ACTA MONTANA IRSM AS CR (1996)
Series A, No. 10 (102), 7–24

# THE FOCAL MECHANISMS AND SOURCE PARAMETERS OF SEISMIC EVENTS INDUCED BY MINING

SŁAWOMIR JERZY GIBOWICZ,
BOGUSŁAW DOMAŃSKI and PAWEŁ WIEJACZ

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

ABSTRACT. Seismic events with non–shearing components often occur in deep mines, where favourable conditions for generation of shear failures with tensile components are present. To represent such sources, seismic moment tensor is used, decomposed into an isotropic part (ISO), a compensated linear vector dipole (CLVD) and a double couple (DC), and relations between these components of focal mechanism are studied. The ratio of $S$– to $P$–wave energy radiated from seismic events in mines, 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. Thus correlations of the energy ratio with the components of focal mechanism would provide an indication of the mode of failure in the source of mine tremors from the energy parameters alone. Correlations between the focal mechanism and other source parameters are also considered.

The focal mechanism was available for 397 seismic events, the energy ratio for 248 events and the other source parameters for 202 events from Wujek and Ziemowit coal mines, from Polkowice and Rudna copper mines in Poland, and from Western Deep Levels gold mine in South Africa.

The double–couple component of the focal mechanism forms in most cases 60–90 percent of the solution, except for the events from coal mines where more prominent non–double–couple components are often observed. There is a strong negative correlation between the DC and ISO and DC and CLVD components, characterized by the correlation coefficient of −0.94 and by the slope of linear approximation of −0.50. A positive correlation between the CLVD and ISO components is described by the correlation coefficient equal to 0.76 and the slope of linear approximation of 0.77. A positive correlation between the logarithm of the $S$– over $P$–wave energy ratio and the DC indicator is also observed, and negative correlations between the logarithm of the energy ratio and the CLVD and ISO indicators are evident. Though the correlation coefficients in all three cases are small, not exceeding 0.5, they are significant with more than 99 % confidence. An attempt to correlate the other source parameters, such as stress drop and apparent stress, directly with the focal mechanism was not successful. The only correlation which seems to be evident is that between the logarithm of the energy ratio and the logarithm of apparent stress when considered for an individual mine, but not for the whole collection of data from different mines.

## 1. Introduction

The most prominent cases of what appear to be anomalous focal mechanism, that is the mechanism with non-shearing components, are reported from studies of seismicity induced by mining. To describe such sources, seismic moment tensor is used which describes completely, in a first order approximation, the equivalent forces of a general point source. A moment tensor decomposed into an isotropic part (ISO), a compensated linear vector dipole (CLVD) and a double couple (DC) seems to be the most interesting for source studies of seismic events induced by mining. The ISO component corresponds to a volumetric change, the CLVD corresponds to a sort of uniaxial compression or tension, and the DC component corresponds to a shear failure. Several works published recently 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; 1995; Feignier, Young 1992; McGarr 1992; Gibowicz, Wiejacz 1994; Gibowicz 1995].

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 a coal mine in the Ruhr basin, Germany, and those induced by the excavation of a shaft in granite at the Underground Research Laboratory provide some evidence for non–double–couple events [Gibowicz et al. 1990; 1991]. It has been found that the ratio of $S$– to $P$–wave energy is often anomalously low and the high $P$–wave energy events are thought to be the most likely candidates for non-double-couple events.

The investigation reported here is focused on a search on the correlations between the components of focal mechanism and source parameters of seismic events induced by mining and is an extension and further elaboration of the previous results published recently [Gibowicz 1995]. 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. If this is the 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 mine tremors. Correlations between the focal mechanism and other source parameters, such as stress drop and apparent stress, are also considered.

## 2. Data

The relevant data, the focal mechanism alone based on moment tensor inversion was available for 397 seismic events, the ratio of $S$– over $P$–wave energy and the focal mechanism were available for 248 events and the other source parameters and the focal mechanism were available for 202 events which occurred at Wujek and Ziemowit coal mines and Polkowice and Rudna copper mines in Poland, and at Western Deep Levels gold mine in South Africa. The original analysis was performed on digital seismic records which were available from each mine.

The data were collected from various sources. The data from Wujek and Ziemowit coal mines were taken from recent publication [Gibowicz, Wiejacz 1994] and supplemented by a set of new observations, the data from Polkowice copper mine are listed in the new report prepared for the U. S. Air Force [Gibowicz et al. the data from Rudna copper mine were collected from the reports prepared for the mine management [Gibowicz et al. 1994; 1995b], and the data from Western Deep Levels gold mine are also elaborated in the recent report [Gibowicz et al. 1995a]. The list of data sources and the range of moment magnitude [Hanks, Kanamori 1979] of selected seismic events at each mine are given in Table 1.

TABLE 1. List of data sources

| Name of the mine | Mine code | Magnitude range | References |
|---|---|---|---|
| Wujek | WJK | 1.1 – 2.2 | [Gibowicz, Wiejacz 1994] and new data |
| Ziemowit | ZMT | 1.1 | [Gibowicz, Wiejacz 1994] and new data |
| Polkowice | PLK | 1.2 | |
| Rudna | RDN | 1.7 – 3.6 | [Gibowicz et al. 1994; 1995b] |
| Western Deep Levels | WDL | −0.2 – 3.1 | [Gibowicz et al. 1995a] |

The selected seismic events occurred between January and July 1993 and between January 1994 and May 1995 at Wujek coal mine, between January and July 1993 and between March and July 1994 at Ziemowit mine, between May 1994 and May 1995 at Polkowice copper mine, 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.

All seismic networks at Polish mines are composed of vertical–component sensors only, except three stations with three–component sensors at Polkowice mine. All seismic stations at Western Deep Levels have three–component sensors.

## 3. THE FOCAL MECHANISM

The main difficulty in the moment tensor inversion for local seismic events is a proper calculation of Green's functions for geologically complex media. The simplest approach in the time domain is to use directly the source radiation formulation for $P$, $SV$ or $SH$ waves in an homogeneous medium. is described in detail by [Wiejacz 1991] who also calculated all moment tensor solutions for selected seismic events from Wujek and Ziemowit mines [Gibowicz, Wiejacz 1994], including the new set of observations, and at Polkowice and Rudna mines [Gibowicz et al. 1994; 1995a;b].

