ACTA MONTANA IRSM AS CR (1996)
Series A, No.9 (100), 7–15

RELATIONS BETWEEN SOURCE MECHANISM AND THE RATIO OF S OVER P WAVE ENERGY FOR SEISMIC EVENTS INDUCED BY MINING

Slawomir Jerzy GIBOWICZ

Institute of Geophysics, Polish Academy of Sciences
ul. Ks. Janusza 64, 01–452 Warsaw, Poland

Abstract. There is growing evidence that alternative earthquake mechanisms other than shear failure are possible. In particular, seismic events with non–shearing components are expected to occur in close vicinity to the mining faces, where favourable conditions for generation of shear failures with tensile components are present. The moment tensor approach is in this respect the most general one. A moment tensor can be decomposed into an isotropic part, a compensated linear vector dipole and a double couple. The ratio of S– to P–wave energy radiated from mine tremors, on the other hand, is in many cases anomalously low, and the high P–wave energy tremors are expected to be generated by the sources with prominent non–double–couple components as estimated from the moment tensor solutions.

The relevant data, the source mechanism and the energy ratio, were available for 158 seismic events which occurred at Ziemowit coal mine (63 events), Wujek coal mine (38 events) and Rudna copper mine (22 events) in Poland, and Western Deep Levels gold mine in South Africa (35 events).

The double–couple (DC) component of the source mechanism forms in most cases 60–90 percent of the solution, though more prominent non–double–couple components are also observed. There is a strong negative correlation between the DC and compensated linear vector dipole (CLVD) and DC and isotropic components, characterized by the correlation coefficient as high as −0.9, and not so clear positive correlation between the CLVD and isotropic components with the correlation coefficient equal to 0.6. The relations between the ratio of S– to P–wave energy and the indicators of a DC, a CLVD and an isotropic components in the general solution are not as straightforward as might be expected. Although there is a positive correlation between the energy ratio and the DC indicator, and negative correlations between the ratio and the CLVD and isotropic indicators, the correlation coefficients in all three cases are small, not exceeding 0.4.

1. Introduction

Recent results from earthquake focal mechanism studies indicate growing evidence that alternative mechanisms other than shear failure are possible. The most prominent cases of what appear to be anomalous focal mechanisms are reported from studies of seismicity induced by mining. The results from studies based on first–motion polarity and radiation patterns were reviewed by Gibowicz (1990).

A more general approach to this problem is based on the moment tensor inversion. Moment tensors describe completely, in a first order approximation, the equivalent forces of general seismic point sources. A moment tensor can be decomposed into an isotropic part, a compensated linear vector dipole and a double couple. Such a decomposition seems to be the most interesting one for source studies of seismic events induced by mining. The isotropic component of the source mechanism corresponds to a volumetric change, the compensated linear vector dipole corresponds to a sort of uniaxial compression, and the double couple corresponds to a shear failure. The application of this technique to local seismic events is a relatively recent innovation, and a few works only have been published so far that are related to the use of moment tensor inversion in studies of seismic events induced by mining [Sato, Fujii 1989; Fujii, Sato 1990; Wiejacz 1991; 1992; Feignier, Young 1992; McGarr 1992]. These were reviewed by Gibowicz (1993).

Spectral analysis of seismic waves, on the other hand, has become a standard technique used in studies of seismic events induced by mining. A study of the source parameters of seismic events at the Heinrich Robert coal mine in the Ruhr Basin, Germany, provides some evidence for non–double–couple events [Gibowicz et al. 1990]. It has been found that the ratio of S– to P–wave energy ranges from 1.5 to 30 for selected tremors occurring in a cluster. The high P–wave energy events are thought to be the most likely candidates for non–double–couple events. A similar result was also found in a study of the source parameters of seismic events induced by the excavation of a shaft in granite at the Underground Research Laboratory in Manitoba, Canada [Gibowicz et al. 1991]. The observed high P–wave energy events were most probably the events with non–double–couple focal mechanisms, implying that shear failures with tensile components were generated by the excavation of the shaft.

The investigations reported here are focused on a search for relations between source mechanism and the ratio of S over P wave energy for seismic events induced by mining. We expect to show that the high P–wave energy tremors are generated by the sources with prominent non–double–couple components, as estimated from the moment tensor solutions. Such seismic events are expected to occur in close vicinity to the active mine faces, where favourable conditions for the generation of tensile failures or shear failures with tensile components are obviously present. If this is the case, then a comparatively simple calculation of P– and S–wave energies would provide an indication of the mode of failure in the source of seismic events induced by mining, when the full moment tensor inversion could not be performed.

