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Relationship between focal mechanism parameters of mine tremors and local strata tectonics

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The research was aimed at establishing a correlation between the local field of tectonic stress obtained from tectonophysical investigations and the distribution of stresses σ_1, σ_2 and σ_3 obtained from the seismological analysis of the focal mechanism parameters of mine tremors. The investigations were carried out in an area characterized by the developed fault tectonics and high seismic activity. The results obtained indicated that a distinct relationship exists between the focal mechanism of tremors and the local tectonic field. For the majority of the investigated tremor sources, shearing processes occurring on a normal fault (the proportion of the shearing component being from 75 per cent to 90 per cent) were found to dominate the mechanism. In addition it was found that the likely fault slip planes at the focus correlated well with the strikes of individual faults referred to as faults II, III, IV and the Klodnicki fault. The local field of stresses σ_1, σ_2, σ_3 defined by the tremor focal mechanisms are similar to the stress field derived from the traces of existing tectonic structures.

Introduction

The investigations were carried out in the area of the Halemba hard coal mine, which is characterized by a high level of seismic activity, and by the occurrence of numerous tectonic structures. One of the main structures is the Klodnicki fault zone, which strikes in an approximately EW direction and is characterized by variable throw and variable angle of dip. The Klodnicki fault forms part of a system of faults having very variable throws, strike traces and sizes. Complicated tectonics, such as this, has a great influence on the nucleation of seismic events in the area. The data set of recorded mine tremors can be classified into the following distinct groups:

- typically mining phenomena (low and medium magnitudes, M_L<2.2
- 'regional' phenomena (high magnitudes, M_L>2.2) that occur mainly in the fault zones.

To evaluate the influence of local rock mass tectonics on the source mechanisms of the mine tremors, focal mechanisms were determined using the seismic moment tensor inversion method formulated by Wiejacz[6]. This work confirms that the source processes of the tremors are distinctly influenced by the field of tectonic stress that exists in the rock mass.

Tectonophysical conditions of the test area

The study area is located in the southern limb of the main saddle, which is a very complicated structure. It consists of a series of elevations and dome folds, with concurrent axes, separated by elevations or similar transverse structures. Additionally, these structures are crosscut by a number of normal and reverse faults. The majority of large faults cutting the main saddle are of the Variscan age. Some of these faults were rejuvenated later, i.e. during the Mesozoic era and the Tertiary periods. In the investigated area, it is possible to distinguish three systems of faults: (1) with EW, (2) NS and (3) NE-SW trends.

The Klodnicki fault falls into the first system (having an EW-trend) and is probably of Variscan origin and was rejuvenated during the Miocene (Figure 1.). It is characterized by a variable throw and dip. Generally, the strata to the south of the fault are downthrown. The throw amplitude ranges from 360 m in the eastern part and decreases to about 20 m in the west. In the test area, this amplitude was about 100 m. The Klodnicki fault is accompanied by a number of minor faults with throws from several metres to more than ten metres, which are step or fan shaped, as well as second order faults with throws from more than ten to several tens of metres. There are also discontinuous deformations of small lengths, up to 150 m, which are referred to as 'plume' faults. The accompanying faults differ in both the strike orientations and the throw amplitudes. The fissures of the Klodnicki Fault and of the accompanying faults are filled with fault breccia of sandstones, mudstones and a coaly substance, as well as blocks of sandstone.

The system of multi-directional lower-rank faults, accompanying the Klodnicki fault, divides the investigated area into a series of tectonic blocks of different size which are displaced one against the other, in both the vertical and horizontal sense. In general, one can conclude that this area is susceptible to various types of deformation resulting from geological events in the past and the more recent extraction of the coal seams.

