cite{12}, the mining front reached the Bytom syncline axis. At this point the seismicity climbed toward stope level, probably along southern limb of the syncline, reaching it at approximately 700 m of exploitation front advance. Rapid increase in a number of recorded events visible in Fig. 2b at approximately 6400 m could be linked to network extension, however the Modified Goodness-of-fit test used to determine $M_c$\cite{28} did not reveal decrease of $M_c$ for catalog after network extension. What is more, such an increase in a number of events was observed not only in panel 3, but also in all other panels of coal seam no. 503 which were monitored by stable seismic network (Fig. 2a). This may indicate that such distribution of events is mainly the result of local geology and tectonics, rather than only the expansion of network. Unfortunately, we could not compare our data with the vertical distribution of seismicity from mentioned panels since we had an access only to mining routine 2D locations. However, according to Ref.\cite{12}, seismic events which occurred in other panels were also located at great depths below the seam.

Interestingly, only vertical distribution of seismicity seems to be unusual; the horizontal distribution follows the typical pattern where mining events occur at close epicentral distances from active mining front (Fig. 3). To verify the unusual seismicity depths, we relocated the strongest events using the single event relocation method based on probabilistic inverse theory.\cite{29} In the second step of depths verification the signals cross-correlation was performed. These two techniques are described below.

4. Events relocation

Seismic events location procedure carried out by mining geophysical surveys usually has to deal with some specific issues. Two of them are crucial for our analysis, namely lack of origin time and, consequently, poor depth estimation. Since network timing is not controlled by any standardized time, it is also difficult to use some relocation approaches based on differences of recorded first arrivals times e.g. Double Difference.\cite{29} Here we used seismic signals recorded on vertical seismometers to relocate induced seismic events of $M_s > 2.3$ associated with LP. The location procedure worked with probabilistic inverse approaches and was already tested for Polish local mining seismic networks. Details of the
procedure are described in Rudziński and Dębski.29 The locations were obtained using mean P-wave velocity of 3850 m/s, based on average velocities estimated for seismic stations at the time of longwall excavation (mining geophysical survey – personal information). Our procedure gave similar results as CMI relocation, with horizontal location differences not greater than 60 m. For five out of nine relocated strong events, new depths were smaller than those reported by CMI, however they were still much below exploited seam, e.g. ≈ 500 m below in case of the M₁.37 event (red star in Fig. 2b). The location errors differ among coordinates. Mean latitude error was 38 m (min: 33 m; max: 46 m) while mean longitude error was 42 m (min: 37 m; max: 50 m). Depths of hypocenters were much more influenced by location inaccuracy with mean error ≈ 130 m (max: 171 m). Even though depths are the weakest point of events location, it did not affect observed seismic pattern. To investigate whether different velocity model could change events’ depths, we performed tests using different velocities by adding and subtracting up to 500 m/s. Final results did not change the general observation that events’ depths changed in time. Thus, the relocation step helped us confirm great depths of observed events and their untypical time pattern. In subsequent steps of the analysis, we applied new locations for the strongest events and CMI locations for the rest of the data bearing in mind small differences between these two relocation results.

