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THE SEISMIC ACTIVITY DUE TO THE BENDING OF EXPLOITED SEAM ROOF

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ABSTRACT

Risk estimation of strong mining tremors in underground mines, only from seismological observations, is not satisfactory. In Poland a strong sedimentary layers appear over exploited seams and most of seismic events is located in roof layers. It seems to be important for seismic activity a bending roof layer into old workers. The plastic deformations and yield fracturing in result of bending are treated in this paper as the main source of seismic events. Dynamic temporal evolution of the rupturing process is related to the event distribution. The elastic stresses have compressed character in the layer underside, while at its over-side layer is stretched. Dislocation creep in the external parts of layer may accelerate the fracture deformation. The plane of failure is formed and the seismic events are related to this surface. The seismic data presented in the paper, has been recorded and collected in the copper mines in Poland. When the fracture is developing in over-side of the layer the energy of events related to this fracture is limited. The penetration of fracture up over layer border or more dangerously down into underside of layer intensively enlarge rupture surface and increases the energy of seismic events related to it. The changes of seismic surface area can be recognized from analyze of the hypocenter position and mining observations.

1. INTRODUCTION

There are still intensive emissions of seismic energy from polish underground mines. Seismic shocks are the results of active ruptures of rock-masses, associated with the release of mechanical energy. Some of the seismic shocks, which are result of lost of underground pillars stability in the surrounding of the mining works, are devastating mining constructions, sometime are fatal to working staff and are called rockbursts.

The aim of many scientific works is an assessment of rockburst risk.

Generally, the rock-burst is the result of stress concentration, which can be calculated by solving the partial differential equations with the finite element method. However, the fracturing of the rock-masses cannot be properly modeled with equations that assume continuity of the medium.

Also, what seems to be important is that each burst releases mechanical energy in the form of a seismic event causes a redistribution of stresses in the surrounding rocks and the stress development takes on a chaotic character, which makes it impossible to apply geomechanical modeling to fully explain the phenomenon.

In Polish underground mines seismological systems have been installed. On the basis of recorded seismological signals, the location of seismic hypocenters and the energy of the seismic shocks are estimated. A statistical processing of recorded data can be designed to assess the seismic hazard in mines (Lasocki, 2005; Lasocki, 2008; Orlecka-Sikora and all., 2010; Orlecka-Sikora, 2009; McGarr, 2005; McGarr & Simpson, 1997). The success in extracting useful information from recorded seismological data, in the assessment of seismic risk in mines, is limited due to lack of a stationary set of seismic events.

In the paper it should been shown, that both recorded seismic data and the ratio of vertical and horizontal deformations (roof bending) of roof layer over the exploited area, should be used in the assessment of seismic risk in underground mines.

2. ROOF LAYER BENDING

When there is a strength layer over the exploited seam it's bending produce the stresses in the surrounding of the exploited area.

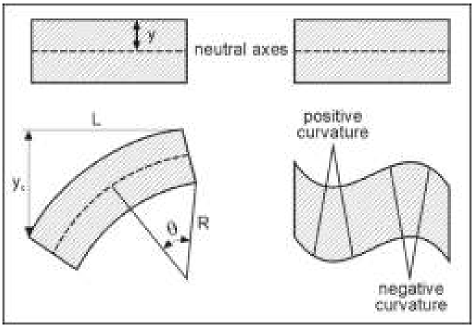

Fig. 1. The beam bendig R - the curvature of the beam. L - distance from the fixed point of beam

When a transverse loaded force stresses the rock beam, the amount of bending deflection depends on the curvature of bending, the value of the force and the beam material properties. The stretched and compressed sides of the beam are opposite when the curvature is changed from positive into negative (Fig. 1).

The bending stress σ_B can be described by the formula:

$$\sigma_B = \frac{M}{I}(y - y_0) = \frac{E}{R}(y - y_0) \qquad I = \frac{mL^2}{12}$$

where M - bending moment (W.L), E - modules of elasticity I - moment of inertia W - load, L - distance from the fixed point of beam $y - y_0$ distance to the neutral axes, R - the curvature of the beam.