The relevant data, the source mechanism and the energy ratio, were available for 158 seismic events which occurred at Ziemowit and Wujek coal mines and Rudna copper mine in Poland, and Western Deep Levels gold mine in South Africa. The analyses were performed on the digital seismic data which were available from each mine.

2. DATA

The relevant data were collected from various sources. The data from Ziemowit and Wujek coal mines were taken from recent publication [Gibowicz, Wiejacz 1994], the data from Rudna copper mine were collected from unpublished reports [Gibowicz et al. 1994; 1995], and the data from Western Deep Levels gold mine were obtained during my visit in 1993 to the ISS International Ltd. in Welkom, South Africa. In Table 1 the number of selected events and their range of moment magnitude [Hanks, Kanamori 1979] are listed.

TABLE 1. List of data sources.

Name of the mine	Mine code	Data numb.	Magnitude range	References
Ziemowit	ZMT	63	1.4 – 2.4	Gibowicz and Wiejacz (1994)
Wujek	WJK	38	1.1 – 2.2	Gibowicz and Wiejacz (1994)
Western Deep Levels	WDL	35	−0.2 – 3.1	New unpublished data
Rudna	RDN	22	1.7 – 3.6	Gibowicz et al. (1994, 1995)

The seismic events selected for investigation occurred between January and July 1993 at Ziemowit and Wujek mines, mostly in 1994 at Rudna mine, and the seismic events selected from Western Deep Levels are those from April 1993, which formed a swarm-like seismic sequence composed of four mainshock–aftershock sequences.

The number of digital seismic stations at particular mines ranged from 12 to 22 (Table 2). Additionally, 7 analogue-recorded stations are in operation at Ziemowit mine and 2 analogue stations are in operation at Wujek mine. All seismic networks at Polish mines are composed of vertical-component sensors only, whereas all seismic stations at Western Deep Levels have three component sensors.

TABLE 2. Correlation coefficients between source mechanism and the logarithm of the energy ratio

Mine code	Number of stations	Correlation coefficient		
		DCT	CLVD	ISO
ZMT	15	0.31	−0.32	−0.34
WJK	12	0.26	−0.28	−0.25
WDL	22	0.55	−0.41	−0.47
RDN	15	0.32	−0.35	−0.24
All		0.36	−0.36	−0.32

3. THE SOURCE MECHANISM

There are various methods of inversion for moment tensor components. The inversion can be done in the time or frequency domain, and different data can be used separately or in combination. These problems were recently reviewed by Gibowicz (1993). The main difficulty in the moment tensor inversion is a proper calculation of Green's functions for geologically complex media. The Green's function is in general different for different displacement components and takes different values for particular stations. The simplest approach in the time domain is to use directly the source radiation formulation for P, SV or SH waves. This approach was used by Wiejacz (1991, 1992, 1995), who also calculated all moment tensor solutions for selected seismic events at Ziemowit and Wujek mines [Gibowicz, Wiejacz 1994] and at Rudna mine [Gibowicz et al. 1994; 1995].

The inversion of moment tensors for seismic events selected from Western Deep Levels was performed by the author in the interactive mode of the ISS data processing system, described by Mendecki (1993). The inversion in the ISS system is done in the time domain. The input data contain the polarities of P waves and the values of the spectral low–frequency level from P, SH and SV waves. The input data also contain quality indices, described in some detail by Mendecki (1993). Normalized values of the spectrum quality index are used as the weighting function for the inversion. In principle, all spectral amplitudes provided by the spectra with prescribed quality indices are accepted for the calculations. Seismic stations located at the surface are the only exceptions because of the free–surface and site effects. From such stations the spectral level from SH waves only is accepted, and the amplitude is divided by two to account for the free–surface enhancement.

The general moment tensor solutions were decomposed into an isotropic part, a compensated linear vector dipole and a double couple. The volumetric component, in a general solution, is the ratio of its value to the sum of absolute values of all three parts in a decomposed moment tensor. Its negative values denote implosion. Similarly, the compensated linear vector dipole component (CLVD) is the ratio of its value to the same sum, and the double couple component is the ratio of its value to the sum. The sign of CLVD depends on whether the dipole is compressive or dilatational.