The inversion of moment tensors for seismic events selected from Western Deep Levels was performed 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 general moment tensor solutions were decomposed into an isotropic part, a CLVD and a double couple. The isotropic component, in a general solution, is the

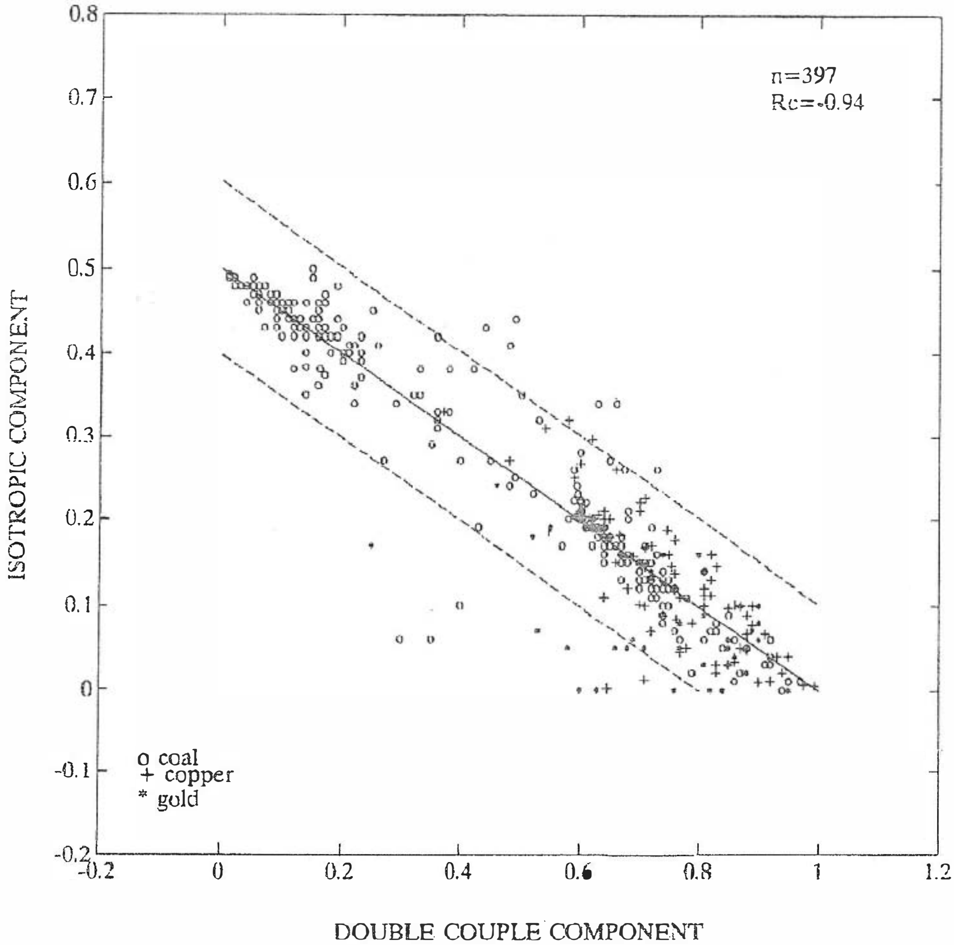


FIG. 1. The isotropic component versus the double couple component of the general moment tensor solution for all selected seismic events. The data from different types of mines are marked by different symbols and the number of observations ($n$) and the correlation coefficient ($R_c$) are also indicated. The approximation of data by linear regression is shown by a continuous line and the confidence levels equal to the double value of standard deviation of a single observation are marked by dashed lines.

ratio of its value to the sum of absolute values of all three parts in a decomposed moment tensor. Its either positive or negative values denote either explosion or implosion. Similarly, the CLVD component 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 absolute values of isotropic and double couple components for all selected seismic events is shown in Fig. 1 and for the events from coal mines only is shown in Fig. 2. Similarly, the relation between the CLVD and DC

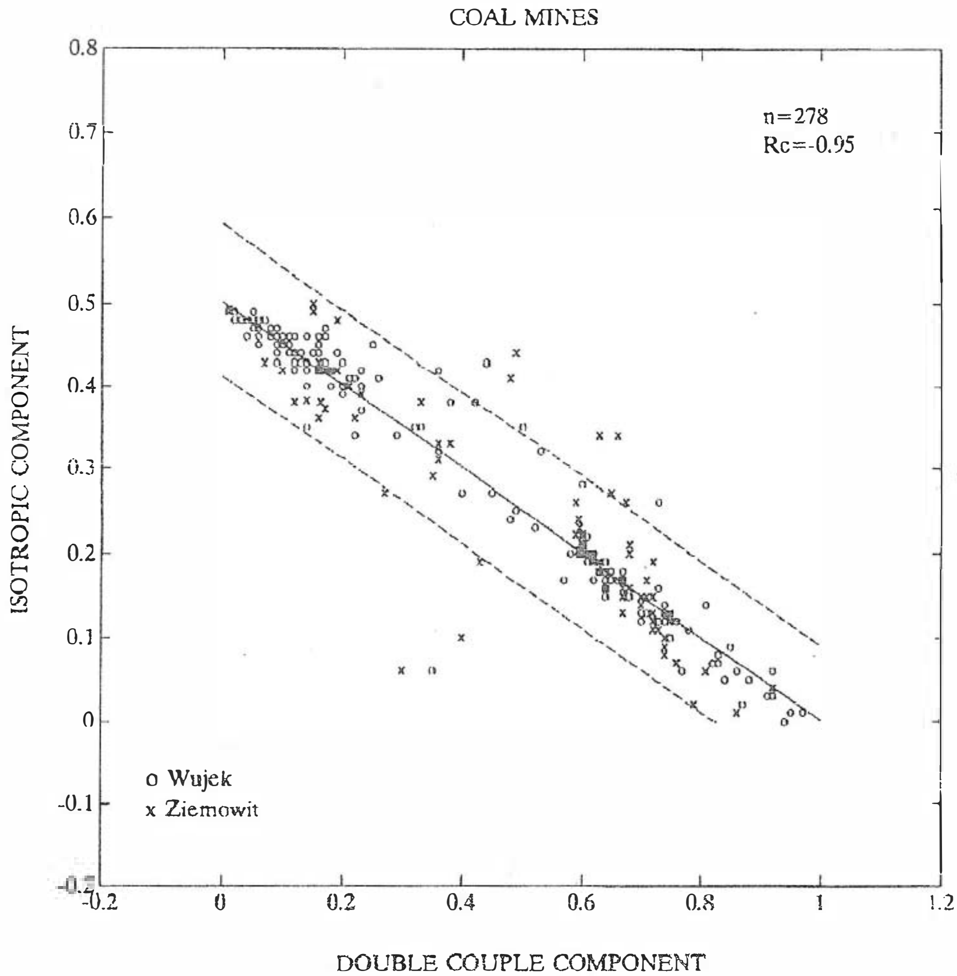


FIG. 2. The isotropic component versus the double couple component of the general moment tensor solution for the events from two coal mines. Their linear approximation is shown by a continuous line and the confidence levels are marked by dashed lines.

components for all events is presented in Fig. 3, and between the ISO and CLVD components is displayed in Fig. 4. The absolute normalized values of the source components are between 0 (or 0 %) and 1 (or 100 %) of the moment tensor solution. The observations from three types of mines (coal, copper, gold) are marked by different symbols and the number of observations and the correlation coefficients are also indicated. The approximation of data by linear regression is shown by a continuous line and the confidence levels equal to the double value of standard deviation of a single observation are marked by dashed lines. A few outliers outside the confidence levels are apparent in each figure.

