



Full Moment Tensor Inversion as a Practical Tool in Case of Discrimination of Tectonic and Anthropogenic Seismicity in Poland

GRZEGORZ LIZUREK¹

Abstract—Tectonic seismicity in Poland is sparse. The biggest event was located near Myślenice in 17th century of magnitude 5.6. On the other hand, the anthropogenic seismicity is one of the highest in Europe related, for example, to underground mining in Upper Silesian Coal Basin (USCB) and Legnica Głogów Copper District (LGCD), open pit mining in “Bełchatów” brown coal mine and reservoir impoundment of Czorsztyn artificial lake. The level of seismic activity in these areas varies from tens to thousands of events per year. Focal mechanism and full moment tensor (MT) decomposition allow for deeper understanding of the seismogenic process leading to tectonic, induced, and triggered seismic events. The non-DC components of moment tensors are considered as an indicator of the induced seismicity. In this work, the MT inversion and decomposition is proved to be a robust tool for unveiling collapse-type events as well as the other induced events in Polish underground mining areas. The robustness and limitations of the presented method is exemplified by synthetic tests and by analyzing weak tectonic earthquakes. The spurious non-DC components of full MT solutions due to the noise and poor focal coverage are discussed. The results of the MT inversions of the human-related and tectonic earthquakes from Poland indicate this method as a useful part of the tectonic and anthropogenic seismicity discrimination workflow.

Key words: Anthropogenic seismicity, moment tensor, focal mechanism, induced seismicity, intraplate seismicity.

1. Introduction

Earthquakes seldom happen in Poland and earthquakes large enough to cause damage are even more rare. About 100 accounts of earthquakes are known from Polish history, starting from the year 1000 A.D. Most of the felt earthquakes took place in the Southern Poland (Fig. 1). The greatest earthquake in

Poland is considered to be the event of December 3, 1786 that has taken the biggest event was estimated at 5.6. The Podhale earthquake from 30th November 2004 $M_L = 4.8$ was the biggest earthquake located in Poland since the instrumental measurements started. (Wiejacz and Dębski 2009). Smaller earthquakes were also observed near Krynica: (Guterch et al. 2005; Plesiewicz and Wiszniowski 2015). The last significant tectonic earthquakes in Poland were located in the Tornquist-Teisseyre zone, where seismic activity was reported in the past (e.g. Guterch 2009), but only the 2007, $M_L = 2.8$ and 2012, $M_L = 3.8$ seismic events located near Jarocin were recorded (Lizurek et al. 2013). The moment tensor solutions were obtained for the strongest event from Podhale and both Jarocin earthquakes. Map of significant historical earthquakes as well as those recorded instrumentally is shown on Fig. 1.

Main sources of the seismic activity in Poland are industrial activities: underground mining in Upper Silesian Coal Basin (USCB) and Legnica Głogów Copper District (LGCD), open pit mining in “Bełchatów” brown coal mine and reservoir impoundment of Czorsztyn artificial lake near Niedzica hydropower plant (Fig. 1). Seismic activity in USCB (Southern Poland) is very high, there are about 3000 events per year recorded by Polish Seismological Network run by Institute of Geophysics, Polish Academy of Sciences. Moreover, there are about 200 events of $M_L \geq 2.4$ annually, and 55 900 events of $M_L \geq 1.5$ occurred over the period 1974–2005 according to Upper Silesian Seismological Network run by Central Mining Institute. There were six large events with $3.8 \leq M_L \leq 4.2$ since 1992 till 2015 (Stec 2007; Marcak and Mutke 2013). The focal mechanisms of significant USCB events are

¹ Institute of Geophysics, Polish Academy of Sciences, ul. Ks. Janusza 64, 01-452 Warsaw, Poland. E-mail: lizurek@igf.edu.pl

