ORIGINAL ARTICLE

Seismic activation of tectonic stresses by mining

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Abstract Hard coal mining in the area of the Bytom Syncline (Upper Silesia Coal Basin, Poland) has been associated with the occurrence of high-energy seismic events (up to 10^9 J; local magnitude up to 4.0), which have been recorded by the local mining seismological network and regional seismological network. It has been noticed that the strongest seismic events occur when the mine longwall alignments coincide with the syncline axis. Data recorded by the improved local seismic network in the Bobrek Mine allow the estimation of the depths of the events' hypocentres during excavation of longwall panel 3 as it approached the syncline axis. The recorded data were also used to estimate the location of the rupture surface and stress distribution in the seismic focus region. It was concluded that tectonic stresses, particularly horizontal stress components, are essential in the distribution of seismic tremors resulting from reverse faulting. The stresses induced by mining activity are only triggering tectonic deformations. The hypocentres of the strongest seismic events during mining of longwall panel 3/503 were located 300–800 m deeper than the level of coal seam 503.

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1 Introduction

There are a few types of induced seismicity. One type is a result of stress formation due to pressure changes in hydrocarbon or gas deposits or in deposits of thermal waters. Studies, such as those by Batchelor et al. (1983), Doser et al. (1991) and Block et al. (1994) have described how the flow of fluid and gas in rocks, as a consequence of oil and gas extraction, entails a pressure change in reservoir fluids followed by local stress, which may cause seismic activity. Studies of seismic tremor mechanisms allowed for the recognition of the location of fault planes on which the seismic displacement occurs. These tremors are the result of stress redistribution sometimes extending beyond the area of intensive extraction of hydrocarbon deposits.

Another type of induced seismicity is caused by mining (e.g. Gibowicz and Kijko 1994; Dubiński et al. 1999). Extraction of coal entails a mechanical imbalance, especially when removal of overburden is considered; in other words, under the force of gravity, extraction causes force imbalances in the part of a rock mass that loses the support of the mined coal seam. The movement of overburden and the resulting elastic stresses may have a complex character. These movements can be modelled by mathematical algorithms based on the elastic theory (e.g. Cai 2008; Xie and Zhao 2009; Poulsen 2010), taking into account the stratigraphic properties of the overburden, especially the presence of strong roof rocks. In addition, stress development in the roof of an exploited deposit may be

the source of seismic activity, which can be associated with inelastic deformations in the bending roof layer (e.g. Brady and Brown 1985; Marcak 2012). In analyses of seismicity associated with mining in Poland, the influence of the geological structure on seismicity and activation of existing faults in the vicinity of the mining excavations can sometimes be observed (e.g. Idziak et al. 1997; Mutke and Stec 1997; Stec 2007).

In this paper, we describe another, yet unidentified (in Poland) cause of induced seismicity. In the mines located in the area of the Bytom Syncline, as shown in Fig. 1, the epicentres of strong seismic shocks are distributed along the syncline axis. Mining in the area of the Bytom Syncline has been active for the last 100 years.

Seismic monitoring networks that allow the locations and sizes of seismic events to be estimated have been operated in these mines for 35 years. These networks recorded very strong seismic events when excavation of the longwall face crossed the syncline axis.

This observation cannot be explained without a detailed description of the mechanisms of these seismic events and estimation of the hypocentre depths. These analyses became possible after installation of the new seismological network in the Bobrek Mine during excavation of longwall panel 3, which is the subject of the analysis presented in this paper.

The new Seismological Observation Network in the Bobrek mine, installed by the Central Mining Institute, has 64 channels. The system consists of 1 Hz triaxial and 1 Hz uniaxial geophones and a recording system that allows the hypocentres to be located.

In Poland, mine seismological networks and interpretation of their seismic records have been developed and improved over many years. The purpose of these improvements has been to obtain the most accurate possible locations of the hypocentres and estimates of the seismic energy. Accurate locations are obtained by the following condition:

– optimal deployment of seismic sensors around the observed mined panels (optimisation software)
– improvements in location software
– the use of underground blasting to identify directional velocity
– join location and velocity determination of seismic events (i.e. Gibowicz and Kijko 1994)

The seismological network at the Bobrek Mine is an example of the progress made in the development of these mining networks. Due to the unique features of mining in the Bobrek Mine (multi-seam excavation, producing excavations at different depths), it was possible to place sensors at various depths, including in excavations at depths greater than longwall panel no. 3 in seam 503. The estimated accuracy in the area of the observations is 20–80 m due the fact that the network optimally spread out, has triaxial sensors and can be calibrated by blasting.