There is a strong negative correlation between the DC and ISO and DC and CLVD components, characterized by the correlation coefficient of $-0.94$ and by

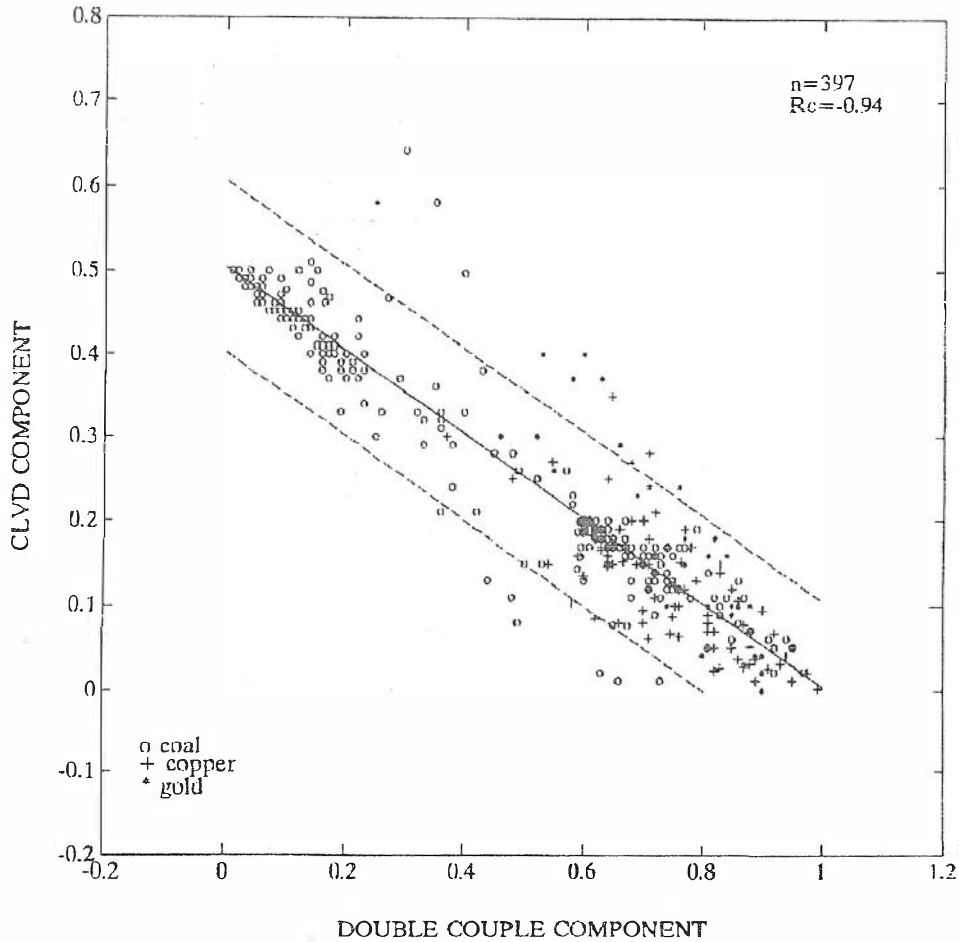


FIG. 3. The CLVD component versus the double couple component of the general moment tensor solution for all seismic events. Their linear approximation is shown by a continuous line and the confidence levels are marked by dashed lines.

the slope of linear approximation of −0.50. A positive correlation between the CLVD and ISO components is described by the correlation coefficient equal to 0.76 and the slope of linear approximation of 0.77. The correlation coefficients and the slopes of linear approximation between the components of moment tensor solutions for seismic events from individual mines are listed in Table 2. The correlation coefficients between the CLVD and DC and ISO and DC components for these sets of data are high, whereas the correlation coefficients between the ISO and CLVD components from the solutions for seismic events from Polkowice and Western Deep Levels mines are close to zero (Table 2). This results from the highly limited range of values of non–shearing components, for which the correlation could not be defined.

In general, for about 90 percent of seismic events from the copper and gold mines the double couple component forms more than 60 percent of the solution. Similarly, for about 80 percent of these events the CLVD component is smaller than

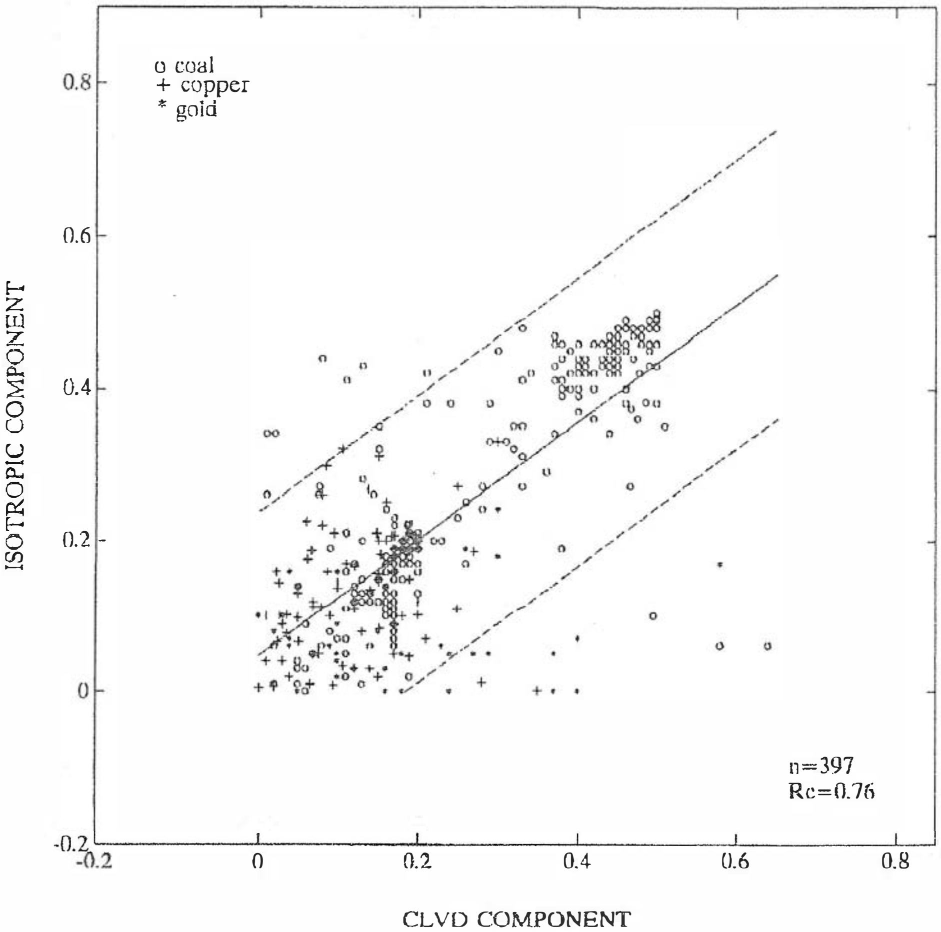


FIG. 4. The isotropic component versus the CLVD component of the general moment tensor solution for all seismic events. Their linear approximation is shown by a continuous line and the confidence limits are marked by dashed lines.