The relation between the isotropic and double couple components is shown in Fig. 1, between the CLVD and double couple components is presented in Fig. 2, and between the isotropic and CLVD components is displayed in Fig. 3. Their absolute normalized values are between 0 (or 0 percent) and 1 (or 100 percent). The correlation coefficient in the first two cases is rather high, −0.9, whereas in the third case it is only 0.6. In general, for about 80 percent of seismic events the double couple component forms more than 60 percent of the solution. Similarly, for about 75 percent of seismic events the CLVD component is smaller than 20 percent of the solution, and for about 75 percent of the events the volumetric component is also less than 20 percent of the general solution.

4. SOURCE MECHANISM AND THE ENERGY RATIO

The integral of the square of the ground velocity is a direct measure of the energy flux of P or S waves. The energy flux, in turn, is a measure of the energy radiated in the P or S waves, which can be calculated from the relation derived by Boatwright and Fletcher (1984). The simplest calculation of the energy flux is done in the frequency domain, following the method described by Snoke (1987), which is used

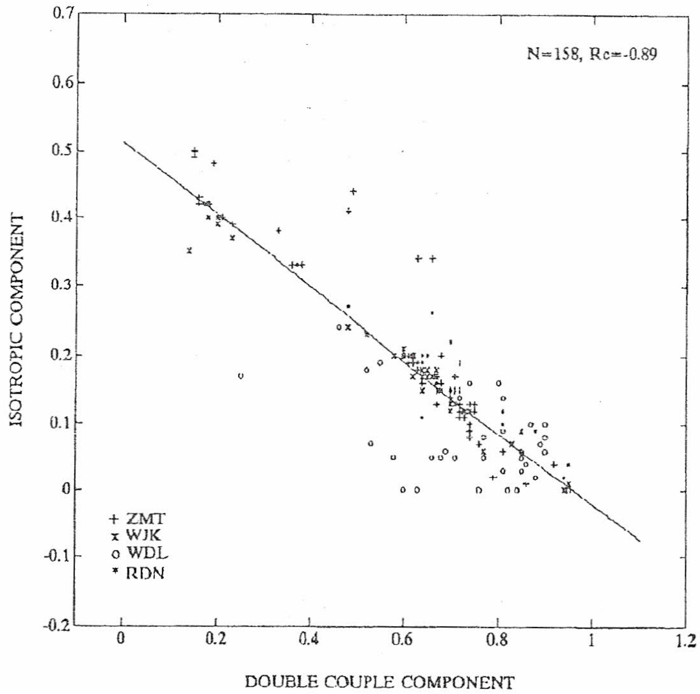

FIG. 1. The isotropic component versus the double couple component of the general moment tensor solution for selected seismic events. The data from particular mines are marked by different symbols and the number of observations and the correlation coefficient are also indicated.

here. Thus, the radiated seismic energy of P and S waves was estimated directly from the integral of the square of the ground velocity divided by the radiation coefficients corresponding to various seismic sensors at selected mines, obtained from moment tensor solutions.

It was found that the correlation between the logarithm of the energy ratio and the source mechanism components is more distinct than that between the energy ratio and the mechanism. The relation between the logarithm of the energy ratio and the double couple component for selected seismic events is shown in Fig. 4, between the ratio and the CLVD component is presented in Fig. 5, and between the ratio and the isotropic component is displayed in Fig. 6. The correlation coefficients for the three relations are marked in figures and are listed in Table 2. In the same table the correlation coefficients for data sets from the four mines are also listed. The data set from Western Deep Levels (WDL), where three-component seismic sensors are in operation, seems to be of the best quality and is characterized by the highest values of the correlation coefficients.

5. CONCLUSIONS

The relations between the ratio of S– over P–wave energy and the indicators of a double couple component, a compensated linear vector dipole and an isotropic part