2 Geological structure of the Bytom Syncline and seismicity in the study area

The Bytom Syncline in Upper Silesia, Poland (Fig. 2) formed at the end of the Carboniferous Period in an area of intense sedimentation. Sandstone, mudstone,
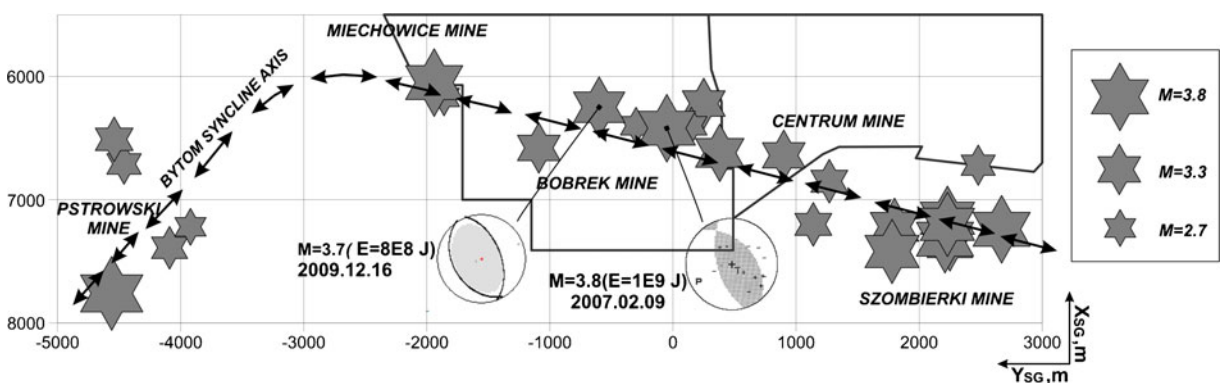

Fig. 1 Location of strong seismic event hypocentres with energy greater than $1 \cdot 10^8$ J ($M_L > 3.3$), which occurred during coal mining in the Szombierki, Centrum, Bobrek, Miechowice and Pstrowski mines since 1977

shell and conglomerate layers with a total thickness of a few kilometres were deposited. As a result of folding, a syncline with relatively steeply dipping limbs developed. After the Carboniferous Period, this syncline received Triassic and Quaternary deposits. The Carboniferous layers contain coal beds that have been intensively exploited via numerous mines for many years. This mining is associated with strong seismic events, a few of which released up to 10^9 J of seismic energy (local magnitude up to 4.0).

The Bobrek Mine is one of the primary mines in the area of the Bytom Syncline. The observations discussed in the paper are related to the excavation of seam 503, which began in 2005. This excavation is located 700 m below the ground surface, which is 400 m below sea level. The excavation along longwalls 1/503, 2/503 and 3/503 progressed from north to south, perpendicular to the axis of the Bytom Syncline. The excavation face and longwall panel were approximately 350 and 1,000 m long, respectively. The coal seam was 3.0–3.5 m thick. The total volume of the mined coal was approximately 3,675,000 m^3. Beyond the southern terminus line of the longwall excavation, the geological layers in the sideslope of the basin dip steeply (Fig. 2e).

Mining of this coal seam was accompanied by intense seismic activity. This activity consisted of 4,722 seismic events, including 570 that were classified as high-energy, i.e. energy levels of at least $1\cdot10^5$ J (local magnitude (M_L)=1.7). The maximum energy release for any single event was 10^8–10^9 J (local magnitude of 3.3–4.0). The hypocentres of the strongest tremors were located at substantial depths (300–800 m under seam 503, from which the coal was mined). A detailed list of the seismic events distributed among ranges of energy levels and magnitudes during excavation of the panels is presented in Table 1.