20 percent of the solution, and for about 85 percent of the events the volumetric component is also less than 20 percent of the general solution. The seismic events with large non-shearing components in their source mechanism are mostly those occurring at two Polish coal mines, where the CLVD and isotropic components form occasionally as much as 50 percent of the solution and the double couple component could be as small as a few percent of the source mechanism (e.g. Fig. 2). These relations are of similar nature at both the Wujek and Ziemowit mines, though they are located in diverse tectonic and geological situations. The rock mass in Polish coal mines is mostly composed of sandstones. The focal mechanisms of seismic events, on the other hand, induced by hard-rock mining at Polish copper mines, where the rock mass is dominated by strong dolomites, and at the South African gold mine, where strong quartzites are present, are characterized by the dominance of shearing components.

TABLE 2. Correlation coefficient $R_c$ and the slope $B$ of linear approximation between the various components of moment tensor solutions: double couple (DC), compensated linear vector dipole (CLVD) and isotropic component (ISO)

| Mine code | Number of obs. | CLVD ~ DC $R_c$ | CLVD ~ DC $B$ | ISO ~ DC $R_c$ | ISO ~ DC $B$ | ISO ~ CLVD $R_c$ | ISO ~ CLVD $B$ |
|---|---|---|---|---|---|---|---|
| WJK | 178 | −0.97 | −0.50 | −0.97 | −0.51 | 0.89 | 0.91 |
| ZMT | 100 | −0.91 | −0.55 | −0.88 | −0.48 | 0.62 | 0.56 |
| PLK | 62 | −0.69 | −0.45 | −0.77 | −0.56 | (0.06) | — |
| RDN | 22 | −0.92 | −0.51 | −0.91 | −0.49 | 0.68 | 0.65 |
| WDL | 35 | −0.91 | −0.81 | (−0.47) | — | (0.08) | — |
| All | 397 | −0.94 | −0.50 | −0.94 | −0.50 | 0.76 | 0.77 |

TABLE 3. Correlation coefficient $R_c$ with its confidence (in brackets) and the slope B of linear approximation between the logarithm of $S$− over $P$–wave energy ratio and the focal mechanism components (DC, CLVD, ISO)

| Mine code | Number of obs. | DC $R_c$ | DC $B$ | CLVD $R_c$ | CLVD $B$ | ISO $R_c$ | ISO $B$ |
|---|---|---|---|---|---|---|---|
| WJK | 92 | 0.42 (99%) | 0.46 | −0.37 (99%) | −0.80 | −0.44 (99%) | −0.95 |
| ZMT | 37 | 0.54 (99%) | 0.54 | −0.51 (99%) | −0.73 | −0.41 (98%) | −0.87 |
| PLK | 62 | 0.33 (99%) | 0.82 | −0.23 (90%) | −0.89 | −0.26 (95%) | −0.88 |
| RDN | 22 | 0.32 (88%) | 0.77 | −0.35 (90%) | −1.49 | −0.24 (75%) | −1.07 |
| WDL | 35 | 0.55 (99%) | 0.95 | −0.41 (98%) | −0.79 | −0.47 (99%) | −1.96 |
| All | 248 | 0.46 (99%) | 0.60 | −0.48 (99%) | −1.15 | −0.37 (99%) | −0.91 |

TABLE 4. Correlation coefficient with its confidence (in brackets) and the slope of linear approximation between the logarithm of $S$- over $P$- wave energy ratio and the logarithm of apparent stress

| Mine code | Number of obs. | Correlation coefficient | Slope |
|---|---|---|---|
| WJK | 46 | 0.36 (90%) | 0.28 |
| ZMT | 37 | 0.36 (95%) | 0.28 |
| PLK | 62 | 0.47 (99%) | 0.36 |
| RDN | 22 | 0.60 (99%) | 0.38 |
| WDL | 35 | 0.30 (90%) | 0.13 |

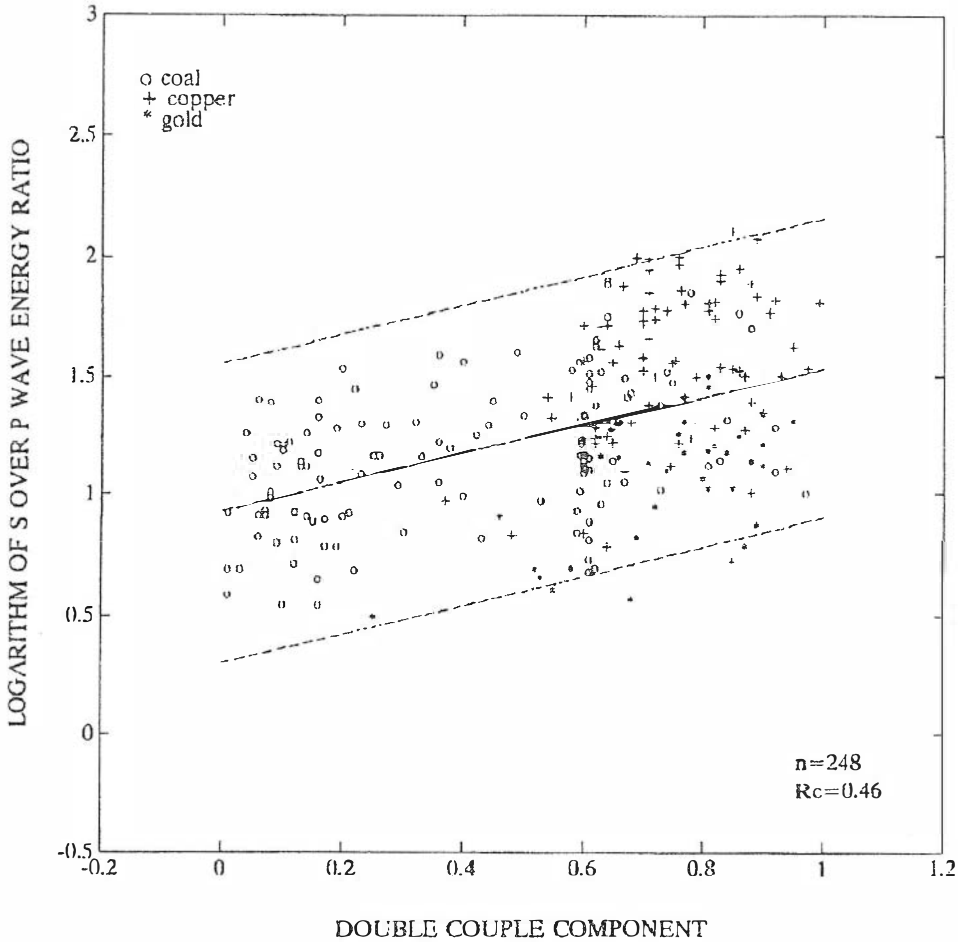


FIG. 5. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the double couple component of the general moment tensor solution. Their linear approximation is shown by a continuous line and the confidence limits are marked by dashed lines.

## 4. THE FOCAL 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, 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 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.