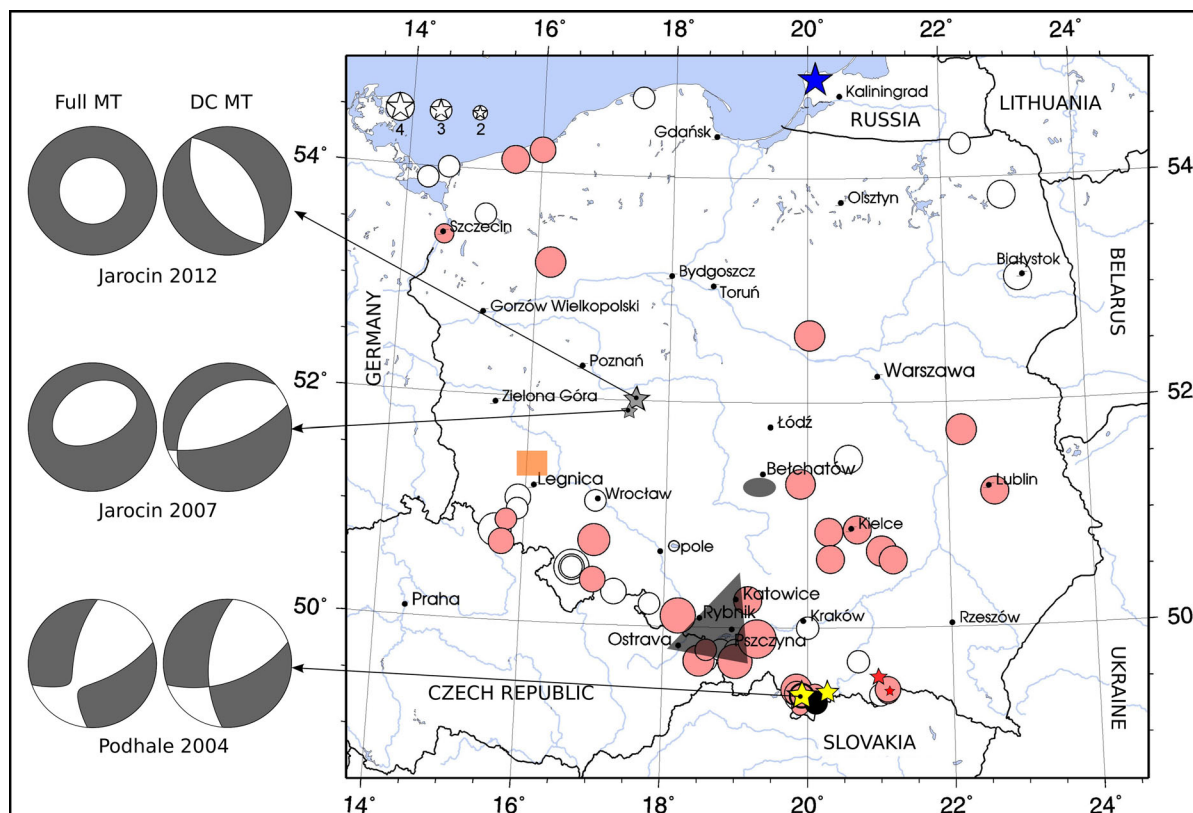


Figure 1

Anthropogenic seismicity areas in Poland on the background of the tectonic seismicity map. *Triangle* denotes USCB, *rectangle* denotes LGCD, *ellipse* marks the Bełchatów open pit and *black circle* denotes Czorsztyn Lake area. *Stars* denote instrumentally recorded events in Poland (*gray ones* for Jarocin earthquakes, *yellow* for Podhale, and *red* for Krynica events, *blue* is the strongest felt event from Kaliningrad), *white circles* denote historical earthquakes with not well-constrained location, *filled circles* denote historical earthquakes with well-constrained location. Podhale event MT in the last row is taken from Wiejacz and Dębski (2009)

available in: Gibowicz and Wiejacz (1994), Gibowicz et al. (1996), Marcak and Mutke (2013), Stec (2007).

The anthropogenic seismic activity of LGCD (SW Poland) is related to the copper ore underground exploitation in 3 mines: “Rudna”, “Polkowice-Sierszowice”, and “Lubin”. These mines produce annually several hundreds of seismic events with local magnitude in the range 0.4–4.5 (Lasocki 2005). The largest events in this area were $M_L = 4.5$ from March 24th 1977 (Gibowicz et al. 1979) and $M_L = 4.3$ from June 20th 1987 (Gibowicz et al. 1989) both located within “Lubin” mine, and $M_L = 4.2$ from March 19th 2013 located in “Rudna” mine (Lizurek et al. 2015; Rudziński et al. 2016). Moment tensor solutions for most of the significant events are available (e.g. Gibowicz et al. 1989; Lizurek et al. 2015; Orlecka-Sikora et al. 2014).