4.1. Signals cross-correlation analysis

According to CMI relocation, events depths changed at the time when mining front approached the axis of Bytom syncline (Fig. 2b). Since inaccuracy in depth estimation could affect our interpretation, we decided to provide some further analysis to verify this unusual distribution of seismicity. Based on the idea that signals of events with close hypocenters and similar focal mechanisms recorded on the same station are very similar, we carried out additional signals processing, namely signals cross-correlation. Assuming close epicentral distance among analyzed events, possible differences in recorded signals are either due to events’ different depths or focal mechanisms. Here, we analyzed only tremors from central part of mining panel 3 to exclude those events which occurred close to panel’s edges where local stress is accumulated (Fig. 4). Thus we could assume that focal mechanisms of analyzed events were similar. If so, only the vertical location could be the factor affecting recorded signals shapes. In our analysis we relied on 50 tremors before and 50 after depth change to check whether their signals differ significantly between and within these groups. We used signals from 1 s before to 4 s after P-wave onsets and their maximum cross-correlation value as an indicator of signals similarities. Fig. 4 shows a matrix of correlation coefficients calculated for all event-event pairs. We used signals from a station with epicentral distance exceeding 900 m to be able to assume similar wave paths for all events. Also, this station was the least noisiest from all distant ones. The mean cross-correlation coefficient within shallow events group – quarter II in Fig. 4– is 0.53. The same value within deep events group – quadrant III - is 0.52. By cross-correlating events from these two groups we get mean coefficient value of 0.48 – quadrants I and IV. The mean values of correlation coefficients are not significantly higher within groups than between them, however there are some event-event pairs with very high cross-correlation close to 1 which occurred within both groups (Fig. 5). What is more, there is highly correlated group of about twenty-five events within quadrant II – shallow events.

The cross-correlation analysis did not give us clear evidence of the changing events’ depth, however it revealed some highly correlated pairs within both deep and shallow events groups. Such high values were not observed when correlating events between groups. It may indicate a changing depth of events.

5. Characterisation of seismic source of M₁.37 event

5.1. Moment tensor solution

We manually picked P-wave onsets on all twelve available in-mine stations and performed moment tensor inversion in the time domain.30 The inversion was performed using FOCI 3.4 software,31 applying the relocated origins and constant velocity and density of 3850 m/s and 2700 kg/m³, respectively. In the inversion procedure the amplitudes and polarities of the P-wave displacement onsets were used. Fig. 5 shows the full moment tensor solution for the M₁.37 event. The full moment tensor solution shows that the earthquake occurred as reverse faulting on a northwest-striking plane which is consistent with approximate strike of Bytom syncline. Nodal plane 1 is almost vertical and plane 2 almost horizontal. Very high double-couple component of the moment tensor solution – almost 95%, can be well explained by the great depth of the event and, thus, supports the idea of its tectonic, rather than purely mining.

Fig. 4. Cross – correlation coefficients matrix for selected seismic station (triangle in 3D view). Note that first 118 seismic events (blue points in 3D view) are stronger correlated among each other in comparison with the rest 118 tremors (green points in 3D view). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
character. The obtained mechanism is similar to the one described in Ref. 12, where authors also present reverse fault mechanism with similar strikes of both nodal planes, however, with different dips. The possible reason for such difference may be the fact that in 2009, when the analyzed event occurred, the mine network was being replaced and extended. At the time of the event occurrence, sensors from both networks, the old and new, modernized one, were in operation. Marcak and Mutke12 presented focal mechanism calculated based on old network recordings, whereas we present new network results. Unfortunately, data from the old network are not available anymore, so we could not compare both solutions.

5.2. Spectral analysis

Spectral analysis was performed using MULTILOK: Mining Tremors Analysis Software developed by CMI. Since data from mine network were mostly clipped, in the analysis of $M_{L}$ 3.7 event we used S waves recorded at the one available at that time GRSS station with epicentral distance of 4.4 km. MULTILOK applies the approach proposed by Andrews32 to use J and K velocity and displacement integrals33 as two independent parameters in frequency domain and based on them to calculate the low-frequency spectral level $Q_{0}$ and corner frequency $f_{0}$. The source radius $r_{0}$, slip $u$ and stress drop $\Delta \sigma$ were calculated using Brune’s source model34 and Aki and Richards35 seismic moment definition. S wave velocity $V_{s}$ and density $\rho$ for GRSS network are 2660 m/s and 2500 kg/m$^3$, respectively, giving shear modulus $G$ value of 1.77 · 10$^{10}$ Pa. Table 1 presents values of source parameters of $M_{L}$ 3.7 event. Based on obtained seismic moment we calculated a moment magnitude of $M_{w}$ 3.8,36 which is close to local magnitude.