From the relation

$$\frac{1}{R} = \frac{M}{EI} = \frac{d^2y_0}{dx^2}$$

the basic equation is obtained.

$$\frac{d^2y_0}{dx^2} = \frac{M}{EI}$$

Budryk (Saustowicz, 1965.) obtained the solution to this equation for conditions, which appear in the underground mines. If p is the vertical stress component in the upper border of the bending layer the solution has the form:

$$y_0 = \frac{p}{c} + e^{-\beta x}\frac{pL}{4\beta^2 EI}(-L\sin(\beta x) + (1 + \frac{2}{\beta})\cos(\beta x))$$

and the vertical stress σ_z in seam can be written:

$$\sigma_z = p - \beta^2 pLe^{-\beta x}(-L\sin(\beta x) + (1 + \frac{2}{\beta})\cos(\beta x))$$

where

$$\beta = \sqrt[4]{\frac{c}{4EI}}$$

c - the elastic compliance.

This equation is used in Poland for estimation of the stress distribution in the roof surrounding of exploited ore. Bending deflection can be controlled with mining means and the exploitation by the room and pillar method allow to designing it.

In this paper the inelastic deformations in the bending roof layer is considered and its connection with seismic emissions in underground mines.

For rocks there are only two possible modes of fracture: namely, ductile and brittle. In general, the main difference between a brittle and ductile fracture can be attributed to the amount of plastic deformations that the material undergoes before fracture occurs. Ductile materials demonstrate large amounts of plastic deformation while brittle materials show little or no plastic deformation before fracture. In this paper the ductile development of seismic emission in underground mines is assumed. Therefore, the elastic deformation of the bending roof layer is discussed.

When the applied stress exceeds the elastic region in the stress-strain relation (Fig. 2) the narrow stress interval of the plastic deformations is reached. There are stages of the plastic deformations such as plastic proportional limits (where the elastic deformation starts), yield stress (for which the material begins to exhibit a permanent deformation), and the ultimate tensile strength (the maximum stress that can be withstood by a structure suffering tension).

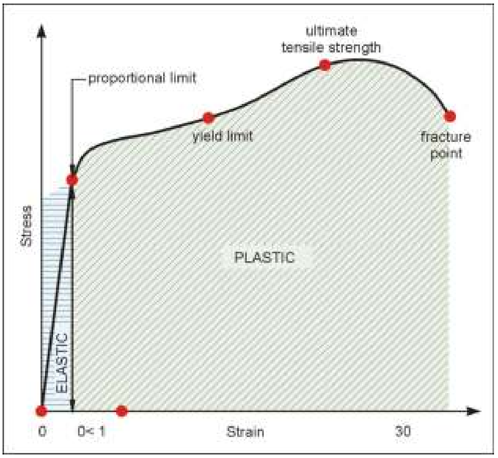

Fig. 2. The elastic and plastic regions in stress-strain relation

The plastic deformation during the roof layer bending phase develops in a specific way.

