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NEW APPROACH TO THE STUDIES OF THE RELATIONS BETWEEN TECTONICS AND MINING TREMORS OCCURRENCE ON EXAMPLE OF THE UPPER SILESIAN COAL BASIN (POLAND).

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Abstract: The newest results of tectonic investigation within the rockburst regions of the Upper Silesian Coal Basin (USCB) are presented.Close relations between USCB Carboniferous structure and global tectonics are shown. The tectonic activity along deep-rooted discontinuities of crystalline basement are described. Three types of shock focal mechanism found in the USCB are defined on the basis of the fault plane solution of mining tremors. The most reliable model of tectonic regime is discussed explaining these 3 focal mechanisms of shock origination.

Key words: tectonics; fault plane solution; deep-seated faults; horizontal stress; Upper Silesian Coal Basin

1. INTRODUCTION.

The mining tremors and rockbursts closely related to them create one of the most important and not fully solved and rocognised hazards in underground deep mines. Considering the nature of these phenomena there is rather commonly accepted concept that they are induced events triggered by the human activity in this case by mining.

Since last few years it has been commonly accepted that in the statistical population of mining tremors at least two broad types of events exist (Kijko *et al*, 1987; Gibowicz, 1990a; Johnston and Einstein, 1990; Knoll and Kuhnt, 1990; Idziak *et al*, 1991a).

- tremors with lower energy (magnitude) directly connected with mining operations,
- tremors with the largest energy, closely related to geological

discontinuities in the area and regarded as unstable movements on major geological faults due to approaching mining. These types of tremors cannot be distinguished from earthquakes.

The exact distinction of these types is not very easy task because it appears the energy border between them is not very sharp; it depends on the geology of the area, and in geologically different parts of the basins is changing (Idziak *et al*, 1991a).

Since the last few years it is also increasing evidence over the world that mine seismicity is strongly affected by local geology specially tectonics and is a result of mutual interaction between mining, lithostatic and tectonic stresses on local and regional scale (Cook, 1976; Kisslinger, 1976; Gibowicz *et al*, 1979, 1982; Gibowicz, 1984, 1990a, 1990b; Dempster *et al*, 1983; Joughin and Jaeger, 1983; Salamon, 1983; Stiller *et al*, 1983; Potgieter and Roering, 1984; Wong *et al*, 1989; Williams and Arabasz, 1989; McGarr *et al*, 1989).

Although the influence of geological factor for mining tremor generation is widely accepted it wasn't proposed a fully reliable model of the deformation style or state of stress in the rock mass which would allow to correlate in a regional scale the result obtained from seismological studies with tectonical ones.

The determination of the basic features of those relations together with their appropriate physical models create the possibility of quantitative estimation of the seismic events parameters as well as the appropriate methods of their alleviation and prevention. The necessity of the solutions of those problems exist for more safe and effective mining operations.

In some papers the explanation of strongest mining tremors with relation to the tectonic stress field was presented. It doesn't mean the sole influence of this field, but the fact that the human activity (e.g. mining) is the triggering mechanism for the energy acumulated in the rock mass. At present the necessary conditions for mining tremors occurrence can be formulated as follows (Salamon, 1983):

"a) The appropriate region of the rock mass must be on the brink of unstable equilibrium either because

- the presence of suitably loaded pre-existing geological weakness such as a joint, fault, dyke or bedding plane; and/or
- the changing stresses are driving a volume of rock towards sudden failure; and/or
- some support system approaches a state of imminent unstable collapse.

b) Some induced stresses must affect the region in question and the magnitude of these stresses changes, however small, must be

sufficiently large to trigger of the instability.
c) Sudden stress change of sizeable amplitude must take place at the locus of instability to initiate the propagation of seismic waves.
d) Substantial amount of energy must be stored in the rock around the instability to provide the source of kinetic energy.

The origin of this stored strain energy is work done by
- gravitational forces and/or
- tectonic forces and/or
- stresses induced by mining."