Seismic activity was relatively minor during the initial phase of the longwall excavation. From the time when the excavation approached the axis of the syncline (there are horizontal areas of the seam more than 500 m north of the syncline axis), strong seismic events were generated. The factors that, in the opinion of miners, influence the occurrence of the strong seismic events are prior mining over the exposed seam, leaving abutments and remnants, irregular excavation of the deposit and advancing the longwall excavation fronts in the 503 seam to approach the slope of the Zabrze Dome and the protection pillars of the primary shafts of the Bobrek Mine. Particularly interesting are the seismic events that occurred during excavation in the area of the axis of the Bytom Syncline. Those seismic events were felt poorly (due to acoustic effects and floor vibrations) by the miners working underground but were felt strongly on the surface approximately 12 km from the epicentres. One of these events released $1\cdot10^9$ J of energy (M_L=3.8); this event was located in line with the end of longwall 1/503, and after this tremor, longwall 1/503 was abandoned approximately 90 m short of its planned line of termination. Two other seismic events, which occurred at the end of 2008 and 2009 during excavation of longwalls 2/503 and 3/503, each released 10^8 J of energy (M_L=3.3).

3 Results of seismicity analysis during excavation of longwall panel 3 in seam 503

The tremors that occurred during excavation of longwall panel 3/503 were first observed in May 2009 and continued until 2010 July 08. In total, there were 3,031 mining tremors with a seismic energy greater than 10^2 J (M_L>0.1). The distribution of seismic energy (Fig. 2b) and seismic activity (Fig. 2d) during excavation of longwall 3/503 reached a distinct maximum: the greatest amount of seismic energy was released when the panel approached the syncline axis.

After crossing the axis of the syncline, less seismic energy was released than while the excavation was intersecting the axis, but there were a larger number of weaker tremors (Fig. 2d). In this region, the floor of seam 503 exposed thick layers of strong sandstone and arenaceous shale interbedded with argillaceous schist.

The depths of the tremors that occurred during excavation of longwall panel 3/503 are presented in Fig. 3b. Before 2010, the hypocentres below the mined seam were concentrated around a plane located at the depth of 1,000 m (600 m below the mining level of coal seam 503).