6. Numerical modelling of the effect of exploitation on analyzed depth rock mass

A numerical modelling approach of past and ongoing exploitation of Bobrek mine coal seams was proposed to study the stress and strain distribution in the rock mass. Particular attention was being paid to the depth range of mine exploitation influence. Our aim was to estimate the magnitude of stress and strain changes at the level of studied earthquake, i.e. $\approx 500$ m below exploited coal seam.

To model the described case FLAC2D (Itasca Consulting Group, FLAC – Fast Lagrangian Analysis of Continua, Ver. 7.0. Minneapolis: Itasca) software was used. It is two-dimensional Fast Lagrangian Analysis of Continua software based on Finite Differences Method (FDM), commonly used to analyze static and dynamic problems. In our study we performed static analysis where modelled stress and strain state resulted from the appearance of the excavation at the particular depth.37 We applied Coulomb-Mohr constitutive model and built a model of rock mass as a $1200 \times 1200$ m continuum in plane strain conditions. The top edge of the model corresponds with sea level. The roof of analyzed coal seam 503 lies at the depth of 455 m bsl, however we are mostly focused on depth of $M_{L}$ 3.7 event, namely around 1000 m.

The model consists of 135 geological layers, represented by four different lithological units: sandstone, coal, sandy shale and clay shale, according to local geology.38 Geomechanical parameters of geological layers used in the model are presented in Table 2. The order of the deposition of the layers and their thickness were precisely read from the three borehole lithological profiles to the depth of 600 m bsl (Mining Geophysical Survey – personal information). Deeper layers were scattered randomly, based on general USC8 geology.39 The grid consists of 257 856 elements (474 elements horizontally and 544 vertically). Boundary conditions were assigned to the edges of the model: zero horizontal displacements on both sides’ edges and zero vertical displacement were applied to the bottom of the model. The additional loading of 7.24 MPa equal to the weight of the overburden was added to the top edge of the model. LP 3 in the coal seam 503 is located within the operating edges of twelve other coal seams. In the model, the order of exploitation has been preserved. The primary stress term, which is used later in the text, refers to the stabilized stress state.

![Focal mechanism of $M_{L}$ 3.7 event (star) obtained by moment tensor inversion of P-wave onsets. The event is shown on corresponding mining layout: dashed areas indicate mining panels: no. 2 (right hand panel – mined-out) and no. 3 (left hand panel – under exploitation at the time of the event). An arrow shows exploitation direction.](image-url)

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**Table 1**

Mean source parameters of $M_{L}$ 3.7 event calculated from six underground mine stations.

<table>
<thead>
<tr>
<th>Seismic moment $M_{0}$ [Nm]</th>
<th>Source radius $r_{0}$ [m]</th>
<th>Slip $u$ [m]</th>
<th>Stress drop $\Delta \sigma$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4 · 10$^{14}$</td>
<td>195</td>
<td>0.21</td>
<td>26</td>
</tr>
</tbody>
</table>

**Table 2**

Geomechanical parameters of geological layers used in model.36,40

<table>
<thead>
<tr>
<th></th>
<th>Volume density $\rho$ [kg/m$^3$]</th>
<th>Frictional angle $\phi$ [deg]</th>
<th>Cohesion $c$ [MPa]</th>
<th>Young’s modulus $E$ [GPa]</th>
<th>Poisson’s ratio $\nu$ [dimensionless]</th>
<th>Splitting tensile strength $R_{t}$ [MPa]</th>
<th>Tension $R_{p}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1290</td>
<td>24</td>
<td>3.3</td>
<td>3.6</td>
<td>0.24</td>
<td>0.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Sandy shale</td>
<td>2690</td>
<td>25</td>
<td>7.2</td>
<td>11.2</td>
<td>0.24</td>
<td>2.1</td>
<td>22.5</td>
</tr>
<tr>
<td>Clay shale</td>
<td>2600</td>
<td>24</td>
<td>6</td>
<td>10</td>
<td>0.25</td>
<td>1.9</td>
<td>19.2</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2510</td>
<td>25.3</td>
<td>11.3</td>
<td>18</td>
<td>0.27</td>
<td>3.3</td>
<td>35.7</td>
</tr>
</tbody>
</table>
resulting from exploitation of mentioned coal seams.