Considering all different factors influencing the relations between tectonics and mining tremor occurrence one can classify them as follows (Sagan and Zuberek, 1986):

a) the recent tectonic stresses occuring in the Alpine orogeny areas and their vicinity (Williams and Arabasz, 1989; Wong *et al*, 1989). The influence of that kind of stress was suggested on the USCB area by Kotas (1972) and Kowalczyk (1972);

b) residual stresses caused by tectonic stress in the past, which are subject to progressive stress relaxation with the time (Varnes and Lee, 1972). Sometimes the distinction between recent and residual tectonic stresses is not clear and easy because only the strains as a result of stresses can be measured. The premises indicating on the presence of such stresses in USCB area were presented by Wojnar (1985);

c) stress concentration in some parts of the tectonic structures e. g. the stress concentration in the syncline core or in the downthrown side of normal fault (Isaacson, 1958; Mukherjee and Singh, 1964; Cochrane *et al*, 1964; Gibowicz, 1990a);

d) activation of the existing and stable faults as a result of balance disturbance of rock mass (Isobe *et al*, 1977; Gaviglio *et al*, 1990; Brummer and Rorke, 1990; Holmes and Reeson, 1990), particulary some greater ones, with the regional importance. The fault planes consist of the natural weakening surfaces in the rock mass and the exploatation activity could cause the additional stresses and the condition change on those surfaces, causing instability and propagation of the fault fissure, below or over exploatation level (Gil and Litwiniszyn, 1972). The results of many papers show that the strongest and most destroying mining tremors occur in the vicinity of the faults (Dempster *et al*, 1983; Potgieter and Roering, 1984);

e) changes of physical properties of the rocks as a result of long stress state influence in the past. The above mentioned observations were done in the NE part of USCB area by Goszcz (1980, 1982, 1985) and show that mining tremors occurence is connected with the areas where the rocks were compressed for a long time and repeatedly during past orogenic phases.

2. FOCAL MECHANISM OF THE MINIG TREMORS IN THE USCB AREA

The focal mechanism solution method (determination of nodal planes orientation) is one of the most effective seismological ways to determine the stress state and to compare it with the spatial distribution of tectonic structures. These studies give spatial orientation of supposing fault plane of the shocks which is easily comparable with tectonic data because of similarity of spatial orientation parameters used by both these methods.

The results obtained by Sagan and Zuberek (1992) from the research in the USCB area (Fig. 1) were used as an original data for the comparison procedure between seismological and tectonic characteristics. The analysed tremors (Sagan and Zuberek, 1992) can be

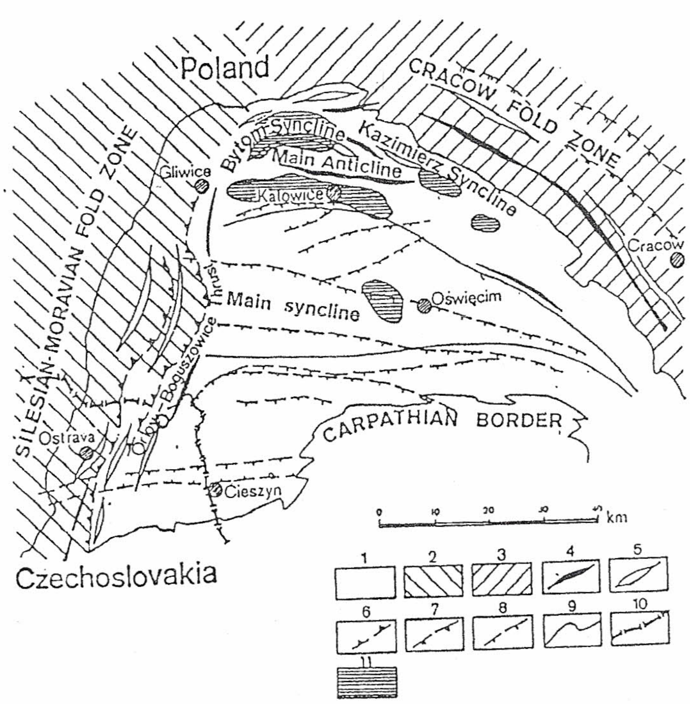

Fig. 1. Tectonic Zones of Upper Silesian Coal Basin

1. zone of disjunctive tectonics; 2. zone of fold tectonics; 3. zone of fold-block tectonics; 4. anticlines; 5. synclines; 6. thrusts; 7. main faults; 8. main Alpine faults or reactivated faults; 9. border of USCB; 10. state border; 11. seismic areas.