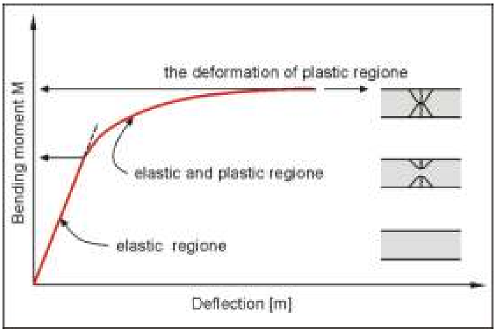

Fig. 3. The plastic deformation during bending of the roof layer

As the bending loading momentum is gradually increased the greatest stresses occur at the extreme (margins) parts of the roof layer. As shown in Fig. 3 the plastic deformations starts from the outer parts of the roof layer whilst the inner section is still elastic. An increase in the strength of bending momentum causes the penetration of plastic regions into the central parts of the layer. These outer parts of the layer then change into a plastic state in many horizontal areas, along the line of maximum bending (lineament). The stresses below the yield point in the plastic region are constant. An increase in the bending momentum results in a considerable increase in strain and deflection at the corresponding plastic section of the layer. When most of the cross-section along the lineament is plastic then the moment of resistance drops and the deflection, which can be measured as a convergence of the exploited area, should increase markedly. There is also a redistribution of stresses. It can be assumed that plastic deformation has a ductile form. Release or dislocation creeps along with enhancement of the deformation due to high stresses is observed, and the intensive increase in shear stress leads finally to the rupture appearance, thereby producing the seismic energy relaxation. The horizontal distribution of plastic volume and seismic events along the lineament develops but as was also shown above, deep penetration by the rupture is expected.

3. ACTIVATION OF SEISMIC ZONES

As a result of ductile deformations just before the seismic event, the stage called “hardening” (Fig. 4) is reached. At such a stage (Rice and Ruina 1983; Rice; 1980) the shear stress τ increases very rapidly (Fig. 4) with only slight deformation. In practical terms the hardening stops deformations, and in particular the bending deflection.

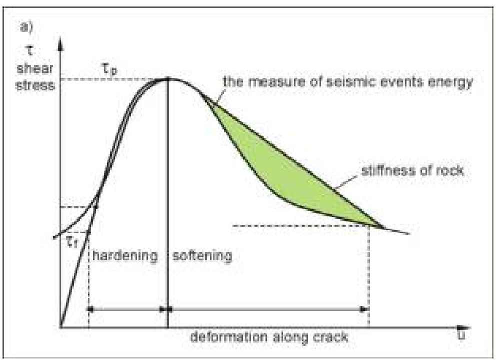

Fig. 4. The relation between shear stresses and deformation along the plane of rupture

After obtaining shears value $\tau_{p,}$ in the second stage of deformation known as “softening”, the very intensive deformation and intensive deflation of the roof layer is associated with seismic energy release. The effect of the seismic energy release can be described with the use of the seismic moment M where

$$M = \mu.\overline{u}.\Sigma$$

where μ - module of rigid, Σ - the area of rupture on which seismic energy is realized, $\overline{u}$ - the average displacement on the Σ surface.

The most important element influencing the seismic moment and energy E of the seismic event can be written as:

$$E = -\vartheta.M\overline{\delta}/\mu$$

where $\overline{\delta}$ - the average stress drops on the rupture and ϑ - the efficiency of seismic process. In the most of the cases it can be generally accepted that the energy of the seismic event is proportional to the Σ.

The strength of roof layers in copper mines in Poland varies (observations from these mines are discussed in the paper) and the thin sub-layers can be distinguished in their structure. Bending of the roof layer causes ductile fracturing of the outer sub-layers in the beginning. Then as is shown in Fig. 3 the fracturing is extending into the inner part of the layer. The extension is also related to the increase in the potential Σ surface and increased strong seismic event probability.

The seismic events registered in Polish underground mines have the form of swarms. The general dynamic equations to describing the temporal variation of mining shocks occurrence have form (Oshuri, 1993).

$$\frac{dn(t)}{dt} = n(t)(\alpha - \beta n(t)) - \int_{-\infty}^{t} n(s)h(t-s)ds$$

where n(t) - denotes the number of shocks, t - time, α - parameter describing production rate, β - parameter describing the reduction of shock production, h(t) - denotes the effect of hysteresis in appearance of the shocks. In the simplest case, when h(t) = const. and β = 0, the number of shocks gradually increases and then decreases. This represents a structure of swarms related to one lineament in the seismic mining emission.

The parameter α is greater than zero when the inelastic deformations in the roof layer take the form of seismic emissions. The swarms start from events having lower energy levels and located outside the neutral line. Then seismic emission develops with the increase in strong seismic events probability and the movement of the seismic source into the inner part of the layer.