Open pit brown coal mining in the Bełchatów area (Central Poland) causes lower seismicity than the underground mining, There are about 60 events recorded by PLSN annually, but 4 events since opening of the mine in 1977 (Gibowicz et al. 1982) had magnitude $M_L \geq 4$. The largest event in this area took place on November 29, 1980 $M_{4.6}$, the latest event of magnitude above M_4 took place on January 22, 2010 (Wiejacz and Rudziński 2010). The last anthropogenic seismic activity is linked to the impoundment of Czorsztyn artificial lake. The lake was created by backing up water by an earth dam of the hydropower plant Niedzica on Dunajec river, southern Poland (Fig. 1). It’s filling ended in 1997. The reservoir of 234.5 million cubic meters capacity is shallow, on average between 20 to 50 m of water column. Between 1995 and 2011 there was only one

event recorded in this area, but since November 2011 seismic activity increased up to about several events per month. The seismicity of the area is considered as the triggered seismicity case (Białoń et al. 2015). Currently there are over 150 events located in this area with M_L from -0.6 to 2.4 . There are 23 moment tensor solutions calculated for the events of $0.2 \leq M_L \leq 2.1$.

The moment tensor (MT) inversion confirmed its importance by allowing to interpret the MT solutions in terms of the dominant stress orientation in the seismic active regions (Hardebeck and Michael 2006) and as one of the main tools to investigate the faulting mechanisms of the significant earthquakes (Ekstrom et al. 2012) as well as the local tectonic seismicity (e.g., Cesca et al. 2006). Full MT inversion is considered as a useful method of investigation of the volcanic, anthropogenic, and other exotic seismic sources (e.g., Cesca et al. 2008; Gibowicz and Kijko 1994; Vavryčuk and Kim 2014; Heimann et al. 2013). Full MT decomposition allows for deeper understanding of the seismogenic process leading to induced and triggered seismic events (e.g., Fletcher and McGarr 2005; Ford et al. 2009). The non-DC component of focal mechanism solution was considered as an indicator of the induced seismicity since 1980's by several authors (e.g., Teisseyre 1980; Rudajev and Šílený 1985), recently the non-DC component of the MT decomposition is proposed as such indicator (Cesca et al. 2013). Moreover, recommendation for discrimination of anthropogenic and natural seismicity included use of MT inversion in the complex investigation procedure described in Dahm et al. (2013). The authors of the latter work also discriminate between triggered and induced anthropogenic seismicity. The procedure of discrimination between natural and anthropogenic, and also between induced and triggered seismicity takes into account a physics-based probabilistic approach as well as the statistics-based seismicity model and source parameter approach. The latter was dedicated mainly into the collapse-type events. In this work the MT decomposition for pure shearing (DC) non-shearing components: isotropic (ISO) and compensated linear vector dipole (CLVD) is proved to be robust tool for unveiling collapse-type events as well as the other purely induced events both in USCB and

LGCD. Nevertheless, the limitation of the methodology of the P-wave first pulse displacement amplitude is also shown upon the synthetic test. The results of the MT inversions of the human-related and tectonic earthquakes from Poland indicate this method as useful part of the discrimination workflow, but it cannot be treated as the main and only input for such discrimination.

2. Methodology of moment tensor inversion

Moment tensors are obtained by inversion of the P-wave amplitudes in time domain (Wiejacz 1992; Kwiatek and Martinez-Garzon 2016). According to Fitch et al. (1980), De Natale et al. (1987) and Aki and Richards (2002), the recorded displacement for the P-wave phase is:

$$\mathbf{U}^P(\mathbf{x}, t) = \frac{\gamma \cdot \dot{\mathbf{M}}\left(t - \frac{r}{\alpha}\right) \cdot \gamma \mathbf{I}}{4\pi\rho\alpha^3 r}, \quad (1)$$

where ρ is the average medium density, r is the source-receiver distance, α is the average velocity of the P-wave, \mathbf{M} is the seismic moment tensor, \mathbf{I} is the P-wave direction at the receiver, and γ is the P-wave direction at the source.