The second fault system in the area has a NS trend. These are the faults marked as II and V in Figure 2. Fault III partially belongs to this system. The interesting feature associated with these faults is that they often split into a number of smaller faults in the zones where they connect with other faults. The magnitudes of the throws of these features are variable and range from 5 to 120 m, while the

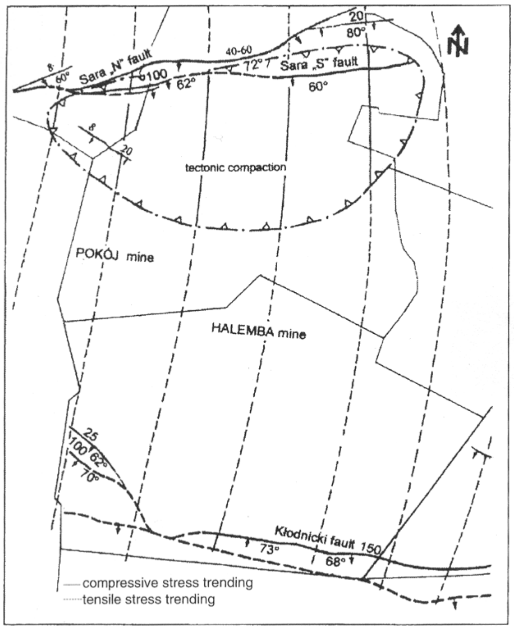

Figure 1. Tectonic stress field induced ground failure I system parallel trending faults

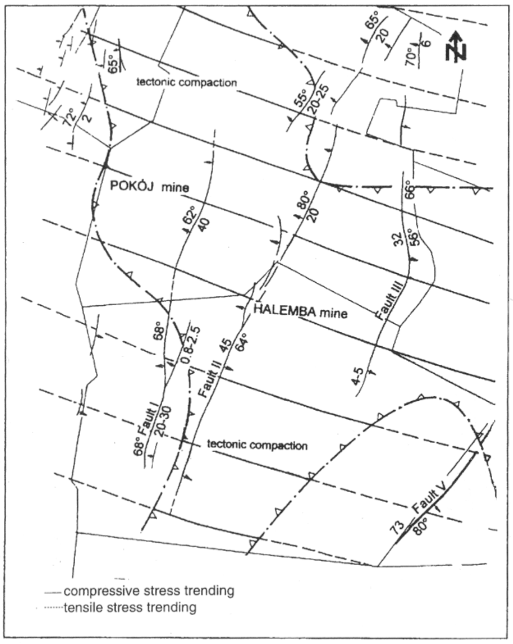

Figure 2. Tectonic stress field induced ground failure II system meridional trending faults

rock mass strata are thrown in either the W or E directions. The dip angles of the fault planes show similar variability and range from 40° to 90°, and the width of the zones varies from the north to the south.

The third fault system, having a NE-SW trend, displaces the strata to the NW or SE and has throws within the range 0 to 30 m (Figure 3). These are relatively steep faults with dip angles ranging from 20° to 70°. Fault IV and part of fault III belongs to this fault system. Fault III has a variable trace and is characterized by throws increasing from north to south, in the range 5 to 30 m. The fault throws the strata to the SE. The dip angle of the fault plane shows similarly variability, changing from a very flat to very steep dip (i.e., from 20° to 70°) but, in the test area, it has a low throw amplitude of 8 m.

Each of the specified fault systems was created as a result of interaction between the tectonic stress field and the rock mass structure. In this case, the stress field can be described by three principal stresses, where σ_1 represents the major stress, σ_2 the intermediate stress and σ_3 the minor stress. The reconstruction of the stress field responsible for forming the described fault tectonics in the investigated area was based on the data characterizing the pattern of fault orientations, cleavage direction, and the occurrence of complementary faults. It was measured using tectonophysical methods[4]. Assuming that the principal stress σ_1 was in the vertical direction and that the direction of the intermediate stress σ_2 was close to the traces of faults on the maps, the trajectories of minor stress σ_3 were determined. Then, the zones of tectonic compaction were found, i.e., the occurrence of the state where on the one hand, all three principal stresses were compressive and, on the other, where the minor stress was tensile (Goszcz[3]). Figures 1, 2 and 3 present the trajectories of the tectonic minor stress σ_3 associated with the three distinct systems of faults (with the EW, NS and NW-SE trends).