The strongest tremor during the mining, with a seismic energy level of $8\cdot10^8$ J (M_L=3.7), took place on 2009 December 16 when the longwall face line approached the syncline axis. The hypocentre depth is an estimated at 1,200 m, which is 800 m below the 503 coal seam. In Fig. 3a, the average of the hypocentre depths during each 20-m advance of longwall 3/503 is shown for all the tremors located below the excavation seam from 2009 May 1 to 2010 July 8, i.e. until the longwall excavation ended. During an initial phase, the tremors were located below seam
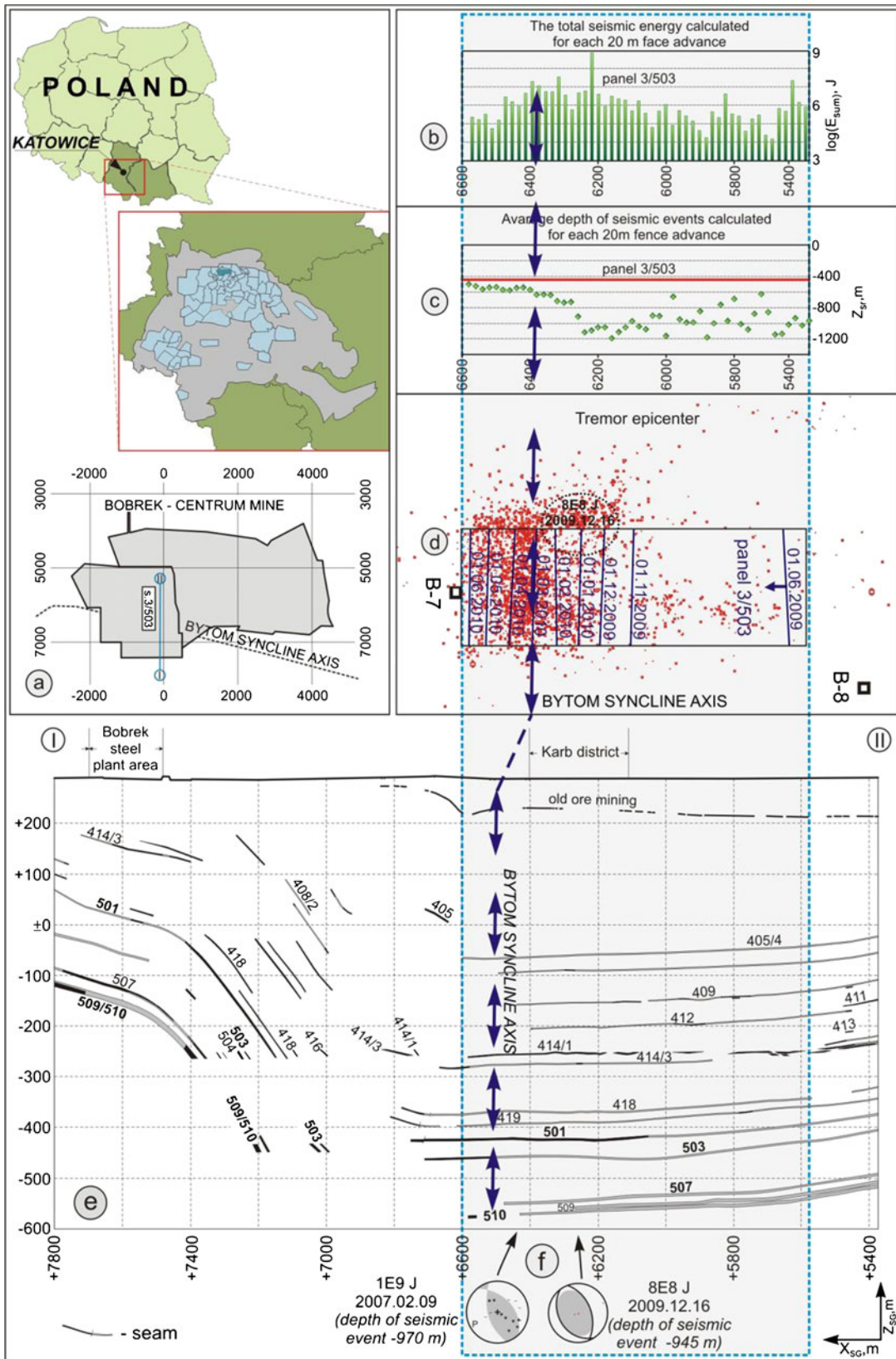
Fig. 2 Seismicity induced by excavation of longwall 3/503 in the Bobrek Centrum mine. *a* Location of the coal mine in Poland and in the region of Bytom Syncline. *b* Logarithm of the sum of seismic energy during excavation of longwall 3/503 from 1 May 2009 to 8 July 2010 for every 20 m of longwall advance. *c* Distribution of the depths of seismic events. *d* The surface distribution of seismic event epicentres. *e* A geological cross-section through the area of study showing the syncline with steeply dipping limbs in the final stage of mining of longwall panel no. 3. *f* Focal mechanism

503 (occasionally, roof tremors were also recorded). As the longwall excavation passed through the fold axis, the tremor hypocentres were deepest, located around a plane at a depth of 1,000 m or in a northerly dipping planar zone. It will be demonstrated in the next section that the deformation caused reverse faulting, which, in turn, caused the seismicity.

While the longwall was extended through the axial plane of the syncline, the most energy was released by the tremors. When the longwall work approached the area of the steeply dipping coal seams in the trough of the Bytom Syncline, the depths of tremors systematically approached the depth of coal seam 3/503 (excavation period from 2009 June 1 to 2010 July 1).

3.1 Mechanism of seismic events

The mechanism controlling the mining tremors that appeared during excavation of longwalls 3/503 and 1/503 was investigated (e.g. Mutke and Stec 2007; Stec 2011). The software program FOCI—elaborated in IGF PAN, Poland, discussed by Kwiatek (2009), was used to model the source mechanisms. This software calculates focal mechanism using the moment tensor inversion technique and using the first P-wave arrivals and their amplitudes and signs. Based on certain estimated values, the location of nodal planes (one of which is a fault plane), the dip and slip angle and stresses in the focal regions, the moment tensor decomposition to the isotropic component ISO, the compensated linear vector dipole moment CLVD and the shear component (double couple) DC can be determined.