divided into three groups according to the different orientation of nodal planes:

a) Both nodal planes are close to vertical orientation, that mean the horizontal movement on the one of these planes occurred (Fig. 2a). The azimuth of strike of at least one of these planes is parallel to the existing disjunctive structures of the USCB area, first of all W-E direction. The direction of the movement on the fault planes is related rather to regional trends, than to local conditions of the slip in the focus vicinity. Most of the tremors has the sinistral, horizontal slip on the latitudinal oriented dislocations, particularly in the Main Anticline Area. Dextral slip component on the NNE-SSW faults is observed in the Bytom Syncline Area.

b) One of the nodal planes has close to horizontal orientation (dip angle to 30°), the second one is almost vertical (dip angle over 70°). There are not the privileged directions of the strike of the nodal planes, and the results of the fault planes solution method are not well documented (Fig. 2b). Most of the observed first motions data are dilatational, that could suggest different type of focal mechanism than pure shearing (f.ex. extension mechanism).

If we assume instead the shear mechanism in the focus, the tremor is probably the result of stresses surrounding the mining excavations (random distribution of the strike azimuth). The vertical plane should be considered as fault plane, as well as the movement vector will be vertical too. The opposite interpretation, that mean assuming that the horizontal planes are the fault planes could suggest the inter-layer displacement.

c) Both nodal planes have a middle dip angle ($40 - 60^{\circ}$) and the strike azimuth vary between 45° and 135° (Fig. 2c). For some tremors the distribution of the first motions data shows the movement consistent with the orientation of oblique-slip faults in the central and southern part of the USCB. A small number of tremors is characterized by the planes with W-E or NE-SW strike.

3. CONCLUSIONS FROM THE STRUCTURAL RESEARCH.

The research of tectonics based mostly on the field observations and the mesostructural measurements has been followed from a couple of years in the same part of the USCB by the team (Teper, 1988, 1990a, b, c, 1992; Ćmiel and Teper, 1988). Its results show that the main tectonic elements of the Carboniferous rockmass were created during the tectogenetic phases following immediately coal-bearing sedimentation and some of them are even syngenetic. It should be emphasized, that a great number of the main disjunctive structures has a nature of the secondary faults, following the older tectonic directions and reflecting the kinematics of the USCB basement block movements. The research followed by the team in the Mesozoic cover of the Paleozoic sedimentary massif both on the USCB area and on its NE boundary proves, that the