The correlation between the logarithm of the energy ratio and the source mechanism components is more distinct than that between the energy ratio itself and

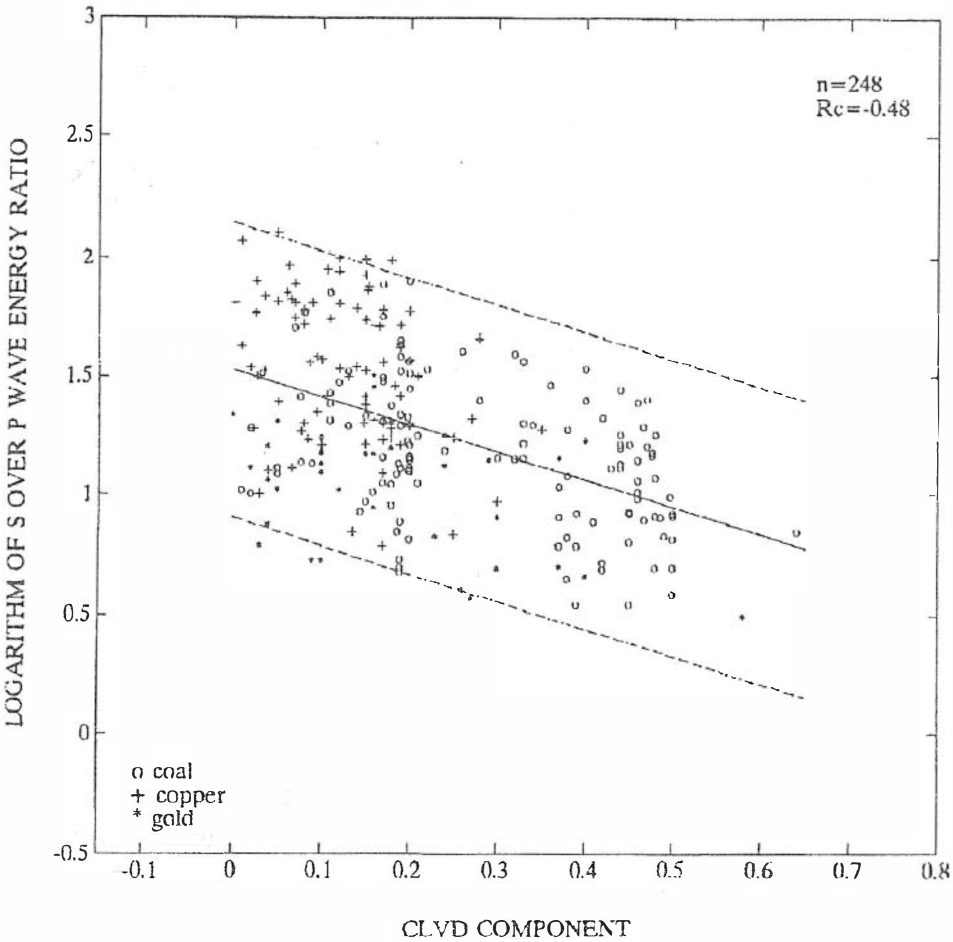


FIG. 6. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the CLVD component of the general moment tensor solution. Their linear approximation is shown by a continuous line and the confidence levels are marked by dashed lines.

the mechanism. The relation between the logarithm of the energy ratio and the double couple component for all selected seismic events is shown in Fig. 5, between the ratio and the CLVD component is presented in Fig. 6, and between the ratio and the isotropic component is displayed in Fig. 7. The approximations of data by linear regression are shown by continuous straight lines and the confidence level equal to the double value of standard deviation of a single observation are marked by dashed lines. The correlation coefficients for the three relations for all data are marked in the figures and are listed in Table 3, together with their confidence in percent, given in brackets, and the slopes of linear approximations. The correlation coefficients are not greater than 0.5 but they are significant with more than 99 % confidence by the Fisher's $z$-test. In the same table the correlation coefficients and the slopes for the data sets from the five mines are also listed. The data from Western Deep Levels (WDL), where three-component seismic sensors are in use,

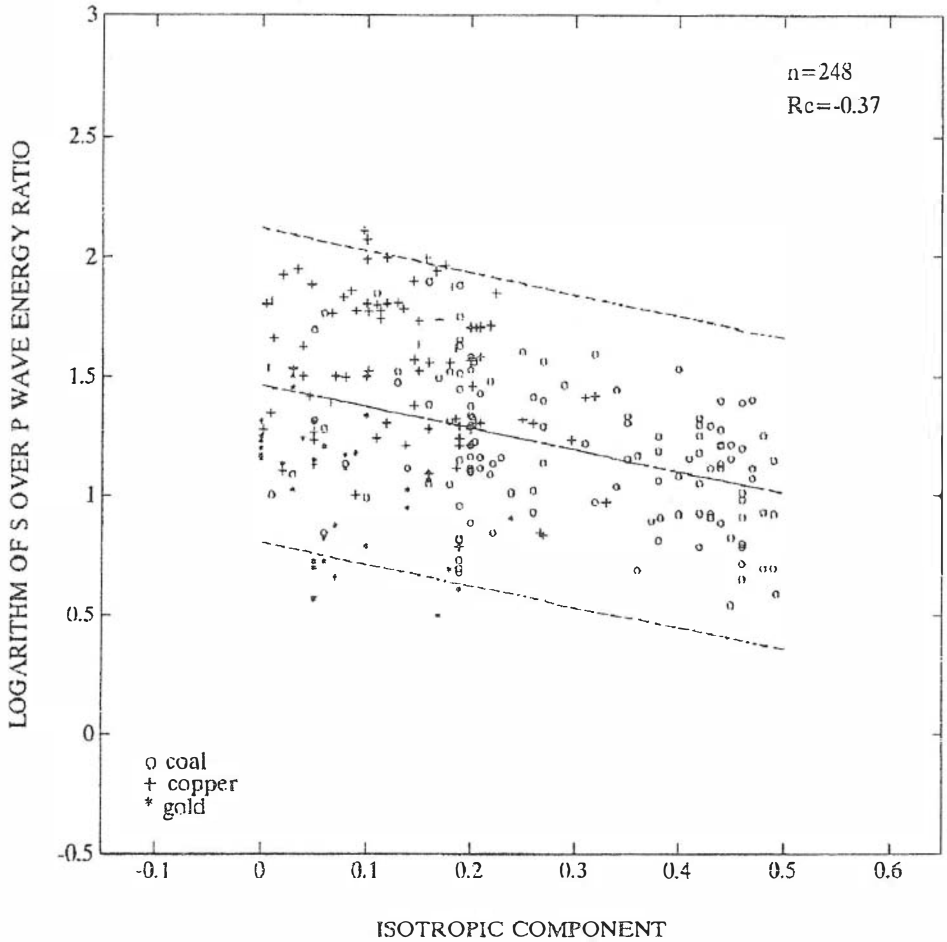


FIG. 7. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the isotropic component of the general moment tensor solution. Their linear approximation is shown by a continuous line and the confidence levels are marked by dashed lines.

seem to be of the best quality and are characterized by the highest values of the correlation coefficient. The correlation of data from the two copper mines (PLK and RDN), on the other hand, is the least reliable, with the smallest correlation coefficients in comparison to those from the other mines.