The carried out numerical modelling of LP 3 exploitation resulted in the 2D distributions of secondary displacement and stress in the rock mass on the plane perpendicular to the mined panel. To carefully investigate the stress and displacement values at the depth of the studied earthquake, horizontal profiles were created (Fig. 6a–d). The location of the west edge of panel no. 3 was marked by a dashed line. Note that studied event’s hypocentre was located ≈ 13 m east from panel’s west edge.

The biggest changes of all studied parameters can be observed near panel’s edge, close to the hypocentre. The exact values read for hypocenter location are presented in Table 3.

Presented results clearly show that past and ongoing mining exploitation has influenced the stress state at the depth of $M_L 3.7$ event. The observed stress changes are close to 1 MPa. An increase of compressive vertical stress around panel’s edge resulted in vertical displacement pointed downwards. The area at the greater distance from panel’s edge axis, especially on its west side, experienced opposite effect – relaxation of compressive stress caused vertical displacement pointed upwards. Such changing vertical stress regime can promote failure on pre-existing almost vertical planes of weakness. The obtained focal mechanism of analyzed event – almost vertical reverse fault – seems to support the presented idea. Also, the amplitude of vertical displacement along the

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**Table 3**

Stress changes in the $M_L 3.7$ event’s hypocentre. Negative values of stress indicate compression, positive – tension.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Primary stress</th>
<th>Secondary stress</th>
<th>Absolute difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical $S_{YY}$</td>
<td>$-31.93$ MPa</td>
<td>$-33.17$ MPa</td>
<td>$1.24$ MPa (increase)</td>
</tr>
<tr>
<td>Horizontal $S_{XX}$</td>
<td>$-10.09$ MPa</td>
<td>$-8.87$ MPa</td>
<td>$1.22$ MPa (decrease)</td>
</tr>
<tr>
<td>Shear $S_{XY}$</td>
<td>$-0.15$ MPa</td>
<td>$0.50$ MPa</td>
<td>$0.65$ MPa (caution – sign change)</td>
</tr>
</tbody>
</table>
profile at earthquake’s depth is of similar order as the slip on the fault – 0.21 m.

7. Static stress transfer analysis

In this chapter we want to investigate whether the strong mining event which occurred in the Bobrek mine affected the distribution of following seismicity. For this purpose we performed static stress transfer analysis, using Coulomb failure function

\[ \Delta CFF = \Delta \tau + \mu \Delta n, \]

where \( \Delta \tau \) and \( \Delta n \) are the shear and normal stress changes along receiving fault, respectively and \( \mu \) is the effective coefficient of friction.\(^{42,43} \) A positive value of \( \Delta CFF \) moves the fault towards failure, which increases the likelihood of fault rupture.