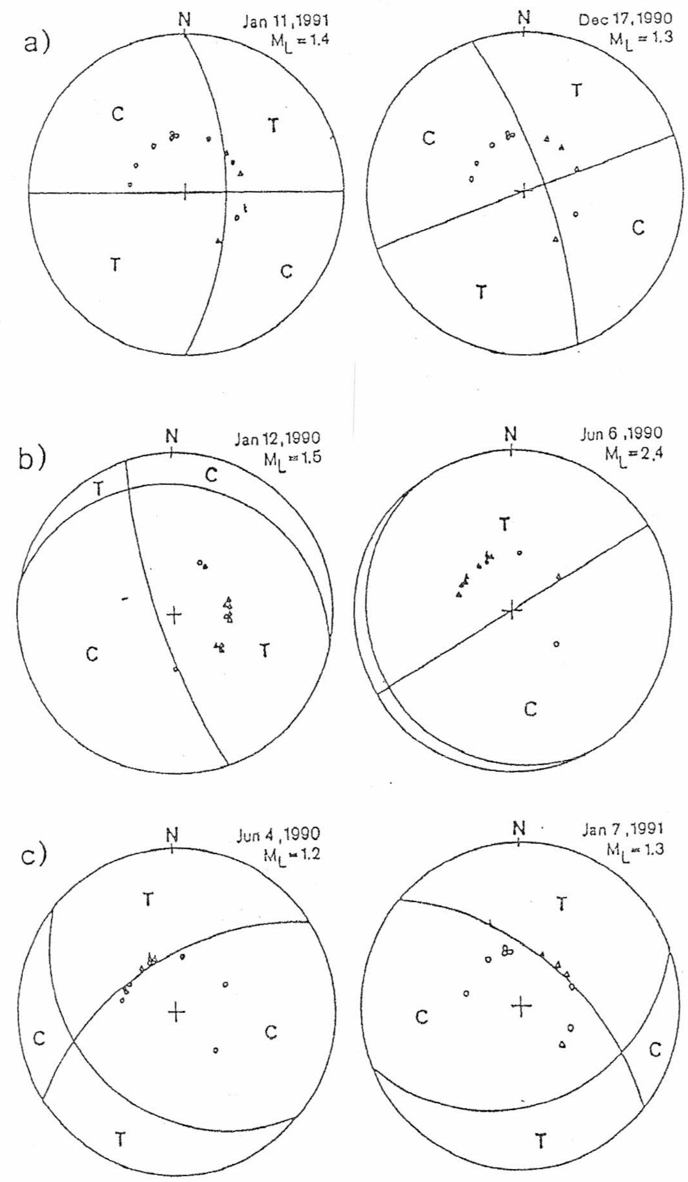

Fig. 2. Examples of Fault-Plane Solution for tremors of Wujek coal mine area (circles denote compression, triangles - tension, lower hemisphere projection)

a) with nodal plane orientations indicating horizontal strike-slip sliding; b) with nodal plane orientations close to vertical sliding on existing normal faults; c) with random distribution of nodal planes orientation.

main structural characteristics in the Alpine stage massif are similar to the ones created before (Teper *et al*,1986; Cabala and Teper, 1990; Idziak *et al*, 1991b). It suggests that the long-drawn influence of the deep basement faults system affects the shape of the tectonics of Silesia-Cracow region. The first rank structure along the NE border of Upper Silesia Massif which presence was mentioned earlier (Bogacz and Krokowski, 1981; Kotas, 1985) played a special part in this problem. The former observations allow to determine the kinematics and the dynamics of this structure and their influence on the rockmass deformation in the USCB and the adjacent region during the Upper Paleozoic and Lower Mesozoic. The activity of this structure (with a different intensity) is not excluded even from Precambrian to Quaternary. The structure called the "Cracow Deep Fault" during Carboniferous and Permian was a dextral strike-slip zone with the minimal horizontal displacement about 90 km. The "Cracow Deep Fault" was the peripheral part of the bigger global fracture, which played a special role in Variscan Foldbelt created on the southern edge of America-Europe Plate that time. The activity of the "Cracow Deep Fault", marked by the periodic succession of transtension and transpression states caused creation of systems of fold and fault structures in the USCB area and its NE boundary. Regularity, geometry and kind of the systems are typical for the strike-slip (wrench) stress field, which model is presented on Fig. 3a.

The structural analysis of the Mesozoic rockmass shows that the inversion of the stress field related to the reversal of relative motion along strike-slip zone took place during the middle part of Middle Triassic. The inversion caused the new type of tectonic deformation in the Mesozoic rockmass, which model is presented on Fig. 3b. A small number of new structural elements was observed then in the Upper Paleozoic sediments. Because of geometric similarity some structures of the Variscan age were renewed. Their rejuvenation created secondary structures in the Mesozoic cover, which caused the seemingly surprising phenomenon of bigger variety of the Mesozoic rockmass tectonics than the Variscan rockmass one.

In the later ages the "Cracow Deep Fault" lost the special significance for the area tectonics. From the Tertiary the above mentioned strike-slip zone is oriented diagonally to the axis of litosphere plates rotation. The new dynamic state of the Earth caused the privileged position for the W-E trending faults (as perpendicular to the global spreading ridge axis). It is referred particularly to the ones which were running tangentially to the fronts of the compressional orogenies created synchronously. The so called "parallel lineaments" suggested by Heyl (1983) in the central and eastern part of American continent occupy such a favorable position, One of them runs further along 50th parallel to the East as a transform fault in the Atlantic ocean crust and then goes across the rift to the "European" part of the Atlantic. It was also detected in the basement of the Bohemian Massif