Results of focal mechanism analyses of mine tremors

Coal mining in the study area had been conducted for a

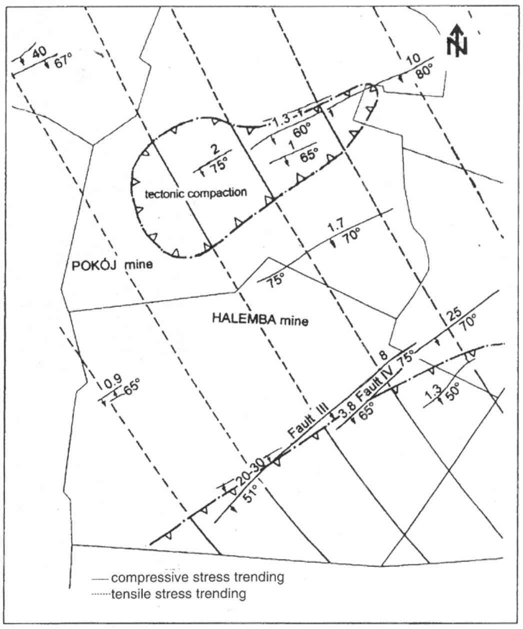

Figure 3. Tectonic stress field induced ground failure IIi system NE-SW subparallel trending faults

unambiguously say that there is a good correlation between the fault plane solutions of the tremors and the strikes of these faults. In general, the focal mechanism of the tremors under consideration, in the case of the full tensor solution, comprised less than 10% implosions, about 10% uniaxial compression and 75% to 90% shear component. The remaining solutions (deviatoric tensor and double couple of forces) indicated that a shear process dominates the normal faulting, as the component of uniaxial compression amounted up to 15%. The best-fit solution was obtained for tremors in the depth range 800 to 900 m. In these cases, both the type of the focal mechanism and the depth of tremor source location clearly show their fault character, reflecting the processes connected with the loss of the rock mass stability in the area of occurrence of complicated tectonic structures. An example of the focal mechanism solution, on the background of tectonic structures in the area, is shown in Figure 4.

Results of an analysis of the regional stress field

Mine seismology provides the only practical method to measure parameters to understand the physical processes that take place in the source regions. The parameters of particular importance from a tectonophysics point of view, which may be determined using specialized interpretations of seismological data, are the directions of the axes of principal stresses σ_1, σ_2, σ_3, and the parameter R which indirectly characterizes the stress relations.

These parameters can be determined from the results of the focal mechanism solutions. To perform such calculations, the FMSI computer programme[2], for the calculation of the angular parameters of the stress field, was used. The output includes the azimuth and rake angles, from which the directions of the axes of principal stresses σ_1, σ_2, σ_3 are determined, after which the parameter R, according by Etchecopar[1], can be computed using:

$$R = \sigma_2 - \sigma_3 / \sigma_3 - \sigma_1 \qquad [1]$$

If $\sigma_1 > \sigma_2 > \sigma_3$, the parameter R falls in the range $0<R<1$: when $R<0.5$, the compression processes dominate; when $R>0.5$, the extension processes dominate. The relationship between the vector of slip on the fault plane and the directions of the axes of principal stresses σ_1, σ_2, σ_3 was determined by McKenzie[5]. The solution was based on the assumptions that the failure process develops along a definite plane and that the vector of slip was parallel to the shear stress acting tangentially on this plane.

The data used for calculations were the results of the focal mechanism study, in which the angular parameters of the axes of principal stresses P and T (azimuth and dip) were determined. The focal mechanism solutions (Table I) were divided into three data sets characterized by similar

Table II
Angular parameters of principal stresses
Az-azimuth, P-plunge, R-parameter

No of data set	σ_1		σ_2		σ_3		R
	Az°	P°	Az°	P°	Az°	P°	
1	11	68	268	5	176	22	0.8
2	238	56	350	17	28	90	0.2
3	215	16	316	33	103	52	0.6