The following structure of seismogenic process due to ductile bending of the roof seam can be obtained:

- Elastic bending gives a small, stable deflationary.
- The ductile deformation on the lineament causes an increase in deflation. Then the generation of seismic emission starts from the external parts of the bending beam (its top or bottom).
- The horizontal extension of seismic fracturing is expected at the beginning of the generation

process.

- As a result of increased stress or creeping on dislocation, development of the ductile fracture proceeds inwards in the roof seam.
- The seismic moment and energy of the seismic event, proportional to the surface of active rupture, can increase rapidly. Due to stress hardening, the deflation should stop before a strong seismic event.
- After a strong seismic event due to stress softening, the deflation phase increases intensively.
- The bending resistance decreases gradually with an increase in the plastic area within the layer cross-section and bending is faster.
- The breaking layer stops the seismic emission. This process can be repeated again on the same or other lineaments.

4. THE CONDITIONS IN WHICH THE DATA WERE COLLECTED

The data presented in the paper were recorded in the "Rudna" mine, Lower Silesia, Poland. The Rudna mine is exploited in deposits comprising three lithological rock zones with copper mineralization; namely: Rotliegendes sandstone, lower Zechstein shale and dolomites. The deposit ore seam thickness varies from 0.5 to 20 m. Exploration is based on the room and pillar method with extra roof support, and partly with the elimination of cavities by rock or hydraulic backfilling and a controlled roof seam bending programme. The ore has been excavated at the depth 850-900 m.

The ore roof is built of beige or gray dolomite, and is very solid, with styloite joints, which can facilitate fracturing. There are also 3,5 cm diameter nets of anhydrite. As it is shown in this Figure 5 there are numbers of banks, which can easily divide the layer into sub-layers (Goszcz 1985).

A seismological measuring system has been installed in the mine and seismological observations have been recorded continuously. Measuring seismological systems record seismological waves throughout the whole mine. The recorded signals are used for the location of event hypocenters and their energy estimation. Seismological catalogues containing times of seismological event occurrences, the coordinates of event hypocenters and their energies are the basis of our considerations.

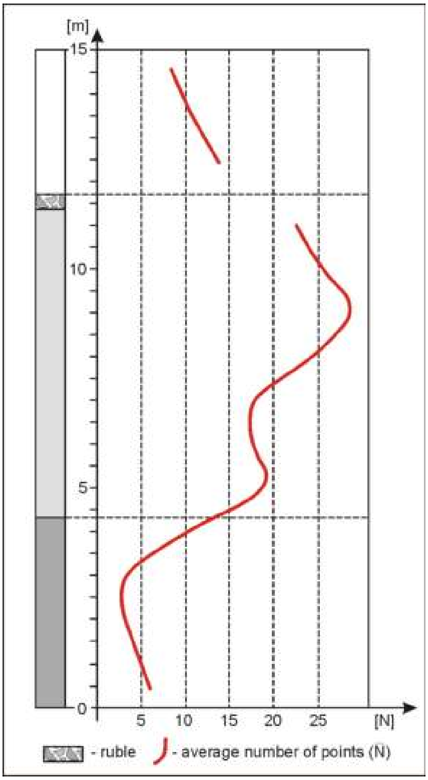

Fig. 5. The distribution of bank numbers across the roof layer divides the rock into plates

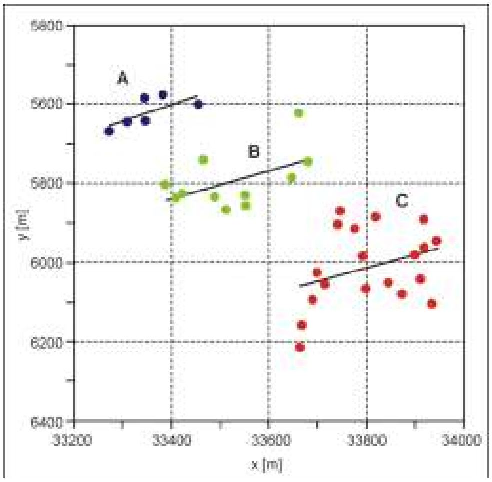

Fig. 6. The position of seismic events during exploitation in the Rudna mine division X/1 between 2005 and 2010 years

The absolute (rather uncertain) and relative values of hypocenter coordinates (with greater accuracy) can be considered. In the paper, trends of the relative strong seismic hypocenter depths are discussed and that makes the measured data more significant than the relative depth of the hypocenter. The example of time distribution of recorded data is shown in Fig. 7 including the total number of seismic events for a full range of energy and energy greater the 10^5J. The position of the epicenters on the mining plane is shown in Fig. 6.