## 5. THE FOCAL MECHANISM AND OTHER SOURCE PARAMETERS

An attempt to correlate stress drop and apparent stress directly with the focal mechanism was not successful. The only correlation which was found is that between the logarithm of the energy ratio and the logarithm of apparent stress considered for individual mines, but not for the whole collection of data from the five mines.

Madariaga (1976) has demonstrated that the apparent stress is proportional to

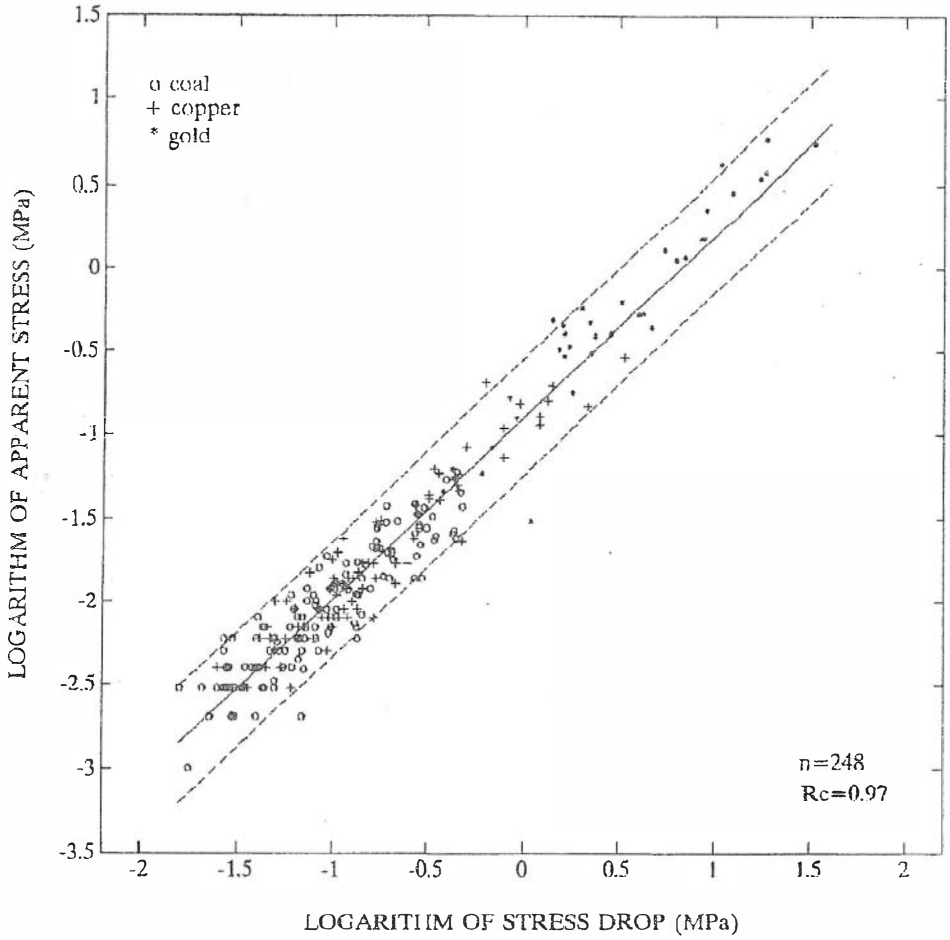


FIG. 8. Logarithm of apparent stress versus the logarithm of stress drop for all seismic events. Their linear approximation is shown by a continuous line and the confidence limits are marked by dashed lines.

the dynamic stress drop, but does not represent an actual stress difference. If the $P$–wave contribution to the seismic energy and the azimuthal dependence of the energy flux are neglected, the Brune stress drop is a constant multiple of the apparent stress [Snoke 1987]. In our case, the energy of $P$ waves is not neglected and the apparent stress is an independent parameter. Nevertheless, from the relation between the logarithm of apparent stress and the logarithm of stress drop shown in Fig. 8 it follows that the apparent stress is about ten times smaller than the stress drop. The slope of linear approximation is close to one and the correlation is very distinct. From Fig. 8 it also follows that the highest stress release is observed at Western Deep Levels and the lowest at Polish coal mines, though occasionally the stress release at copper mines is also low.

The correlation coefficients with their confidence levels and the slopes of linear approximation between the logarithm of $S$– over $P$–wave energy ratio and the

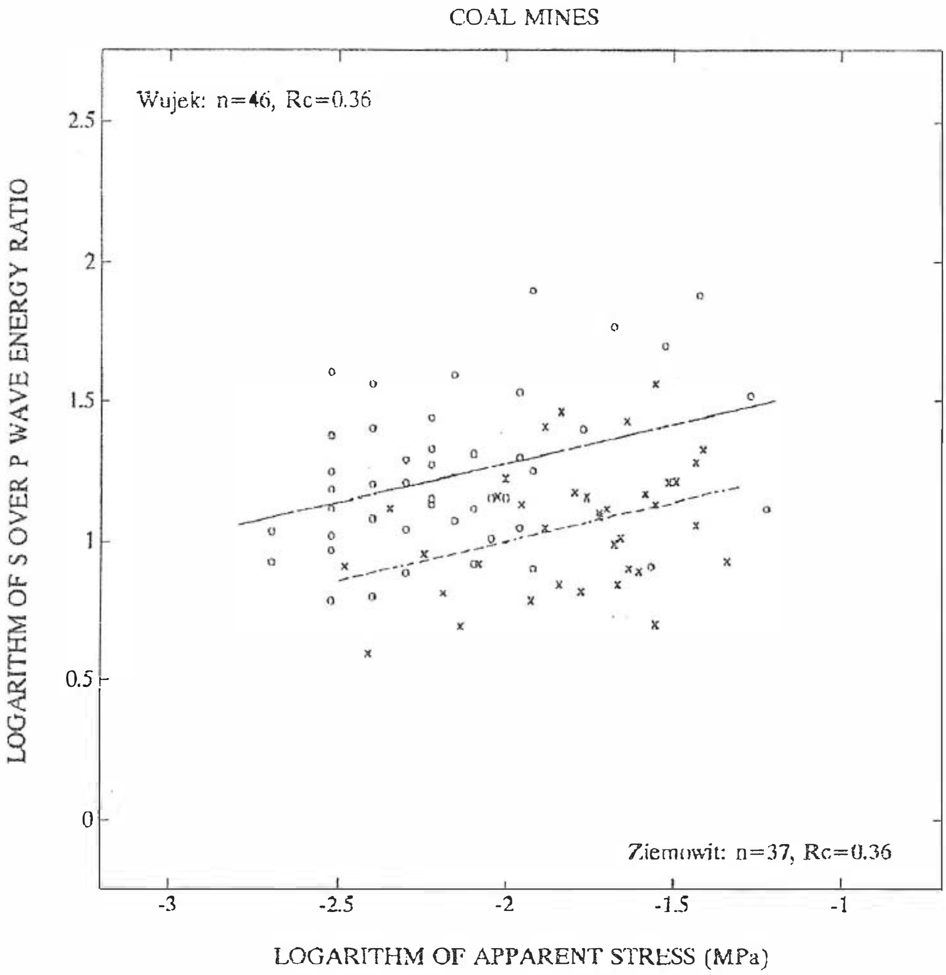


FIG. 9. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the logarithm of apparent stress for the events from the Wujek coal mine (marked by open circles) and the Ziemowit coal mine (marked by x). Their linear approximation for the events from the Wujek mine is shown by a continuous line and for the events from the Ziemowit mine is shown by a dashed line.