Although the strongest tremors occurred during excavation of seam 503 in the Bobrek Mine, the source mechanisms were studied in a continuous manner. At the beginning of the excavation of the seam 503 longwall panel no. 3, tremors occurred primarily in the roof (normal mechanism), in the coal seam being mined and underneath the mining excavation; these tremors had lower magnitudes ($M_L < 2.5$). As the mining

Table 1 Comprehensive list of seismic events distributed among ranges of energy levels and magnitudes during mining of the northern panels in seam 503 of the Bobrek hard coal mine

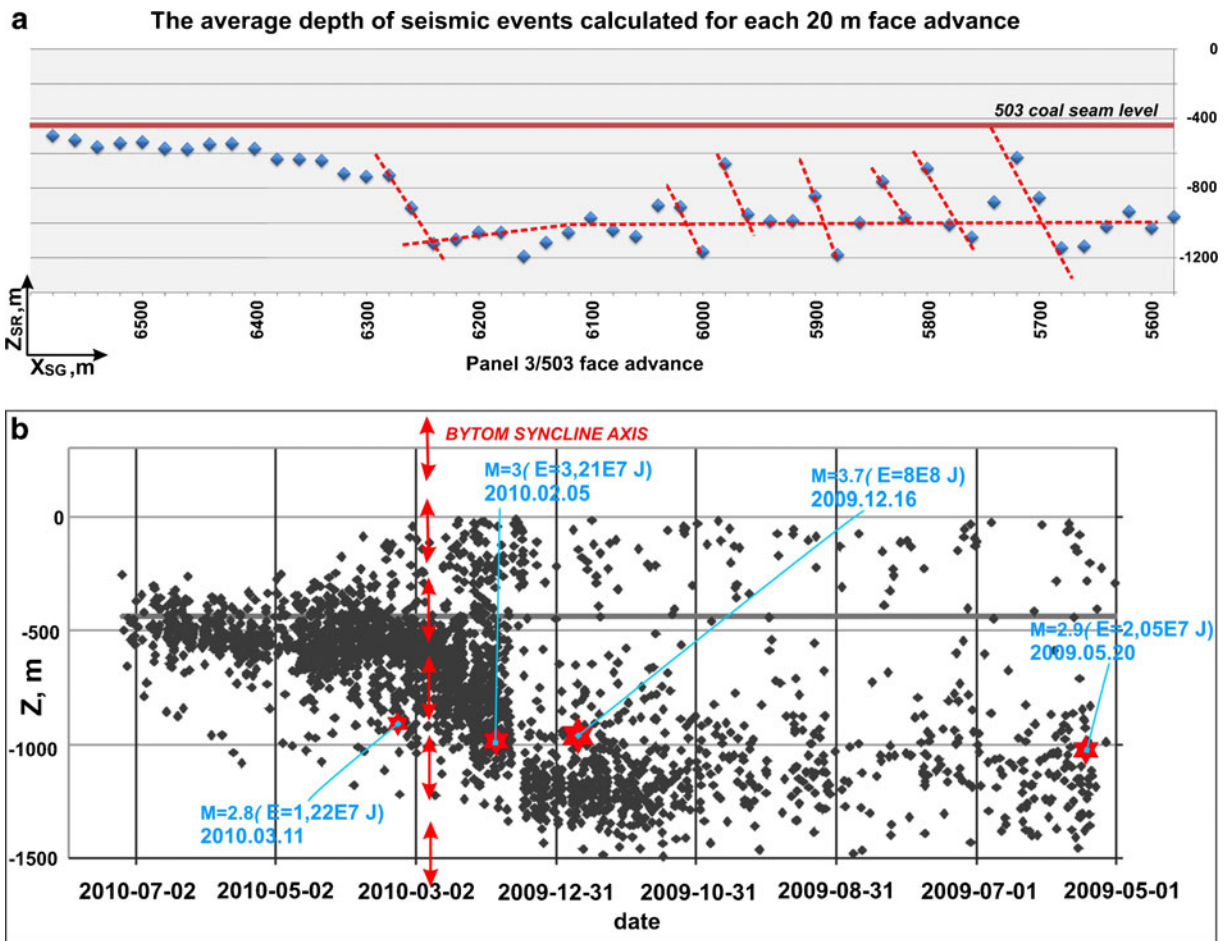| Longwall panel	$1\cdot10^2 \le E < 1\cdot10^3$ J, $0.1 \le M < 0.6$	$1\cdot10^3 \le E < 1\cdot10^4$ J, $0.6 \le M < 1.2$	$1\cdot10^4 \le E < 1\cdot10^5$ J, $1.2 \le M < 1.7$	$1\cdot10^5 \le E < 1\cdot10^6$ J, $1.7 \le M < 2.2$	$1\cdot10^6 \le E < 1\cdot10^7$ J, $2.2 \le M < 2.7$	$1\cdot10^7 \le E < 1\cdot10^8$ J, $2.7 \le M < 3.3$	$1\cdot10^8 \le E < 1\cdot10^9$ J, $3.3 \le M < 3.8$	$1\cdot10^9 \le E < 1\cdot10^{10}$ J, $3.8 \le M < 4.3$	Total number of seismic event
1/503	137	454	121	11	0	1	0	1	725
2/503	159	468	267	67	5	0	0	0	966
3/503	1,355	1,072	490	98	13	2	1	0	3,031
Sum	1,651	1,994	878	176	18	3	1	1	4,722