Moment tensor is obtained by solving of a set of N equations of type (1), where N is the number of stations that recorded the event. Six independent components of moment tensor require minimum of six equations, but the more the better. The system of Eqs. (1) is overdetermined and solved for using a least-squares approach (L2 norm) with the cost function being the sum of squares of residuals. When the condition of the zero trace is imposed on the solution, the deviatoric moment tensor may be determined, which excludes mechanism with volumetric change in source. When the conditions of the zero trace and zero determinant are set, the solution is limited to the double-couple source. The full moment solution can also be decomposed into the isotropic (ISO), compensated linear vector dipole (CLVD) and double-couple (DC) parts of the mechanism following the default decomposition scheme of Knopoff and Randall (1970) with percentage of decomposed tensor elements calculated by either Knopoff and Randall (1970) or Vavryčuk (2001, 2015). This

decomposition shows usually complexity of the source process and is used to check the quality of the solution (Wiejacz 1992). Uncertainties of the estimated moment tensors can be estimated through the normalized root-mean-square (RMS) error between theoretical and estimated amplitudes (Stierle et al. 2014a, b):

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^N (U_i^{\text{measured}} - U_i^{\text{th}})^2}{\sum_{i=1}^N (U_i^{\text{measured}})^2}}. \quad (2)$$

All of the studied MT solutions in this work were obtained with above described method. Nevertheless, not for all of them the uncertainty estimates are available.

3. Moment tensor solutions of tectonic earthquakes

Moment tensor solutions of three tectonic events are available in Poland; event from Podhale and two events from Jarocin (Table 1). Full moment tensors (full MT), deviatoric (trace-null MT), and double-couple (DC MT) solutions were calculated for Jarocin earthquakes, while in case of Podhale there were full and DC solutions available. The Podhale earthquake full MT was obtained with 19 regional broadband stations (Wiejacz and Dębski 2009). The decomposition of the full MT following Knopoff and Randall

(1970) approach shows very small non-DC part in the focal mechanism, which is expected in case of the tectonic earthquakes.

The two Jarocin events were recorded at different sets of stations. The 2007 Jarocin event was recorded at 12 good quality recordings available from the PLSN and PASSEQ broadband stations. The epicentral distance varied from 40 to 260 km. Most of the stations were local stations from the PASSEQ project (Wilde-Piórko et al. 2008), only two stations were the PLSN broadband ones (OJC and KSP). The 2012 earthquake was recorded at 15 stations of PLSN and VEBSN (Virtual European Broadband Seismic Network), temporary mobile seismic monitoring network, “Żelazny Most” repository lake temporary monitoring short period network and one station from the Bełchatów Mine local network. The azimuthal coverage was worse than in case of the 2007 event. The NW quadrant had only one station, namely GKP. The epicentral distance varied from 110 to 430 km, with most of the stations located about 200 km or further from source. The 2007 Jarocin event results show almost 40 % of non-DC components and the 2012 full MT has an unrealistically high non-DC component with negligible DC part of the mechanism. Such solution may be a result of the noisy data, improper velocity model or the anisotropy of the rocks. In case of tectonic earthquakes, the non-DC

Table 1

Moment tensor solutions of tectonic earthquakes in Poland

Event	November 30, 2004, Podhale	May 6, 2007, Jarocin	January 6, 2012, Jarocin
Magnitude M_L	4.8	2.8	3.8
Location			
Longitude (°)	19.899	17.496	17.533
Latitude (°)	49.445	52.009	52.007
MT components (Nm)			
M_{11}	1.03×10^{15}	3.81×10^{12}	4.82×10^{16}
M_{22}	-2.75×10^{15}	1.93×10^{12}	4.82×10^{16}
M_{33}	-3.78×10^{15}	-8.08×10^{12}	-4.98×10^{16}
M_{12}	2.08×10^{15}	-2.27×10^{12}	4.21×10^{13}
M_{13}	1.54×10^{15}	-5.27×10^{12}	-1.51×10^{13}
M_{23}	2.68×10^{15}	0.97×10^{12}	-4.53×10^{12}
MT decomposition			
ISO (%)	-2	-7.7	19.2
CLVD (%)	2.4	-30.1	-80.7
DC (%)	95.6	62.2	0.1