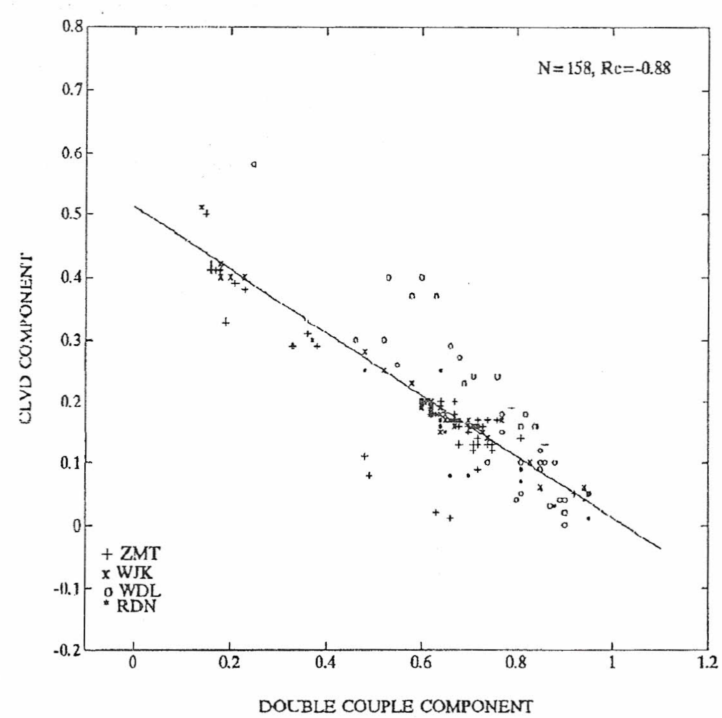

FIG. 2. The CLVD component versus the double couple component of the general moment tensor solution for selected seismic events.

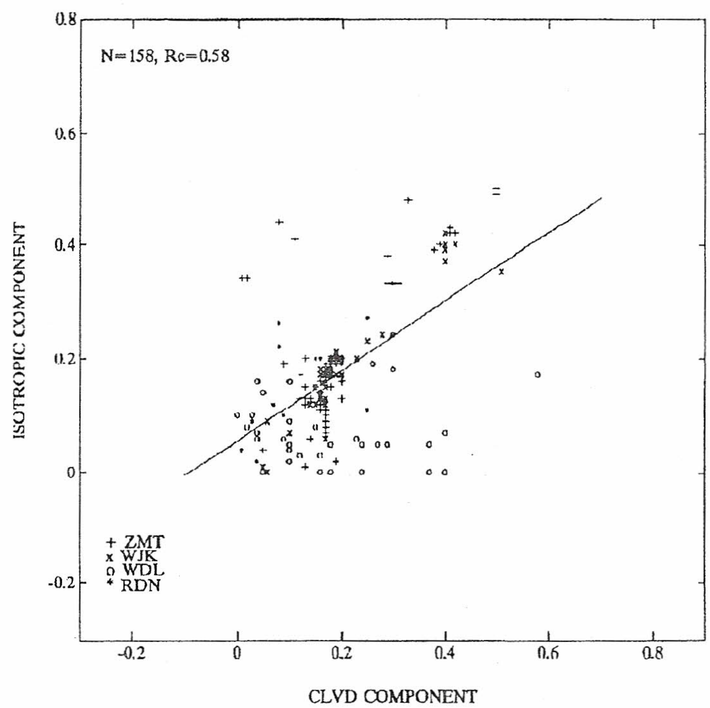

FIG. 3. The isotropic component versus the CLVD component of the general moment tensor solution for selected seismic events.

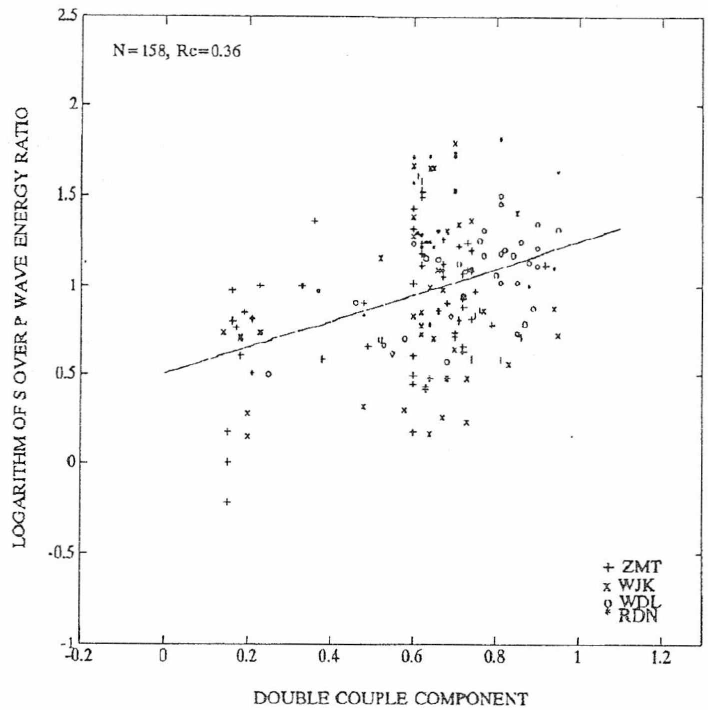

FIG. 4. Logarithm of the ratio of S–wave over P–wave energy versus the double couple component of the general moment tensor solution for selected seismic events. The data from particular mines are marked by different symbols and the number of observations and the correlation coefficient are also indicated.

in the general solution are not as straightforward as it was expected. Although there is a positive correlation between the energy ratio and the double–couple indicator, and negative correlations between the ratio and the compensated linear vector dipole and volumetric change indicators, the correlation coefficients in all three cases are small, not exceeding 0.4. The general tendency, however, points into right direction. On the average, the high values of the S– over P–wave energy ratio are associated with seismic sources with dominant double couple components.