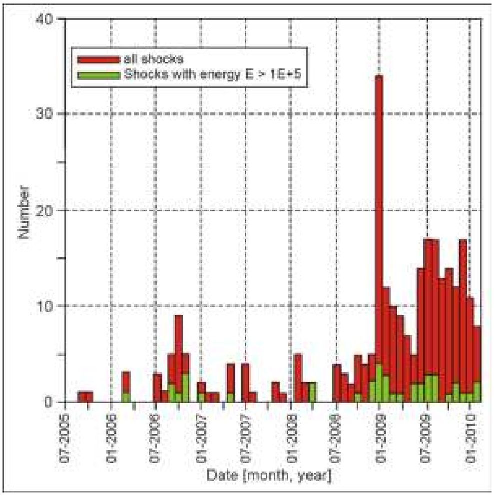

Fig. 7. Time distributions of the seismic events number in Rudna mine division X/1 between 2005 and 2010 years

5. MINING OBSERVATIONS

There are mining observations that show the results of ductile deformations.

Orzepowski (1998) carried out the measurement of roof deformation in a copper mine, with the sensors measuring changes in a borehole diameter in fixed horizontal directions. His results provide reliable evidence to demonstrate the development of ductile deformation in roof strata. Strain sensors are installed at two depths; 10 m and 30 m above the exploited area (dD10 m and dD30 m in Fig. 8). From 25.01, a diameter at dD10 m increases, while dD30 m decreases, thereby suggesting that the roof is bending down or buckling above the roof of the exploited area. Ductile deformation in this case produced a deformation lasting 15 days. This example is chosen from many measurements, with most cases measured only with sensors 30 m deep. Significant deformations as shown in Fig. 8, usually appear about 10 days before the strong seismic events appear (Orzepowski, 1998).

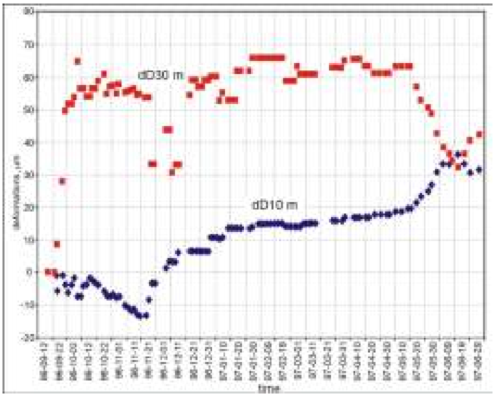

Fig. 8. Temporal change in diameter of a vertical holes at depths of 10 m and 30 m in a roof in a copper mine (after Orzepowski 1998)

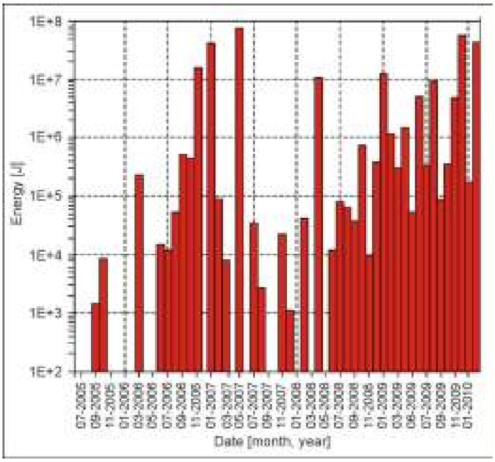

Fig. 9. Time distributions of shocks energy in Rudna mine division X/1 between 2005 and 2010 years