Parameters of Podhale event from Wiejacz and Dębski (2009)

components are considered as a result of anisotropy of the rocks. Even pure shear faulting the non-DC values derived from full moment tensor solution can reach up to 30 % (Vavrycuk 2005; Davi and Vavrycuk 2012). On the other hand, the non-DC components obtained in the amplitude inversion can be a product of noisy data and effect of the poor coverage of focal sphere Wiejacz (1992). The latter seems to be the case of the full MT inversions of the Jarocin events, where 12 and 15 stations were available, and focal coverage was limited (Fig. 2). Moreover, the 1D velocity model in case of regional epicentral distances in Poland seems to be very general approximation (Rudziński et al. 2016) and

due to the complex geology of Poland it may be the source of the errors. It is proved that Tornquist–Teisseyre zone influence the S-wave splitting (Wiejacz 2001). Detailed analysis of the full, deviatoric and pure DC solutions of both Jarocin events unveil, that deviatoric solutions show the DC component as the main part of the mechanism in both cases in contrary to the full MT solution of the 2012 event. (Table 2).

The synthetic tests of the focal coverage and noise influence on the results of full MT solutions were carried out to investigate the reliability of the full MT result. Synthetic amplitudes and polarities were generated for a priori known fault orientation—

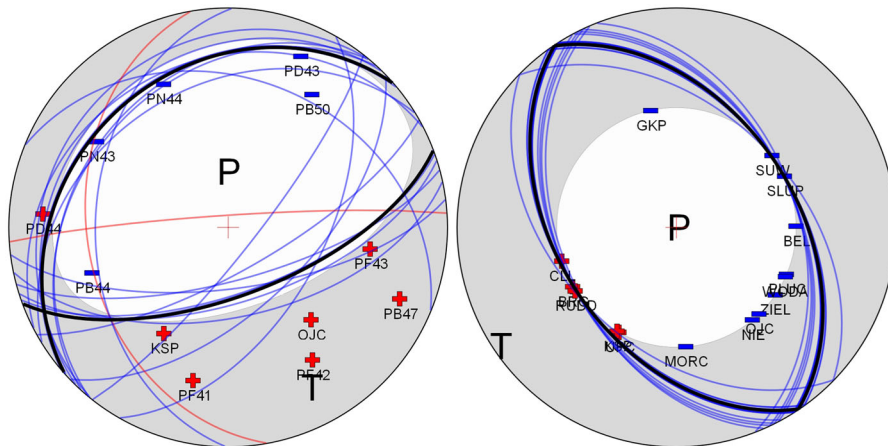


Figure 2

Full moment tensor solutions of Jarocin 2007 (*left*) and 2012 (*right*) earthquakes with stations and all possible nodal plane solutions

Table 2

Moment tensor solutions of Jarocin earthquakes

Event	May 6, 2007, Jarocin		January 6, 2012, Jarocin	
	Full MT	Null-trace MT	Full MT	Null-trace MT
MT components (Nm)				
M_{11}	3.81×10^{12}	3.17×10^{12}	4.82×10^{16}	1.81×10^{13}
M_{22}	1.93×10^{12}	1.75×10^{12}	4.82×10^{16}	5.37×10^{13}
M_{33}	-8.08×10^{12}	-4.92×10^{12}	-4.98×10^{16}	-7.19×10^{13}
M_{12}	-2.27×10^{12}	-2.12×10^{12}	4.21×10^{13}	4.00×10^{13}
M_{13}	-5.27×10^{12}	-5.09×10^{12}	-1.51×10^{13}	-1.55×10^{13}
M_{23}	0.97×10^{12}	1.10×10^{12}	-4.53×10^{12}	-0.56×10^{13}
RMS error	0.39	0.40	0.49	0.50
MT decomposition				
ISO (%)	-7.7	-	19.2	-
CLVD (%)	-30.1	-16.6	-80.7	15.7
DC (%)	62.2	83.4	0.1	84.3