Should this be a case, then a comparatively simple calculation of P– and S–wave energy would provide an indication of the mode of failure in the source of seismic events induced by mining, when the full moment tensor inversion could not be performed. It should be noted that in most cases only single–component seismograms were available for this study, and that this could well be an important factor in our approach to a search for non-shearing components of the source mechanism of seismic events induced by mining.

Acknowledgments. The new data from Western Deep Levels were collected during my 6 month consulting work at the ISS International Limited in Welkom in 1993. I am grateful to Dr. A. J. Mendecki, Managing Director, for his interest, assistance and permission to use these data in the study and to his staff for their

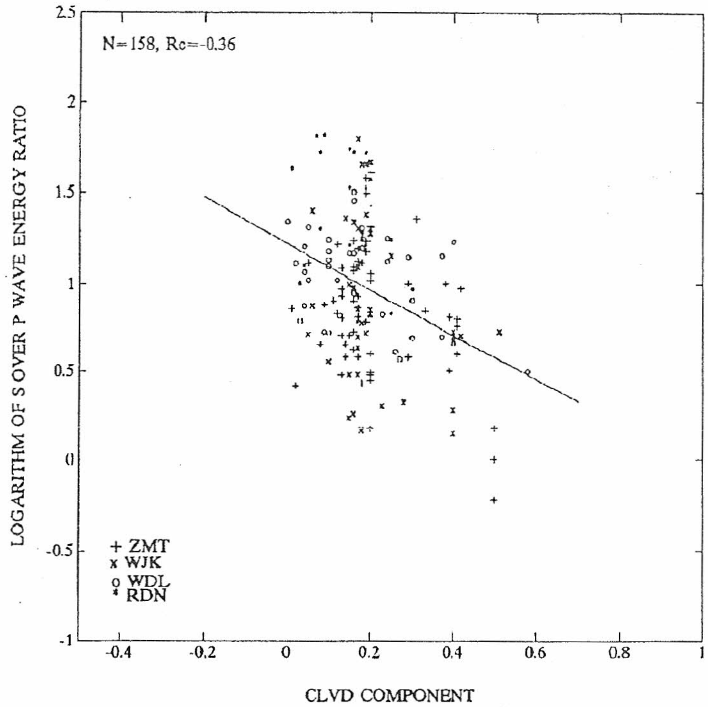

FIG. 5. Logarithm of the ratio of S–wave over P–wave energy versus the CLVD component of the general moment tensor solution for selected seismic events.

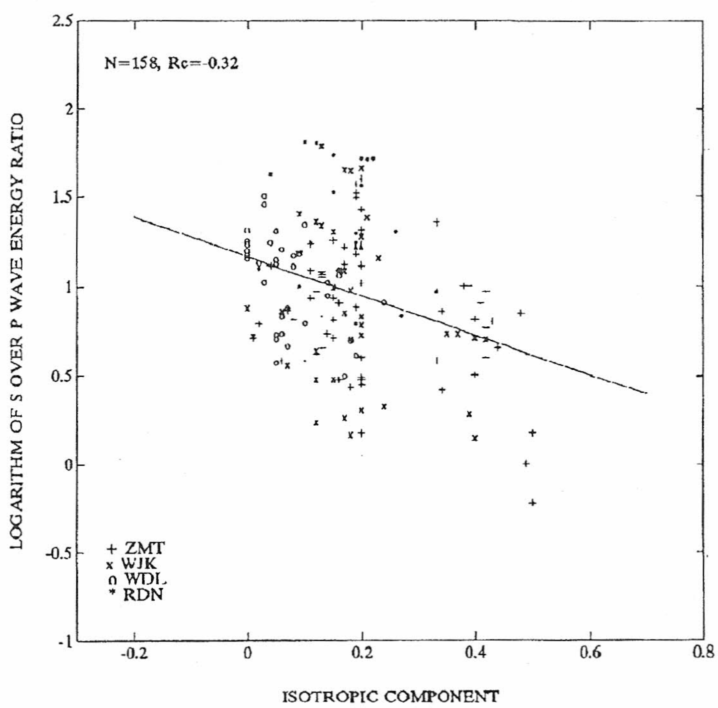

FIG. 6. Logarithm of the ratio of S–wave over P–wave energy versus the isotropic component of the general moment tensor solution for selected seismic events.