The relation between the convergence value (the tightness of exploited area) and the seismic activity depends on the inclination of the rupture (if rupture is horizontal there is very small relation). However in many cases the vertical component of rupture is important and the convergence can be used for seismic risk estimation. The convergence before a strong seismic emission, in one of copper mine has been analyzed in the paper (Gogolewska and Bartoś, 2008). The average convergence of 4 mm/day increased regularly before a strong seismic shock of up to 7-10 mm/day. However a sudden drop of this value was observed just before a strong energetic event, down to 1 mm/day. After strong seismic relaxation the convergence was increased up to 30 mm/day. The proposed ductile bending roof layer can explain these observations.

6. SEISMIC OBSERVATIONS

Two catalogs of seismic data are discussed in the paper.
The first catalog consisting of observations from the mining region X/1 in the period 1.07.2005-9.02 2010 has 262 records, and 33 data related to events with energy greater than 10^5J. The shocks energy distribution and the shocks number distribution in time are shown in Fig. 9 and Fig. 7.

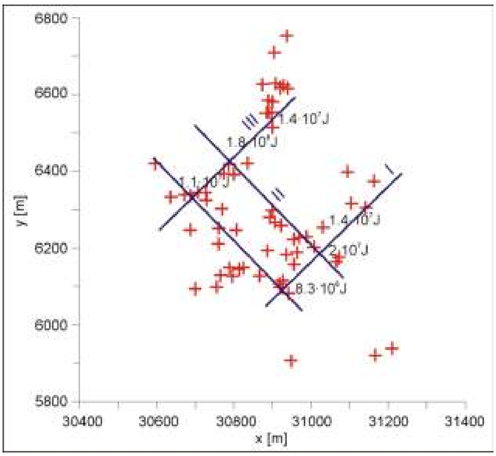

Fig. 10. The space distribution of seismic events in region 7/1

Fig. 11. The space distribution of seismic events in region X/1

Three linear elements can be distinguished describing the space distribution Fig. 6 and Fig. 11 of the seismic epicenters. The first two are related to the initial period of intensive seismic activity, and the third to the second period.
In the second catalog, which is a set of seismic data from March 2000 to February of 2003 recorded in 1/7 divisions, four periods of intensive activity can be recognized (Fig. 12). The first of them comprise records from the year 2000, the second from June-August 2001, the third from December 2001 - January 2002, and the last from the end of 2002.
Three lineaments are appointed (Fig. 10). The first period is related to the first lineament, second period to second lineament whilst the third and forth period are connectred to the third lineament.

7. DISCUSSION OF THE SEISMIC DATA

The discussion of seismic data is based on the strongest seismic events with energy over 10^5J.

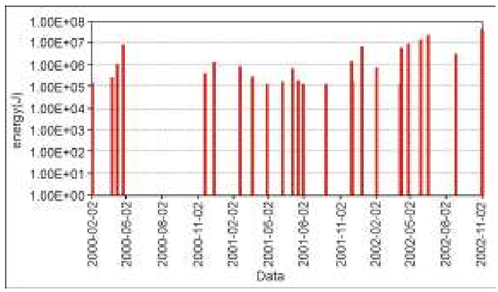

Fig. 12. Time distributions of shocks energy in Rudna mine division 7/1 between 2000 and 2002 years

There are two reasons for such a decision. From one side the area at which such seismic energy is realized is large enough to be treated as the area of plastic deformation in the roof layer. On the other hand the accuracy of estimation of a weak seismic events hypocenter is small, due to the complicated structure of the wave field.
The hypocenters of seismic shocks localize at the beginning of the seismic rupture. The development of the depth of hypocenters shown in (Fig. 13) is treated as the expected position of the plastic volume during bending of the roof layer. In all periods of intensive seismic activity, the hypocenters move in unison from the bottom and top of the layer, in the first stage of seismic activity, and reach the middle central line of the bending in the second stage, where the largest energy is released and the strongest seismic event is found. This process is repeated for all lineaments.
The movement of the hypocenter from the external parts of the roof seam into the center prior to the strong seismic event is evident here. Also such a conclusion can be obtained from the observations in 1/7 region in the period 2000 - 3003 (Fig. 14).