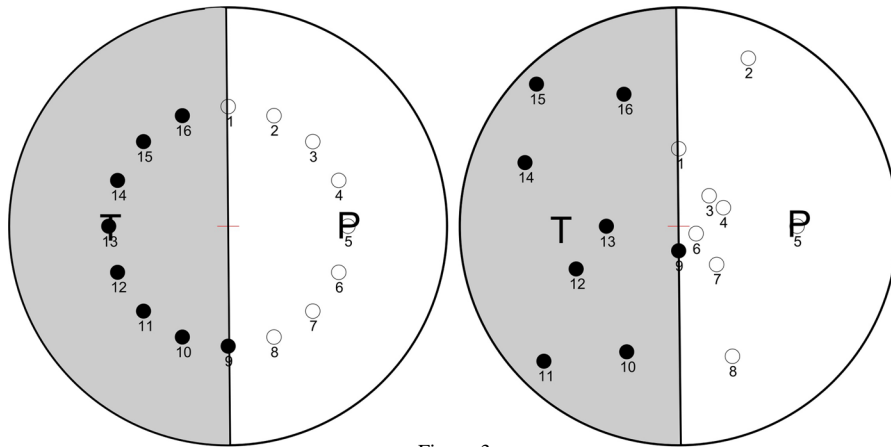


Figure 3

Vertical fault with strike N-S geometry used in the testing procedure. *Black dots* denote the positive polarities and *white dots* denote negative polarities. *Left beach-ball* shows the same take-off angles on all stations, *right beach-ball* shows good focal coverage of stations, both network configurations were used in synthetic tests

Table 3

Results of Jackknife tests of station on P-wave amplitude MT inversion

	Double-couple solution		Null-trace solution			Full solution			
	RMS	DC (%)	RMS	DC (%)	CLVD (%)	RMS	DC (%)	CLVD (%)	ISO (%)
Poor focal sphere coverage	0.009–0.01	100	4×10^{-7} – 5×10^{-7}	99.9–100	0–0.1	4×10^{-7} –0.02	84–100	–12 to 0	0–4
Good focal sphere coverage	0.009–0.01	100	4×10^{-7} – 6×10^{-7}	99.9–100	0–0.1	4×10^{-7} – 6×10^{-7}	99.9–100	0 to 0.1	0–0.1

vertical fault with strike N–E. The synthetic input data were amplitude and polarities of displacement following the proper focal sphere quadrants to the configuration with the maximum amplitudes following the P and T axes for the assumed fault. The RMS error of all MT solutions for such prepared synthetics was smaller than 0.01. First, test was run with 16 stations covering uniformly all azimuthal range with 22.5 degrees between every station. Second, the take-off angles were set to cover well the focal sphere (Fig. 3). In both cases, the jackknife station rejection test and bootstrap amplitude resampling tests were conducted. In case of the jackknife test, the seismic moment tensor inversion was performed using all available stations. Then, the inversion was performed 16 times and each time different station was removed before inversion was performed. In amplitude resampling procedure, the random noise was

introduced to input amplitude data. The amount of noise added to the original amplitude was specified as a random number drawn from Gaussian distribution with mean 0 and standard deviation of 0.1, 0.3, and 0.5. The noise to input amplitude data reached a factor of 0.2, 0.6, and 1, respectively. The number of bootstrap samples was 100, which generated 100 resampled moment tensors (Kwiatek and Martinez-Garzon 2016). Since the noise experiment is only made for amplitudes, it doesn't take into account contamination of the whole seismogram by a noise. In a high noise contamination, also the arrival time of the maximum amplitude could be missed and the damaging effect of the noise could be enhanced.

Results of the jackknife test show that the influence of a single station on MT decomposition is moderate (Table 3), while in case of the nodal plane orientation is almost negligible (Fig. 4, upper row), even if the