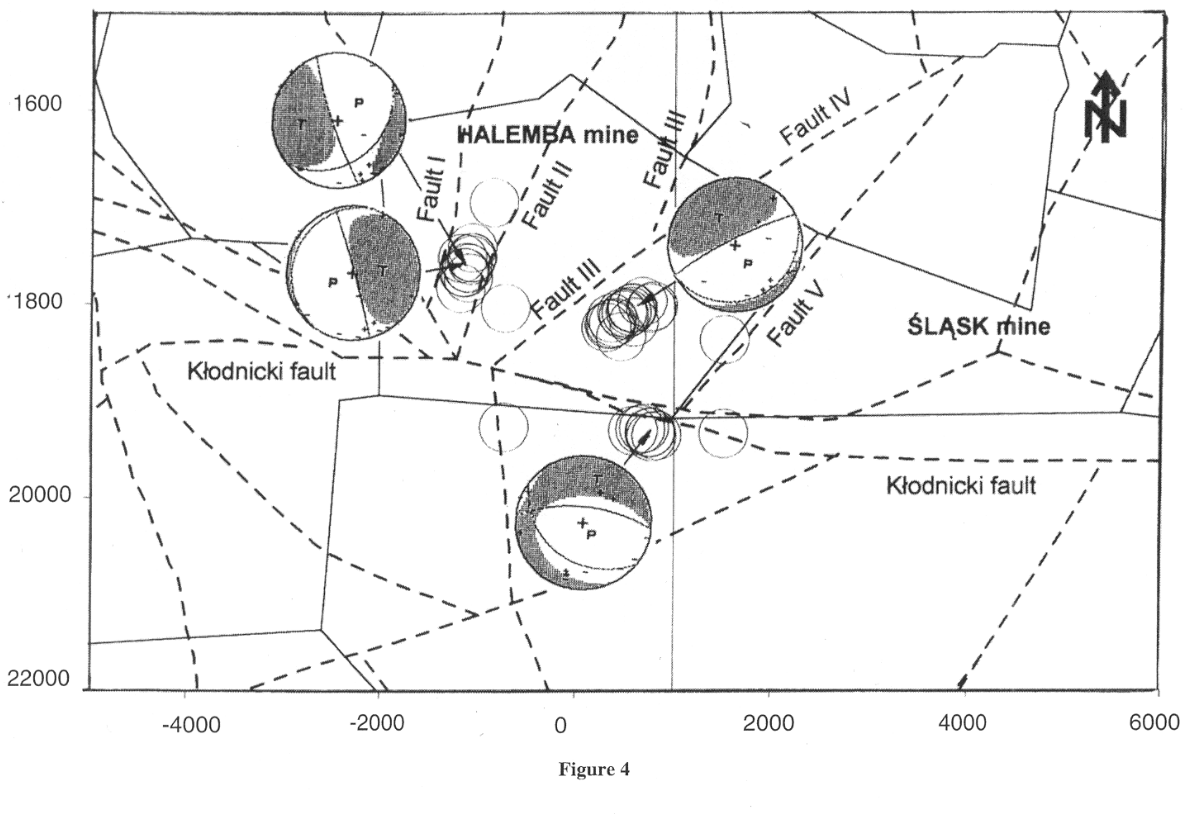

Figure 4

source locations. The tremors of data set 1 occurred in the area of Klodnicki fault which is part of the failure system having an EW trend, data set 2 comprised the tremors occurring in the proximity of faults I and II (NS), and data set 3 comprised the tremors occurring in the area of fault III (NE-SW failure system).

The angular parameters of the principal stresses σ_1, σ_2, σ_3 (azimuth and plunge) and the coefficient R were determined for each of the three data sets. These parameters were found to correlate with the field of tectonic stress characterizing each failure system (Table II). The error of fit for the results obtained is +20°.

Interesting relationships, which support the idea that the presently occurring mine tremors induced by mining activities are influenced by the same fields of stress that influenced the formation of the tectonics in this area, were found. It can be assumed that the phenomenon observed here is due to the 'memory of the rock mass' which manifests itself despite the assumed total relaxation of tectonic stress. It causes the rock mass to be prone to the types of failure similar to those that occurred in the far geological past.

For data set 1 (consisting of the tremors occurring in the region of the Klodnicki fault) the distribution of the local field of stress obtained from the analysis of tremor focal mechanism is similar to the regional stress field in the area. Tensile stress dominates this field, evident by the value of coefficient R being equal to 0.8. The major compressive stress σ_1 is approximately vertical (the plunge is about 70°); the intermediate σ_2 and minor σ_3 stresses are close to horizontal (they plunge at 5° and 22° respectively). The orientation of σ_2 is close to E-W (azimuth 268°) and that of σ_3 close to N-S (azimuth 176°). The dominant type of focal mechanism in this data set is normal faulting, where the fault plane has an E-W strike and it dips steeply at ~60° (Figure 4). A tectonophysical analysis for this area (Figure 1) has revealed the occurrence of mainly extensional processes. The minor stress, σ_3, is tensile, and it trends N-S.