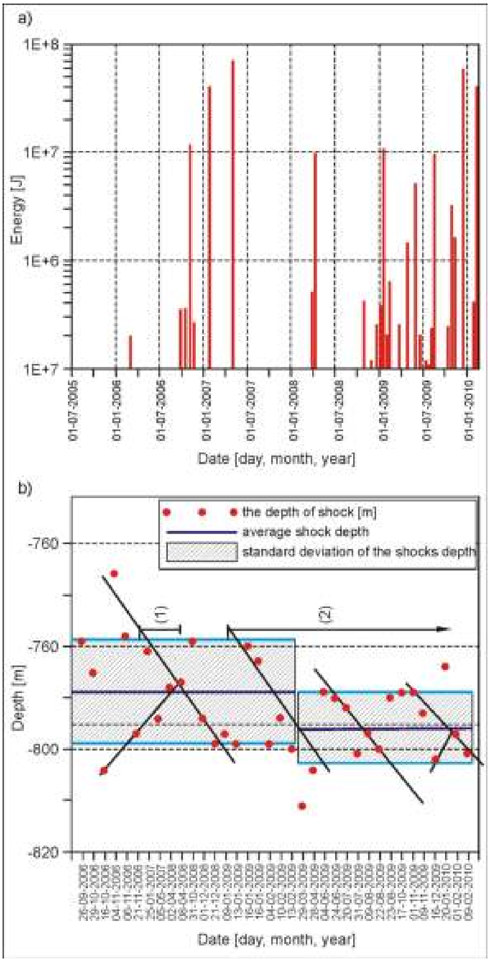

Fig. 13. The time distribution of the strong seismic events (a) and the distribution of the hypocenters depths (b) from the seismic catalogue X/1

Activation of each lineament (after a long period of small activity (Fig. 14c) begins as the emission of the strong seismic events located up and over the main line of seismic relaxations hypocenter depth. The strongest energetic relaxation is always preceded by a downward movement of hypocenters into the central line in the roof layer (Fig. 14a). Also, the relaxation along one lineament has the form of a swarm and is very intensive in the final part of the deformation phase.

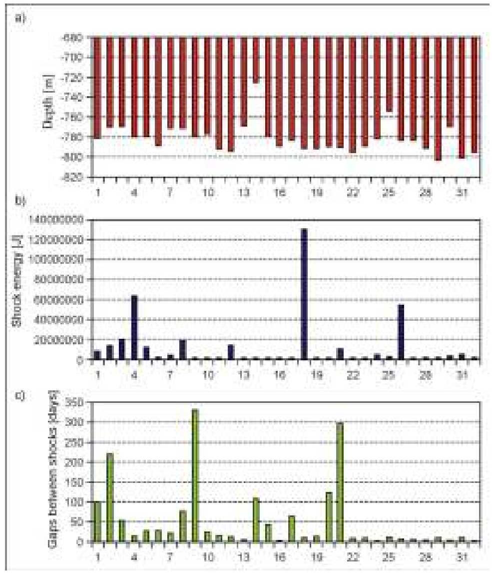

Fig. 14. The distribution of seismic events energy (a)and depth of hypocenters (b) for the catalogue X/1

8. CONCLUSIONS

The rockbursts in underground mines in Poland are dangerous and their appearance is often associated with the distressing news that miners have been badly injured or killed. Unfortunately the assessment accuracy of the rockburst risk is limited, due to the chaotic nature of the seismic emission process. The statistical processing of registered seismic data allows for the extraction of useful information related to the risk of a strong seismic event. The use of registered mining measurements and the depths movements of seismic hypocenters can help improve determination of seismic risk in the mines, where bending of the strength roof layer is the main source of seismic emission.

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