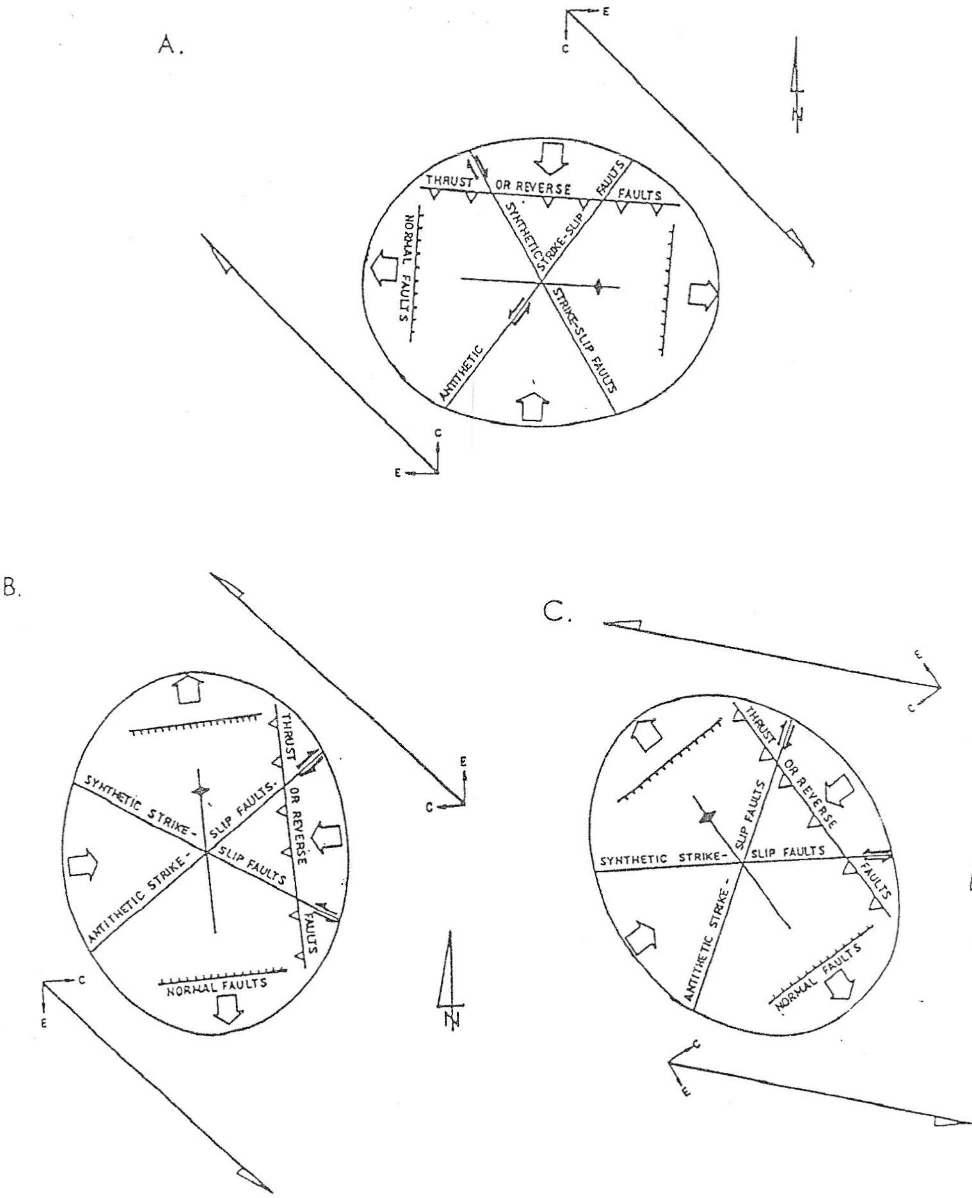

Fig. 3 Structural pattern of USCB
a) in Carboniferous-Permian; b) from middle Triassic; c) from Tertiary.

("the Fifty-north fracture zone" of Kutina, 1976) and its probable extension was suggested in the crystalline basement of the USCB on the Praha-Cracow line (tangentially to the front of Western Carpathians).