E seismic energy, M_L local magnitude

Fig. 3 **a** Distribution of the potential discontinuities and average depths of seismic events during excavation of longwall panel 3/503 from 1 May 2009 to 8 July 2010, calculated as an average value for each 20 m of longwall advance. **b** Distribution of the hypocentres of seismic events of energy $E{\geq}1\,10^{3}$ J ($M_L{\geq}0.6$) during excavation of longwall panel 3/503 from 1 May 2009 to 8 July 2010

approached the axis of the syncline, the average depth of the tremors increased with each 20 m of longwall advance. During that time, significantly more tremors occurred deep beneath the level of excavation (more than 600 m below coal seam 503, i.e. more than 1,300 m below the ground surface). In addition, the strongest tremors (including the strongest of all, with M_L=3.7) occurred at that time, and reverse faulting mechanisms were usually observed. Source mechanism parameters of selected seismic events that occurred during excavation of longwall panel no. 3 in coal seam 503 in the Bobrek Mine are shown in Table 2.

At the beginning of the excavation of seam 503 longwall panel no. 3, tremor source mechanisms were characteristic of normal faulting and the compressional

stresses were primarily vertical whereas the tensile stresses were horizontal, as may be expected in the case of roof tremors. However, the tremors located near the axis of the Bytom syncline were of a different character. Typical of these tremors was one that released $1{\cdot}10^{9}$ J of energy (M_L=3.8) on 2007 February 9, which was significantly earlier than the tremors associated with longwall 3/503 and during excavation of longwall 1/503. Analysis of the mechanism of this tremor indicated that the compressive stresses were horizontal and the tensile stresses were vertical; a characteristic of a reverse fault. The nodal plane of the fault had a NW–SE strike (azimuth 165°). Similar results were obtained from investigation of the strong tremors that occurred during the second stage of longwall

Table 2 Parameters of the focal mechanisms of selected seismic events that occurred during excavation of longwall panel 3 in coal seam 503 in the Bobrek mine

Date	Seismic energy, J	Nodal plane A $\Phi^0/\delta^0/\lambda^0$	Nodal plane B $\Phi^0/\delta^0/\lambda^0$	Stress axis P Φ^0/δ^0	Strain axis T Φ^0/δ^0	Part of moment tensor, % ISO	Part of moment tensor, % CLVD	Part of moment tensor, % DC
2009 May 15	6E5	140/60/−79	297/30/−110	274/71	222/16	−15	−19	66 NO
2009 December 16	8E8	339/53/96	149/37/82	64/8	276/81	−7	5	88 RE
2010 February 05	3.2E7	326/62/106	115/32/63	45/15	269/69	24	10	66 RE
2010 March 11	1.2E7	351/52/120	127/47/57	60/3	323/66	13	10	77 RE
2010 April 17	2E6	201/54/−132	79/53/−47	51/57	320/0	−16	−17	67 NO

$\Phi^0/\delta^0/\lambda^0$ nodal plane azimuth A, B/dip of plane A, B/slip angle; Φ^0 P,T axis azimuth; δ^0 P,T plunge of axis; NO normal fault; RE reverse fault; ISO percentage of isotropic component; CLVD percentage of compensated linear vector dipole component, compression (−) and tension (+); DC percentage of shear component (double couple)

3/503 excavation. The compressive stresses, as shown by the tremor source mechanism, were horizontal.