The detailed analysis of \( \Delta CFF \) influence on seismicity distribution has been already performed for copper ore mines in Poland.\(^{15} \) The results indicated clear influence of Coulomb stress changes on rate and location of following seismicity. In the case of the Bobrek mine, the seismicity rate variation in time shows no increase in activity right after the occurrence of \( M_L3.7 \) event (Fig. 7). The mean daily rate in the week preceding the event was 10 events/day, whereas in the week following the event it was eight events/day. However, looking only at the number of strong events of energy \( > 10^6 \mathrm{J} \) ( \( > M_L2.2 \) ) before and after the event, an increase is observed. Within two months after studied earthquake, eight events of energy \( > 10^6 \mathrm{J} \) ( \( > M_L2.2 \) ) have occurred, including one of energy \( > 10^7 \mathrm{J} \) ( \( > M_L2.7 \) ). For comparison, in the same period prior to the studied earthquake, only three events of energy \( > 10^6 \mathrm{J} \) had occurred (none \( > 10^5 \mathrm{J} \)). It may indicate that \( M_L3.7 \) event caused an increase in number of strong events. One of possible explanations could be either static or dynamic stress change. However, eight mentioned events did not happen immediately after the main one, which excludes the dynamic character of the triggering effect\(^{44} \) (Table 4). Thus, to study the influence of \( M_L3.7 \) event on following ones, we performed the static stress transfer analysis using Coulomb 3.0 software.\(^{45,46} \) Since mentioned strong events could also change the stress distribution in studied area, we included their effect in the performed modelling.

The stress changes caused by exploitation promote vertical rather than horizontal fault rupture. Thus, in case of \( M_L3.7 \) event, nodal plane 1 was accepted as the correct fault plane. Since data from mine network were clipped, we could not investigate the rupture’s directivity. Hence, we assumed the event’s hypocentre in the middle of the fault plane. We relocated all eight strong events and determined their focal mechanisms using methods described in previous sections (Fig. 9). To choose one of the nodal planes we relied on the results of Ref. 21. The author analyzed the focal mechanisms of mine tremors occurring in USCB and identified three types of seismic sources coupled to exploitation. In all three types the fault planes dips were greater than 45°. We performed our analysis accepting nodal planes which fit this pattern. The \( M_L3.7 \) event and two strong following ones were close both in time and location – they occurred within eleven days and at hypocentral distance not exceeding 65 m. They had also similar mechanisms. Thus, we assumed that they represent continuing rupture and set hypocenters of strong events 1 and 2 in the lower edges of fault planes (Fig. 8). For the rest of strong events 3–8 we assumed the hypocenter in the middle of nodal planes.

In the modelling we used the shear modulus and Poisson ratio values of 2.2 GPa and 0.24, respectively, which correspond to the mean values of those parameters for four floor strata.\(^{38} \) Fig. 9 presents the cumulative static stress changes due to \( M_L3.7 \) and following events on receiver planes and at depths of target events 1–8.

To investigate the influence of \( M_L3.7 \) event on distribution of following weaker seismicity we divided the study area in three regions A–C, representing different parts of the panel (Fig. 10). For each region

![Fig. 8. Map of fault projections of the \( M_L3.7 \) (star) and 1–8 strong events (circles). All planes are presented as projections at the hypocentres depths.](image)

![Fig. 7. Seismic activity in LP 3 in time.](image)

Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>( M_L )</th>
<th>Energy ([\mathrm{J}])</th>
<th>Depth ([\mathrm{m}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.12.2009</td>
<td>2.4</td>
<td>( 2 \times 10^6 )</td>
<td>1179</td>
</tr>
<tr>
<td>2</td>
<td>31.12.2009</td>
<td>2.4</td>
<td>( 2 \times 10^6 )</td>
<td>1224</td>
</tr>
<tr>
<td>3</td>
<td>6.01.2010</td>
<td>2.3</td>
<td>( 1.4 \times 10^6 )</td>
<td>899</td>
</tr>
<tr>
<td>4</td>
<td>13.01.2010</td>
<td>2.3</td>
<td>( 1.6 \times 10^6 )</td>
<td>1159</td>
</tr>
<tr>
<td>5</td>
<td>4.02.2010</td>
<td>2.5</td>
<td>( 3.2 \times 10^5 )</td>
<td>1302</td>
</tr>
<tr>
<td>6</td>
<td>5.02.2010</td>
<td>3.0</td>
<td>( 3.2 \times 10^7 )</td>
<td>1290</td>
</tr>
<tr>
<td>7</td>
<td>12.02.2010</td>
<td>2.4</td>
<td>( 2.5 \times 10^6 )</td>
<td>1224</td>
</tr>
<tr>
<td>8</td>
<td>19.02.2010</td>
<td>2.3</td>
<td>( 1.7 \times 10^6 )</td>
<td>1093</td>
</tr>
</tbody>
</table>
Fig. 9. Cumulative static stress changes due to $M_{L} 3.7$ and following events on receiver planes and at depths of target events 1–8 ((a–h)). $M_{L} 3.7$ event is marked by a black star, subsequent strong events’ epicentres are marked by black points. The rectangles represent mined-out areas, the position of front line of LP 3 corresponds to its actual position on events’ occurrence day.
we determined the representative focal mechanism based on observed events, separately for upper and lower part of the region. In case of regions B and C, seismic events both in the upper and lower part had similar mechanisms. It is consistent with the assumption made in paragraph 4.1. In region A, seismic events closer to exploited seam had different mechanisms from the deeper seismicity. This part of LP is most affected by the exploitation geometry and stress changes are the greatest (Fig. 6). It may explain changing focal mechanisms of observed events. The fixed representative fault planes are as follows: upper region A: Strike = 222°, Dip = 67°, Rake = -52°, lower region A: Strike = 130°, Dip = 72°, Rake = 121°; region B: Strike = 265°, Dip = 76°, Rake = -108°; and region C: Strike = 129°, Dip = 62°, Rake = 102°. We performed the Coulomb stress change modelling accepting representative fault planes as receiver planes in each region separately. Fig. 10 shows the results together with seismicity observed in each region coloured according to the occurrence time.

Both performed analyzes showed that two strong events, no. 1 and 2, occurred within negative stress changes areas caused by $M_{3.7}$ event. However, their close distance to event’s fault plane lets us suppose that they were the continuation of its rupture. The actual stress change close to causative fault plane may be different from the one presented here due to complex slip distribution in the fault zone which cannot be well modelled without detailed knowledge of source geometry.47

8. Discussion and conclusions

The presented results of $M_{3.7}$ event relocation, moment tensor and spectral analysis show that it was strong and deep earthquake with almost vertical fault plane and reverse faulting mechanism. It clearly shows that the event could not be directly induced by mining exploitation – the great depth of the event below exploited seam, $\approx 500$ m, and almost vertical fault plane, with strike at an angle relative to panel’s edges, do not match typical mining tremors observed in USCB and described in Ref. 21. The author identified three types of seismic sources coupled to exploitation based on seismicity of one of USCB mines with similar geology and exploitation depth to the one analyzed in present study. The first type are high energy tremors occurring in sandstone beds overlying the coal seam, with dominant normal faulting and fault

![Fig. 10. Static stress changes due to $M_{3.7}$ event shown in three cross sections A-C. Seismicity following the event is shown as points coloured according to occurrence time: black – events which occurred before strong event no. 2, green – before event no. 3, pink – before event no. 4, grey – before events no. 5 and 6, red – before event no. 7, orange – before event no. 8, and points with no fill – after event no. 8. Strong events 1-8 are marked with stars coloured in the same manner as smaller events. An arrow indicates exploitation direction. The dashed line in section A marks the limit between $\Delta$CFF calculated for receiver planes defined for upper and lower part of the region. Note that cross section A intersects the $M_{3.7}$ event’s hypocentre.](image-url)
planes at an angle of \( \approx 45^\circ \) to the face line of LP. The second type events are mostly of normal faulting type, parallel to the coal face, within roof strata. The third type events have high explosive component and are coupled to the failure of coal seam. High energy seismic events occur mostly in roof strata, whereas low energy events are coupled to coal seam. The analyzed event clearly does not fit into any of these types.