In the next step of the structural analysis one can identify some premises of the presence of a latitudinal deep fault structure. The modification of folds and faults geometry, reconstruction of the fault network and some mesotectonic phenomena observed in the folds, flexures, faults and joints allow to show the Tertiary deformation model (c.f. Fig. 3c). The stress field responsible for creating of the new structure pattern is really typical for the tangential acting of force couple causing the sinistral, horizontal displacement of the basement blocks along the W-E direction.

The homothetic strike-slip faults as an important component of this model occur widely on the USCB area as the W-E oriented, secondary sinistral oblique-slip faults. The superposition of the sinistral slip on the former tectonics is well visible in the Malinowice Synclinal Unit, Main Antycline, Jastrzebie Fold, and Knurów Fold.

The sinistral sense of the USCB structures is usually referred to the rotation of Internal Carpathian Massif (Bogacz, 1980; Herbich, 1980; Bednarek *et al*, 1983; Birkenmajer, 1989). Assuming existence of the fundamental "Fifty-north fracture zone", one can notice the correlation between the rotation of the compressive orogeny internal massives (Carpathian Massif) and the rifting (the Atlantic Rift) which is realised by transform faults and continental strike-slip zones. The rifting process and the transform fault one can observe *in status nascendi*, thus above mentioned conclusion has an important significance to consider the present stress state in the USCB rockmass above the deep-seated fault. If we add the information about the recent sinistral horizontal displacements suggested by the geodetic measurements on the surface (Kowalczyk, 1964; Siporski, 1975) and the direct masurements of the horizontal residual stress in the mining excavation (Wojnar, 1985) it can be assumed that the recent tectonic state of USCB massif is unbalanced and related to sinistral fundamental fault activity.

Accepting the strike-slip style of the deformation we should take into account the presence of inter-layer slip which direction, sense and size are determined by the causal movement along the wrench fault. This kind of strike-slip displacement is inherent in the stress field in which both σ_1 and σ_3 components act horizontally and middle main stress - vertically. The model research (Odonne and Vialon, 1983) shows that the displacement of the basement blocks along the strike-slip fault causes the slip on the inter-layer planes in the cover as well as on the basement-cover boundary. During the movement the lower layers of the cover are pulled by the basement stronger than the upper ones. The relative displacement among the cover layers occurs along the horizontal shear planes arising paralelly to the basement-cover contact. The direction and the sense of the shear are related to the direction and to the sense of a tectonic transport along the main fault, however the relative displacement among the cover layers has an opposite sense (Fig. 4).

The events of inter-layer slip in the USCB area have been described (Teper, 1990a, b, c, 1992). There are mainly: horizontal shear zones, tectonic deformation of coal seams and slickensides widely noted on the bed surfaces. The horizontal and vertical slip diversification (Fig. 4) is a reason of arising and modification of the "en echelon" folds above a wrench fault. The shearing nature of the fold structures in the USCB area and the modification of their geometry during the Alpine phases (discrete migration of the fold axis planes in particular bed sets etc.) are the subject of the recent research carried by Teper and his co-workers.

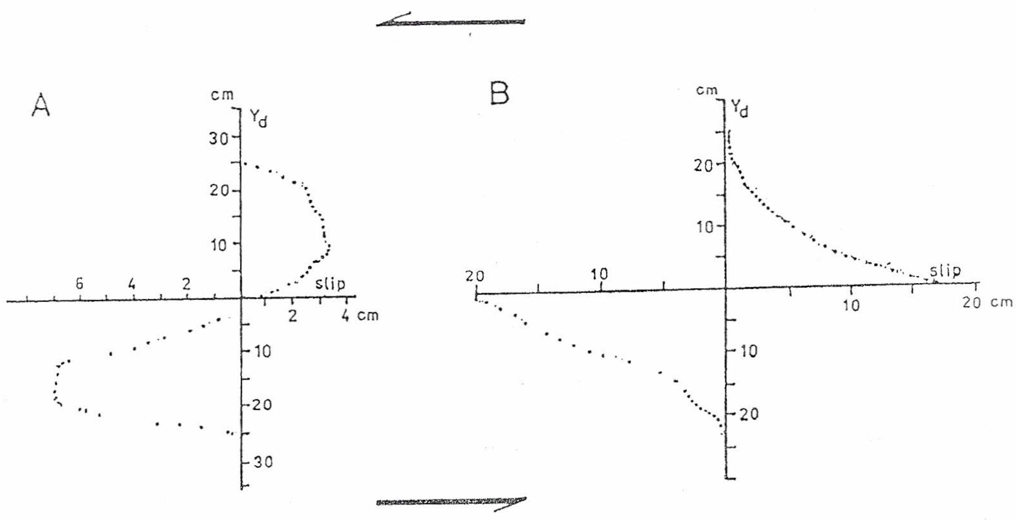

Fig. 4 Inter-layer slip caused by strike slip movement in basement (after analogue models by Odonne, Vialon, 1983)