logarithm of apparent stress for seismic events observed at the five mines are listed in Table 4. The correlation coefficients vary between 0.30 for the WDL data and 0.60 for the RDN data. It should be noted that the slopes of linear approximation are the same for the two coal mines and again almost the same for the two copper mines. The relations between the energy ratio and the apparent stress for the events from the coal mines is shown in Fig. 9, for the events from the copper mines are displayed in Fig. 10, and for the events from the WDL gold mine is presented in Fig. 11. From Fig. 9 it follows that for a given apparent stress the ratio of $S$– over $P$–wave energy is higher at Wujek mine than that at Ziemowit mine, though its

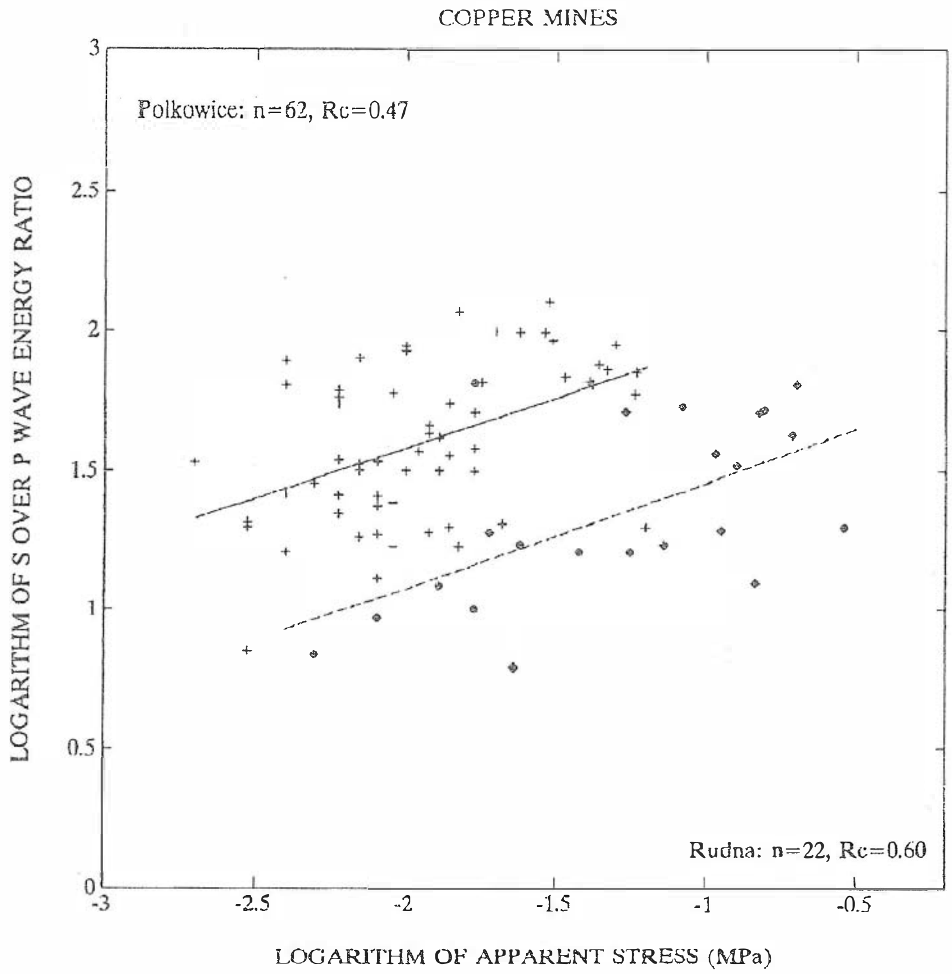


FIG. 10. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the logarithm of apparent stress for the events from the Polkowice copper mine (marked by crosses) and the Rudna copper mine (marked by stars). Their linear approximation for the events from the Polkowice mine is shown by a continuous line and for the events from the Rudna mine is shown by a dashed line.

increase rate with the apparent stress is the same at the both mines. Similarly, the energy ratio at Polkowice mine is higher than that at Rudna mine (Fig. 10). The data from all the events and their individual approximations are shown together in Fig. 12. From this figure it follows that for a given apparent stress the energy ratio is the highest at Polkowice mine and the lowest at WDL mine. This means that seismic events from WDL mine are characterized by the largest energy of $P$ waves in comparison with the energy of $S$ waves.

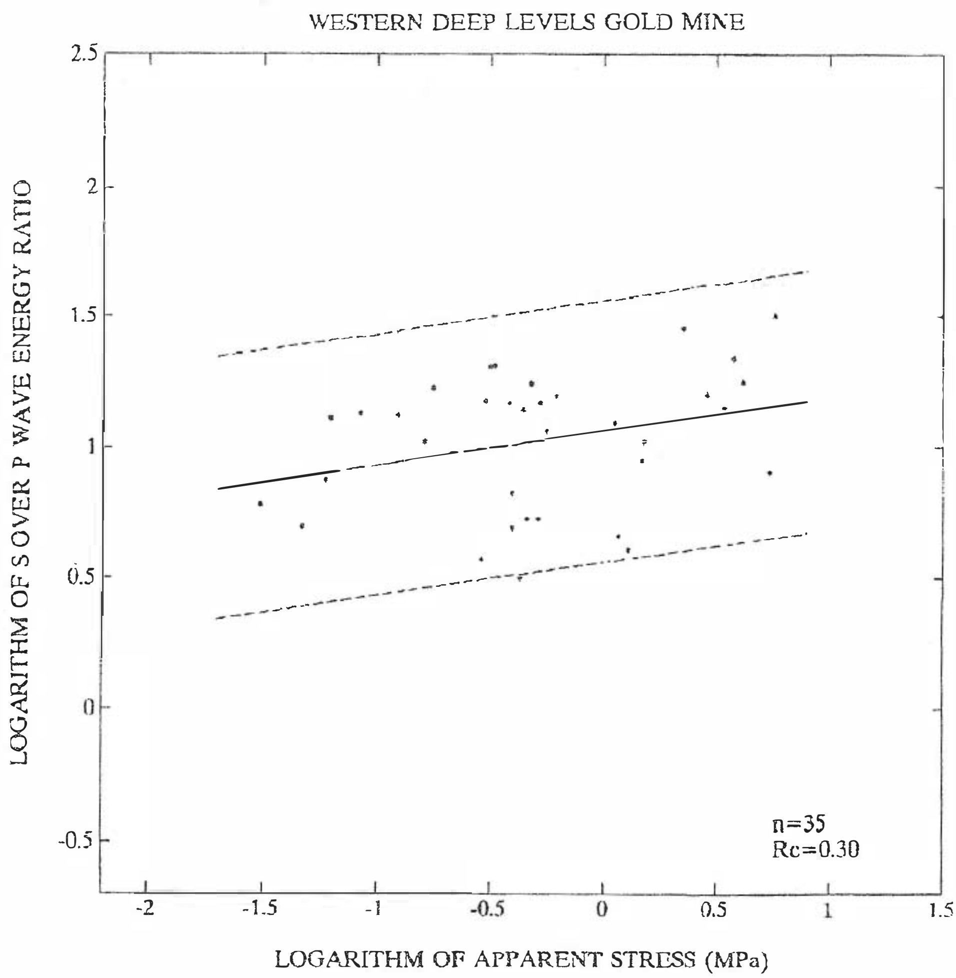


FIG. 11. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the logarithm of apparent stress for the events from the Western Deep Levels gold mine. Their linear approximation is shown by a continuous line and the confidence limits are marked by dashed lines.