The calculated stress drop of analyzed event – 26 MPa, is in the range of both tectonic and induced earthquakes’ values. There are studies which present low stress drop values for mining induced events,48,49 however, other studies present values similar to those of natural earthquakes.50,51 Dubinski and Mutke52 estimated the stress drops of earthquakes observed in USCB within limits of 0.028–32 MPa. Kwiatek et al.53 analyzed stress drops of micro-earthquakes with \( M_w \) range from –4.1 to –0.8, recorded in a South African mine. Their study revealed changing stress drops between events close to the stope area and those at greater distances, within undamaged diorite dikes. The values varied from \( \approx 0.6–1.5 \) MPa close to the stope area to \( \approx 2–8 \) MPa within undamaged dike. It suggests that low values of stress drops are linked to damaged zone surrounding the exploited area. The event analyzed in this study occurred at a depth that was great enough to assure undamaged rock and, as a result, stress drop comparable to natural earthquakes.

Surprising is that after such strong deep event no clear after-shock sequence has been observed. This could be related to velocity of rupture and heterogeneity of the rock environment. The general approximation of rupture velocity can be based on the average relation of corner frequency for P-and S-wave spectra [Ref. 54 and the reference there]. Walter and Brune55 suggest that for seismic events with very rapid rupture the corner frequency ratio is around 1.4–1.5. For seismic events characterized by slow rupture, the discussed ratio is close to 1.0. In the case of the analyzed strong event the corner frequency ratio, estimated from the records of regional network GRSS, has an average of 1.0, suggesting slow rupture case. This would agree with other studies of mining induced seismic events56,57 implying slower rupture velocities than natural earthquakes of similar magnitudes.

Although we assumed that mining exploitation did not cause fractures at the depth of \( \approx 500 \) m below exploited seam, we analyzed its impact on the stress state on this depth. The numerical modelling showed that past and ongoing exploitation influenced the rock 500 m below. The magnitude of stress change at this depth, close to the hypocentre, is around 1 MPa. For comparison, modelled vertical stress change only 20 m below exploited seam, in the event’s epicenter, is close to 10 MPa, whereas below pillars or intact rock it can even reach 40 MPa. It shows that mining tremors which occur in close vicinity to the mine shaft are induced by stress change much higher than the value observed at analyzed target depth. Also, the event’s stress drop is much higher than stress change caused by mining. It means that the event could not be directly induced by exploitation, but rather triggered.

The Coulomb stress change analysis was performed to investigate if the \( M_{3.7} \) and subsequent strong events could influence the distribution of following seismicity. The obtained results, combined with numerical modelling of exploitation effect, showed that the magnitude of stress changes caused by mining \( \approx 500 \) m below its level are of the same order as Coulomb stress changes due to \( M_{3.7} \) event, i.e. around 1 MPa. Thus, the distribution of seismicity at this level could have been driven by both exploitation and coseismic stress changes. Fig. 10 supports this idea – the seismicity which occurred within few weeks after \( M_{3.7} \) event, at the same level, followed positive stress changes. Two strong events which occurred soon after the main one occurred within negative stress changes, however, their hypocenters where very close, mechanisms similar, so we assumed that they represent the rupture on the same, continuing fault zone. The majority of other strong events occurred within positive areas. The sudden change of depth distribution of seismicity which occurred few weeks after \( M_{3.7} \) event was, according to Ref. 12, caused by mining front crossing the axis of Bytom syncline, which at this point continued as steeply dipping limb. The Coulomb stress change at this level had magnitudes many times smaller than the exploitation influence. Thus we can conclude that the seismicity which occurred after depths change, closer to mined seam, was induced by ongoing exploitation. However, as visible in Fig. 10 A, the \( M_{3.7} \) event could have influenced the tectonically vulnerable area close to mined seam and promote its seismic activation.

The tectonic stress analysis presented in Ref. 12 supports the hypothesis that \( M_{3.7} \) event was the result of tectonic deformations caused by local geological structures. The complex analysis presented in this study let us prove that the event was the tectonic earthquake triggered by ongoing exploitation and that the distribution of following seismicity was affected by coupled natural, exploitation-induced and coseismic stresses.

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