a) between the cover layers; b) between the cover and basement.

4. THE INFLUENCE OF TECTONICS ON TREMOR OCCURRENCE IN THE USCB AREA.

Possibility of the effect of the relative basement movement on the seismic events occurrencre in the USCB area has already been suggested (Janczewski, 1957). The research on the important role of tectonic directions for anisotropy of elasticity properties of fractured rock-mass was followed by Idziak team (Idziak, 1988, 1991a, b; Idziak *et al*, 1991b; Idziak and Teper, 1992) and its result seems to prove the physical sense of the correlation between the seismic events and the tectonic discontinuities of rock massif. The tensor calculus applied to analysis of azimuthal distribution of seismic wave velocities gives opportunity to compare the different rockmass characteristics and, by the way, to define areas with different elastic rock properties and different tectonic pattern.

The comparison between the general types of the distinguished focal mechanism and the present stress state should be done to determine the eventual relationships between tectonics and the tremor occurrence. The present stress state is similar to the one presented on Fig. 3c. The problem is to determine present intensity of the horizontal movement, which is the base of the calculation of σ_1, σ_2 and σ_3 components. It should be also taken into consideration that the

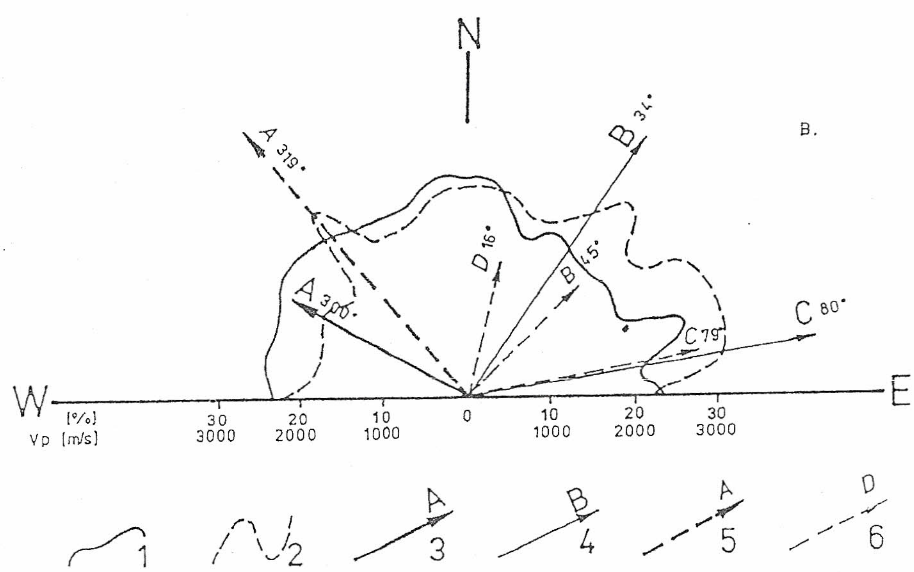

Fig. 5 Analytic view on seismic anisotropy against tectonic structure of Alpine stage deposits

1,2- p-wave front; resultant vectors of 3- first order fault groups, 4- second order fault groups, 5- main joint sets, 6- other joint sets.

deformation presented on Fig. 3c was overlapped on the former state of stress result (Figs. 3a, 3b). Therefore the relaxation of recent stresses could be realized partially along the reactivated older structures. It may be well to add that, in fact, different stress states haven't changed the geometry of the original structural system in general (c.f. Figs. 3a, 3b and 3c). The direct meso- and macrotectonic observation as well as indirect mesostructural study performed using seismic measurements were applied to determine the deformation pattern adequate for the youngest tectogenetic phases - Fig. 5 (Teper *et al*, 1986; Idziak and Teper, 1992).