## 6. CONCLUSIONS

1. The focal mechanism of selected seismic events from copper and gold mines shows that for about 90 percent of seismic events the double couple component forms more than 60 percent of the solution. Similarly, for about 80 percent of seismic events the CLVD and isotropic components are smaller than 20 percent of the general moment tensor solution. The seismic events with large non-shearing components are mostly those occurring at two Polish coal mines, where the CLVD and ISO components form occasionally as much as 50 percent of the solution and where the rock mass is mostly composed of sandstones. The rock mass at Polish copper mines is dominated by strong dolomites, and at the WDL gold mine strong quartzites are present.

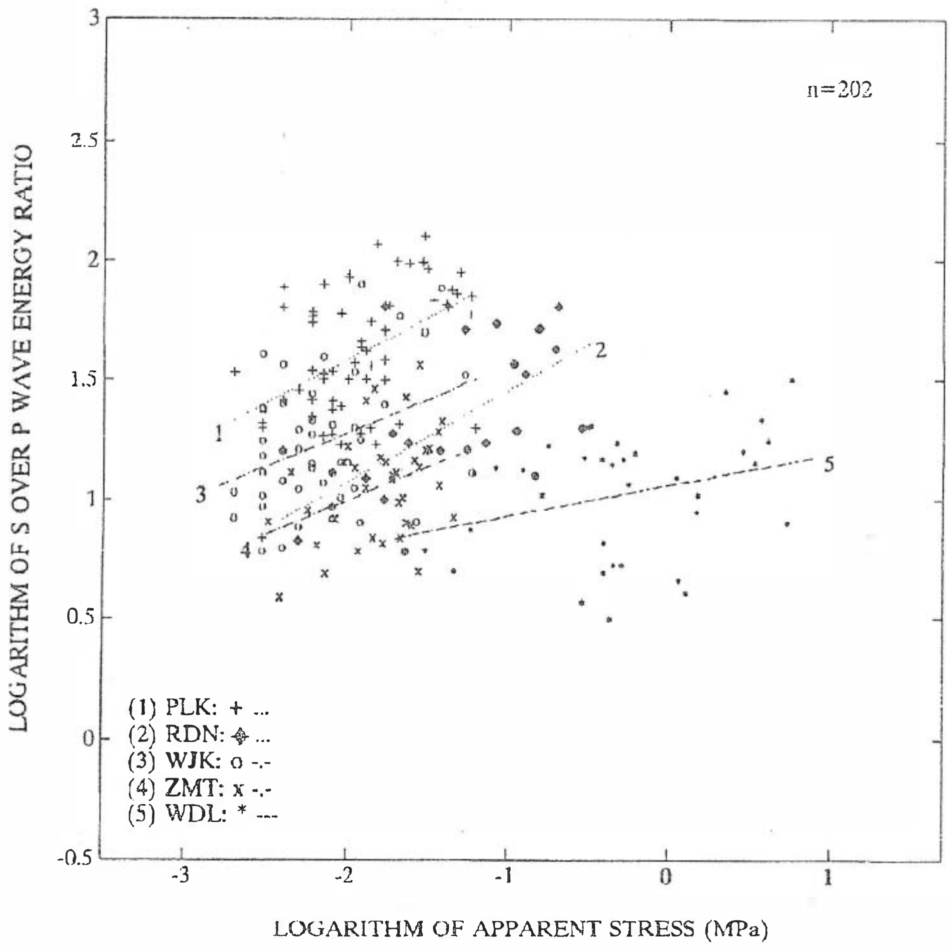


FIG. 12. Logarithm of the ratio of $S$-wave over $P$-wave energy versus the logarithm of apparent stress for all seismic events. The data from the five mines are marked by different symbols and their linear approximations are numbered and shown by different line types.

2. There is a strong negative correlation between the DC and ISO and DC and CLVD components, characterized by the correlation coefficient of $-0.94$ and by the slope of linear approximation of $-0.50$. A positive correlation between the CLVD and ISO components is described by the correlation coefficient of 0.76 and the slope of 0.77.

3. The simple relations between the ratio of $S$– over $P$–wave energy and the indicators of a DC, CLVD and ISO components in the general moment tensor solutions seem to be valid, though the scatter of data is considerable. The correlation coefficients in all three cases are small, not exceeding 0.5, but they are significant with more than 99 % confidence by the Fisher's $z$–test. The data set from Western Deep Levels, where three–component seismic sensors are in use, is of the best quality and is characterized by the highest values of the correlation coefficients.

4. The highest stress release is observed at Western Deep Levels and the lowest at Polish coal mines, though occasionally the stress release at copper mines is also low. The apparent stress, an independent source parameter, is about ten times smaller than the stress drop. The slope of linear approximation between the logarithm of apparent stress and the logarithm of stress drop is close to one and the correlation is very distinct.

5. An attempt to correlate stress drop and apparent stress directly with the focal mechanism was not successful. The only correlation which was found is that between the logarithm of the energy ratio and the logarithm of apparent stress considered for individual mines, but not for the whole collection of data from the five mines. The slopes of linear approximation are the same for the two coal mines and again almost the same for the two copper mines. For a given apparent stress the energy ratio is the highest at Polkowice mine and the lowest at WDL mine. This means that seismic events from WDL mine are characterized by the largest energy of $P$ waves in comparison with the energy of $S$ waves.

## Acknowledgments

The work on processing and interpretation of new data from the Wujek and Ziemowit coal mines was financially supported by the Polish Committee for Scientific Research under Grant No. 9 S601 008 06.

## REFERENCES

Boatwright J., Fletcher J.B. (1984), *The partition of radiated energy between P and S waves*, Bull. Seism. Soc. Am.vol 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. (1995), *Relations between source mechanism and the ratio of S over P wave energy for seismic events induced by mining*, Acta Montana **A9** (100), 7–15.

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., Domański 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., Domański B., Wiejacz P. (1995a), *Source parameters and source mechanism of seismic events occurring in sequences at a Polish copper mine and South African gold mine: Search for possible time variations*, Report SPC–94–4073 for the U.S. Department of the Air Force, European Office of Aerospace Research and Development, London.

Gibowicz S.J., Domański B., Wiejacz P. (1995b), *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.

Madariaga R. (1976), *Dynamics of an expanding circular fault*, Bull. Seism. Soc. Am. **66**, 639–666.

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.