aid with data processing. The work on interpretation of these data was financially supported by the European Office of Aerospace Research and Development in London, U. S. Department of the Air Force, under special contract SPC–94–4073. The data from the Rudna copper mine were collected from several studies supported financially by the mine management.

REFERENCES

Boatwright J., Fletcher J. B. (1984), *The partition of radiated energy between P and S waves*, Bull. Seism. Soc. Am. **74**, 361–376.

Feignier B., Young R.P. (1992), *Moment tensor inversion of induced microseismic events: Evidence of non–shear failures in the* $-4 < M < -2$ *moment magnitude range*, Geophys. Res. Lett. **19**, 1503–1506.

Fujii Y., Sato K. (1990), *Difference in seismic moment tensors between microseismic events associated with a gas outburst and those induced by longwall mining activity*, In: C. Fairhurst (ed.), "Rockbursts and Seismicity in Mines", Balkema, Rotterdam, pp. 71–75.

Gibowicz S.J. (1990), *Seismicity induced by mining*, Adv. Geophys. **32**, 1–74.

Gibowicz S.J. (1993), *Keynote address: Seismic moment tensor and the mechanism of seismic events in mines*, In: R.P. Young (ed.), "Rockbursts and Seismicity in Mines", Balkema, Rotterdam, pp. 149–155.

Gibowicz S.J., Wiejacz P. (1994), *A search for the source non–shearing components of seismic events induced in Polish coal mines*, Acta Geophys. Pol. **42**, 81–110.

Gibowicz S.J., Harjes H.P., Schafer M. (1990), *Source parameters of seismic events at Heinrich Robert mine, Ruhr basin, Federal Republic of Germany: Evidence for nondouble–couple events*, Bull. Seism. Soc. Am. **80**, 88–109.

Gibowicz S.J., Young R.P., Talebi S., Rawlence D.J. (1991), *Source parameters of seismic events at the Underground Research Laboratory in Manitoba, Canada: Scaling relations for the events with moment magnitude smaller than* -2, Bull. Seism. Soc. Am. **81**, 1157–1182.

Gibowicz S.J., Domanski B., Wiejacz P. (1994), *An analysis of selected seismic events from the Rudna copper mine*, manuscript, Institute of Geophysics, Polish Academy of Sciences, Warsaw. (in Polish)

Gibowicz S.J., Domanski B., Wiejacz P. (1995), *An analysis of selected seismic events from the second half of 1994 at the Rudna copper mine*, manuscript, Institute of Geophysics, Polish Academy of Sciences, Warsaw. (in Polish)

Hanks T.C., Kanamori H. (1979), *A moment magnitude scale*, J. Geophys. Res. **84**, 2348–2350.

McGarr A. (1992), *An implosive component in the seismic moment tensor of a mining–induced tremor*, Geophys. Res. Lett. **19**, 1579–1582.

Mendecki A.J. (1993), *Keynote address: Real time quantitative seismology in mines*, In: R.P. Young (ed.), "Rockbursts and Seismicity in Mines", Balkema, Rotterdam, pp. 287–295.

Sato K., Fujii Y. (1989), *Source mechanism of a large scale gas outburst at Sunagawa coal mine in Japan*, Pure Appl. Geophys. **129**, 325–343.

Snoke J.A. (1987), *Stable determination of (Brune) stress drops*, Bull. Seism. Soc. Am. **77**, 530–538.

Wiejacz P. (1991), *Investigation of focal mechanisms of mine tremors by the moment tensor inversion*, Ph.D. Thesis, Institute of Geophysics, Polish Academy of Sciences, Warsaw. (in Polish)

Wiejacz P. (1992), *Calculation of seismic moment tensor for mine tremors from the Legnica–Glogow copper basin*, Acta Geophys. Pol. **40**, 103–122.

Wiejacz P. (1995), *Moment tensors for seismic events from Upper Silesian coal mines, Poland*, In: H.P. Rossmanith (ed.), "Mechanics of Jointed and Faulted Rock", Balkema, Rotterdam, pp. 667-672.