A different stress field characterizes the region of occurrence of tremors in the zone with the NS oriented system of faults—system 2, data set 2. The local stress field calculated from the mechanisms of mine tremors indicates the domination of compressive processes. In this case, the coefficient R is equal to 0.2. The compressive stress σ_1 is oblique (plunge ~55°), the intermediate stress, σ_2, with azimuth of 350° is nearly horizontal and the minor stress, σ_3, is also close to horizontal and trends E-W. The focal mechanism describing most of the tremors was of the normal slip type. The azimuth of a selected focal plane had a NW-SE trend and its dip was about 85°. The tectonic stress field in this area shows typically compressive features and indicates that this is an area of tectonic compaction. The trajectory of tectonic stress σ_3 is approximately E-W trend (Figure 2).

The mine tremors associated with the sub-parallel (NE-SW) system of tectonic structures (data set 3 of tremors) occur at the boundary separating an extension zone from a compression zone. The coefficient R for this area is 0.6. Here σ_1 (azimuth 215°, plunge 16°) is nearly horizontal, the intermediate stress, σ_2, (azimuth 316°, plunge 33°) and the minor stress, σ_3, (azimuth 103°, plunge 52°) are oblique. When analysing the tectonic stress field in the area of fault III (Figure 3), it should be noted that the boundary of tectonic compaction borders on fault III, which is probably reflected by the type of focal mechanism of mine tremors. The azimuths of selected fault planes of the sources trend NS-SW and these faults are characterized by a steep angle of dip of about 85°. The focal mechanism is of the normal type with marked horizontal slip movement.

The correlation performed between the distribution of tectonic stress field and the stress field obtained from the mine tremor focal mechanism solution indicates that the tectonic stress field is a basic factor influencing the source rupture process. The tremors occur in weak fault zones in the rock mass which is in a state of virgin stress, and the fault planes in the source can be correlated with the trajectories of intermediate stress σ_2. This results from the fact that, keeping in mind tectonophysical aspects, it is argued that the direction of rock weakening under the influence of tectonic stress is perpendicular to the trajectory of stress σ_3, i.e., it is in accordance with the direction of stress σ_2.

It follows from the analyses performed that the knowledge of the stress field distribution is very useful for the purposes of prediction and evaluation of the seismic hazard in mines.

Summary

The performed investigations revealed that a clear dependence of parameters of the focal mechanism of tremors on the local tectonics. This was confirmed by an analysis of the results of specialized tectonophysical investigations and by the data obtained from determining the distribution of principal stresses σ_1, σ_2, σ_3 obtained by the seismological method.

The investigation area is characterized by a dense network of faults, both of a regional character, with long strike lengths and a range of throws, and local character with minor throws. Three systems were distinguished having EW, NS and NE-SW trends which, according to the tectonophysical analysis, had originated from a variable field of tectonic stress. Not only did this stress field influence the formation of the tectonics of the area but it also resulted in the creation of definite properties of rocks surrounding the coal seams, which led to the present character of mining-induced seismicity.

The past and currently conducted mining of coal seams in the area under study, performed with a varying intensity in the northern block of the Klodnicki fault, resulted in uneven undermining of coal seams in the upthrown and downthrown sides of the existing faults, which gave rise to the occurrence of high seismic activity.

An analysis of the focal mechanism of strong tremors occurring in the fault zones have clearly shown the influence of tectonic structures on the processes taking place in the tremor sources. For the majority of the investigated seismic phenomena, the shear processes in the sources on normal faults were dominant (the shear components range from 75 per cent to 90 per cent), and the possible fault planes in the sources correlated well with the strike traces of the main I, II and III faults and the Klodnicki fault.

An analysis of the stress field performed on the basis of tremor focal mechanism has shown that the determined stresses σ_1, σ_2, σ_3 correspond to the stress distribution reconstructed using the tectonophysical data of the trends of existing tectonic structures.

The results obtained indicate that such analyses can be useful in the assessment of seismic hazard, and, indirectly, of the potential for rockbursts. The methodology applied has great possibilities for practical applications and could be used to improve seismological evaluations of seismic hazard.

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