Figure 1 presents the parameters of the source mechanisms calculated from seismological data related to seismic events with energy levels of at least $1\cdot10^7$ J ($M_L>2.7$) that occurred since 1977 in the following mines: Szombierki, Centrum, Bobrek and Miechowice. All of the strongest seismic events, i.e. with energy levels of at least E8 J, were located along the axis of the Bytom Syncline. The mechanisms of tremors associated with excavation of longwalls 1/503 and 3/503 in the Bobrek Mine as the mining approached the axis of the syncline (the tremor of 2007 February 7, with seismic energy of $1\cdot10^9$ J [M_L=3.8], and the tremor of 2009 December 16, with seismic energy of $8\cdot10^8$ J [M_L=3.7]) are also presented in Fig. 1 and are of a reverse fault character.

4 Discussion of tectonic activation of rock masses as a result of mining

It can be concluded that once the longwall crossed the axis of the syncline, the seismic events exhibited the following properties discussed below.

The seismic tensor components produced horizontal compressive stresses and vertical tensile stresses, as indicated by the tremor sources. Under such conditions, a reverse fault developed and the source mechanism was a double-couple moment.

The depths of the hypocentres increased markedly. It seems evident that the stresses produced by the geological structure caused the changes in the mining seismicity. The following explanations for these observations can be considered:

- Stresses resulting from the large curvature of strata flexure. Bent strata where the curvature is significant (along the fold axis) are subject to stresses similar to those seen in a bent beam, in which a neutral axis is present and the compression is proportional to the height above the neutral axis and the tension is proportional to the depth below the axis. Such tectonic stresses have been analysed by, for example, Avouac et al. (1992) and Carminati et al. (2010). These stresses can be increased as a result of mining.

- The heterogeneity in the mechanical properties of the layers. The rocks that make up the southern limb of the Bytom Syncline are alternating sandstone, shale and coal. There are significant differences in the elastic properties of these three types of rocks (Young's modulus: coal, E=2,100 MPa; clay shale, E=5,600 MPa; sandstone, E=11,000 MPa. Compressive strength: coal, R_c=11–20 MPa; sandstone, R_c=32–52 MPa; shale, R_c=20–38 MPa). Stresses assumed by the shale are generally smaller than those assumed by the sandstone. In practice, this means that the sandstone must transmit the weight resulting from the gravimetric load of the syncline's limb. There is also a possibility of exceeding the shear strength of the material along the shale–sandstone contact, and slip along these contacts is likely. As a result, there is an additional horizontal compressive stress along the axis of the syncline, and the principal stresses are rotated.
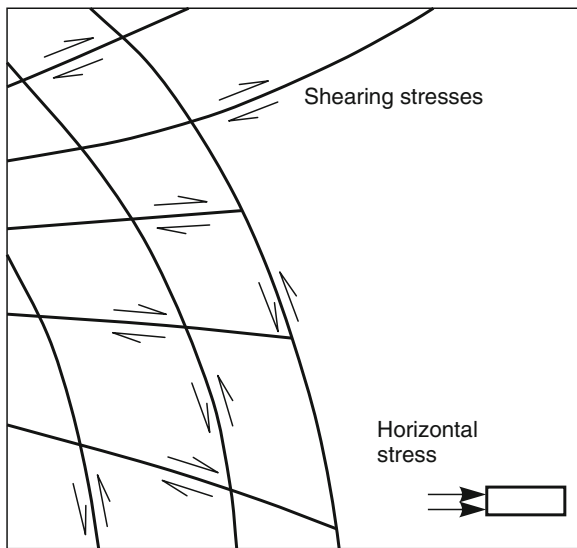
Fig. 4 The distribution of the primary directions of shear stresses in a rock block subjected to horizontal stress when the horizontal stress decreases exponentially in horizontal direction (according to Hafner (1951))
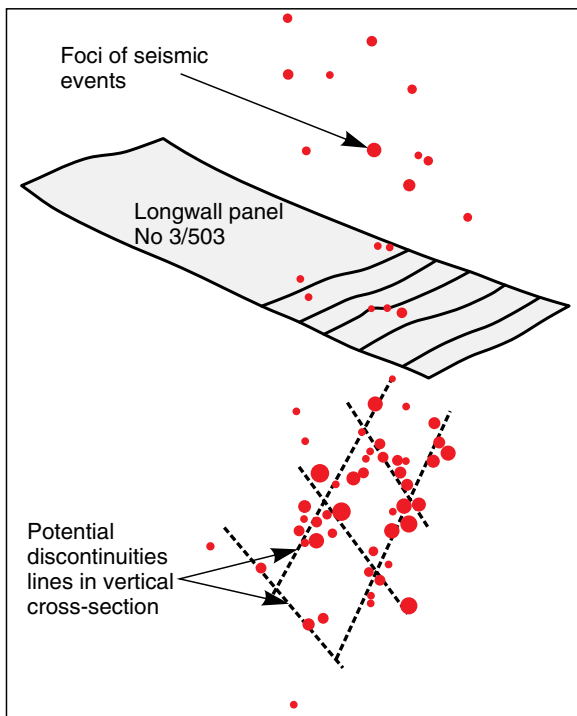