The relationships between induced seismicity and recent stress state can be interpreted as follows:

a) the sum of mining stress and horizontal component of tectonic stress cumulated on the discontinuity planes can be assumed as the cause of the first group tremors (Fig. 2a). The mentioned discontinuities are mainly homothetic, sinistral, oblique-slip faults with the latitudial orientation and the NNE-SSW oriented antithetic, dextral faults (Fig. 3c).

b) The second group of tremors (Fig. 2b) is probably generated due to superposition of mining stress on tectonic stress originated by the inter-layer slip. It is difficult to show this slip on the deformation model directly. It can be deduced from the orientation of the fold axes created by movement along the main deep-seated wrench fault (Fig. 3c).

c) the inequilibrum state producing the third group of tremors (Fig. 2c) is connected with interference between the mining stress and the vertical component of the tectonic stress. The interference occurs mainly along the dip-slip faults. These fault systems are NW-SE and SW-NE oriented (Fig. 3c). They create the large dispersion of the nodal plane orientations, which was detected.

5. CONCLUDING REMARKS

The state of stresses in the rockmass has an important influence on mining hazard situation and on geotechnical conditions of mining works. The state is determined by the virgin stresses (gravitational and/or tectonic) and the mining induced stresses. It is commonly accepted practise in the rock mechanics that the vertical stress components are assumed to be the largest, neglecting any tectonic forces, considering only the gravitational forces as a main source of virgin stresses in the rock mass. It is a growing evidence over the world that this assumption may not be valid and we can't neglect the tectonic influence even in areas considered as so stable as USCB basin. As a result we have to accept the increase of horizontal stress components at least in some areas and directions what may change the models of tremors occurrence. To this day it is not satisfactory explained if the USCB is a geostatic or geodynamic area. Therefore the corresponding increase of horizontal stress due to depth was interpreted in the qualitative terms on the base of mesotectonic premises (Teper, 1988). The univocal qualification of that question has an important significance for mine design and for safe mining operations. The correlation of the expected in USCB geodynamic zones (and connected recent movements of the litosphere) with the size and directions of neotectonic and/or residual stresses could also have a fundamental significance for the explanation of the mechanism of the strongest mining tremors occurrence in the area. The size of those strongest events sometimes exceeds the local Richter's magnitude $M_L = 4.0$ causing the significant damage on the surface (rarely in the mining excavations). There is no doubt that some number of events is a result of the slip on fault surfaces, due to shear stresses of mining as well as regional origin.

The process of stable or unstable deformation on the faults induced by approaching exploatation will depend on the conditions of fault development, its age, orientation, shape of fault surface and filling of fault fissure. The research and explanation of the relationships between the seismicity of these areas and the properties as well as parameters of fault systems will allow, as we expect, to determine the maximum energy and the maximum reccurrence time for the largest tremors.

Properly designed research connected with appriopriate prophylactic and prevention measures will result in optimal and safe development and exploatation of the deposit especially in geodynamic areas in the vicinity of some fault zones. Also one may expect that the exact explanation of the deformation style and tectonics of the deposit in connection with appropriately designed prevention action (e.g. water injection, destressing blasting) may facilitate the stable energy release and alleviate the existing hazard of sudden, unstable events with large magnitude. In that way one can try to confine the maximum energy or can increase the reccurrence time of the largest tremors induced by mining. The development of the fracture zone surrounding the openings is very important during safe mining at large depth under increased tectonic stress. The tremor and rockburst occurrence and other dynamic energy release events are closely related to that fracture zone formation. Therefore it will be important to determine how this zone is developing when mining approaches active faults. It could be expected that the decreasing extent of the fracture zone would be related to the hazard increase and on the contrary the fracture zone increase would reduce the danger of unstable energy release.

The presented results indicate that the synthetic generalisation of conclusions drawn from different methods of the rockmass properties determination is very important and cognitive. The satisfactory results and their utility prove the sense of research followed by interdisciplinary teams, which assemble mining and structural geologists, tectonophysicists and geophysicists alike.

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