Fig. 5 Distribution of mining tremor hypocentres in a plane perpendicular to the longwall. Seismic events occurred when the excavation of longwall panel no. 3/503 was near the axis of the Bytom Syncline

- Ductile deformation in the flexure zone (e.g. Mugnier et al. 1994; Morley 2007) can occur and, as a result of mining activities, the equilibrium in the zone can be disturbed.

Regardless of which tectonic explanation (or combination thereof) holds true, in the case of the seismicity in the Bobrek mine, the horizontal compressive stresses and vertical tensile stresses are present along the lines shown in Fig. 3a.

The biharmonic equation that describes the distribution of stresses in a two-dimensional medium (in which x is the horizontal direction perpendicular to the fold axis and z is the vertical axis) takes the following form (e.g. Jaeger and Cook 1969):

$$\frac{\partial^4 U}{\partial^4 x} + \frac{\partial^4 U}{\partial^2 x \partial^2 z} + \frac{\partial^4 U}{\partial^4 z} \tag{1}$$

where U is such a potential that:

$$\tau = \frac{\partial^2 U}{\partial x \partial z} \tag{2}$$

This equation has a solution in the form

$$\tau = \sum_{\omega=1}^{\infty} b(\omega)\sin(\omega.x + \varphi)\exp(-az) \tag{3}$$

The parameters a, φ, and $b(\omega)$ in this solution depend on the boundary conditions. These conditions cannot be determined without recognition of the geomechanical conditions in the rock masses. However, the general character of the formula provides the possibility of obtaining a periodic solution.

The horizontal compressive stresses along lithologic contacts between rocks with sharply contrasting elastic properties also produce horizontal tensile stresses, while a periodic solution for τ gives vertical tensile stresses. Both styles create blocks as shown in Fig. 3a. Movement along the block boundaries can result in the seismic events observed.

Studies of the shear stresses and related strains in rocks in which the horizontal stresses fade exponentially with distance was analysed by Hafner (1951). The distribution of the primary directions of shear stresses in a rock block subjected to horizontal stresses is shown in Fig. 4.

Hafner (1951) expected that in this case, reverse faults should develop, and certain blocks should be displaced

upward as a result of sliding along the vertical and horizontal surfaces represented by lines shown in Fig. 4.

When longwall 3/503 reached the fold axis, the depths of the hypocentres increased markedly. Figure 5 shows the hypocentres in a cross section drawn perpendicular to the longwall face.

The distribution of the hypocentres, shown in Fig. 5, is similar to the distribution of the primary shear stresses shown in Fig. 4. These findings therefore may be regarded as confirmation of the hypothesis that the deep and high-energy mining tremors that occurred during excavation of longwall 3/503 in the Bobrek Mine are a result of deformations caused by stresses imposed by the steeply dipping limbs of the Bytom Syncline.

5 Conclusions

The analysis of recorded seismological data for events in the vicinity of longwall panel no. 3 in the Bobrek Mine shows that as excavation progresses near the axis of the Bytom Syncline, significant changes in mining seismicity caused by the steeply dipping fold limb are observed. These changes may be summarised as follows (Fig. 2):

1. The magnitude and energy of the seismic phenomena clearly increase.
2. Most of the tremors are located much deeper than the mined coal seam (300–800 m below the coal seam level)
3. After crossing the axis of the syncline, the seismicity is characterised by lower-magnitude events and the majority of the hypocentres are slightly (less than 200 m) below the mined coal seam.

The style of deformation in the rock mass and the associated seismicity are a result of tectonic stresses arising from the geological structure of the Bytom Syncline; the mining stresses triggered only the deformation and seismic activity. It seems that a similar style of seismicity develops in a majority of mines where excavation is conducted near the axis of a syncline.

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