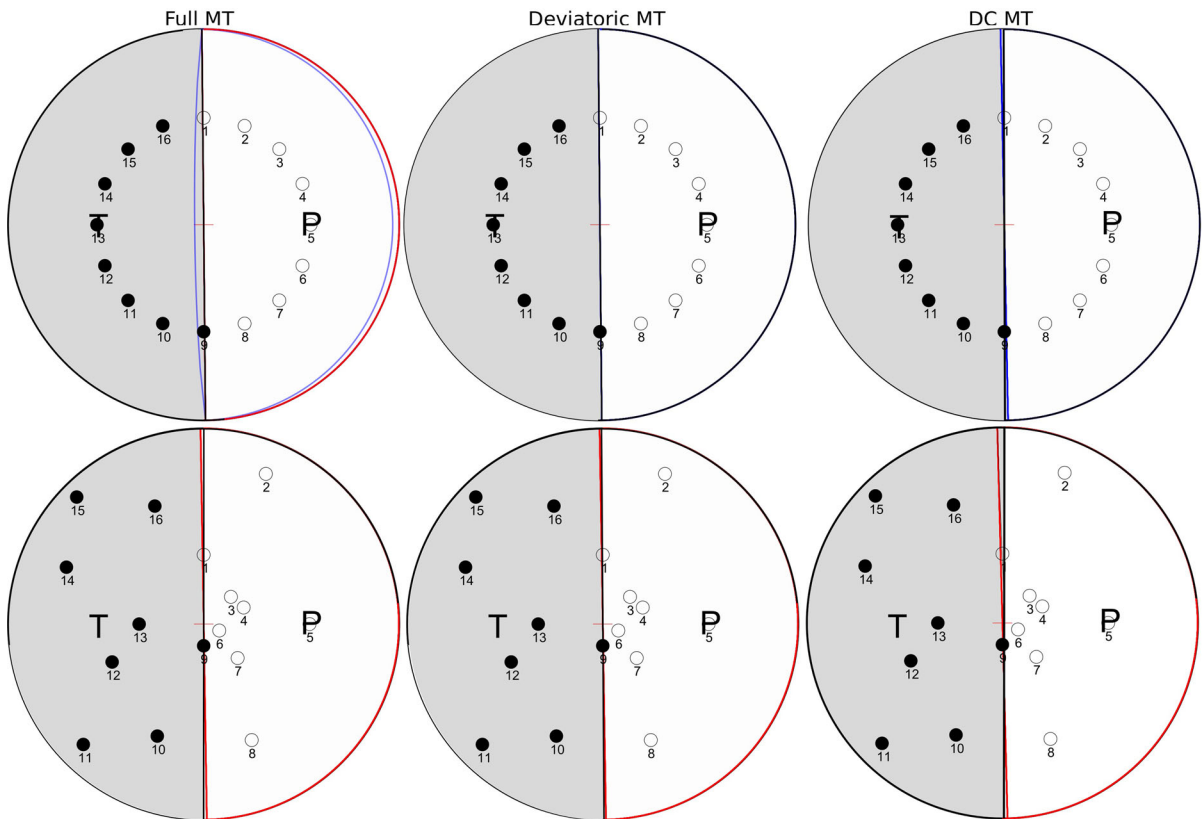


Figure 4

Results of the jackknife station rejection test. *Upper row* represents the results of tests for network configuration with the uniform take-off angle on all azimuths. The *lower row* represents network configuration with the different take-off angles covering the focal sphere well

take-off angles are similar or equal. The non-DC components of the solutions were up to 16 % in case of poor focal sphere coverage in the full MT solution but only up to 0.1 in the null-trace solution. In case of good focal sphere coverage the non-DC components in both full and null-trace solutions are negligible. The nodal plane orientation is not influenced by the single station in all tests.

The bootstrap amplitude resampling test results show the take-off angle and focal sphere coverage role in full MT inversion of noisy data (Figs. 5, 6; Table 4). The obtained DC components of MT are negligibly small in case of vast majority of the solutions obtained for the same take-off angle configuration. Variability of the P and T axes is high and highly noise dependent—the higher noise applied the higher variability in P and T axes orientation (Fig. 5). The non-DC components are

retrieved badly even in case of small noise contamination of the input data. The influence of the amplitude noise amount is significant, but there is a decrease of the solutions with DC of 50 % and above (Fig. 6) for the higher noise contamination. In contrary, the DC component is dominant in case of trace-null solution. On the other hand, the DC components in case of good focal sphere coverage showed the dominance of the DC component in solution even when up to 100 % noise was applied (Fig. 6). The null-trace solutions are in agreement with full MT solutions in terms of DC component for the good focal sphere coverage configuration. The RMS error estimates don't differ much for both configurations, but obviously the bigger noise applied the higher RMS errors. However, even in case high noise contamination of the input data the RMS didn't exceed the 0.3 value.

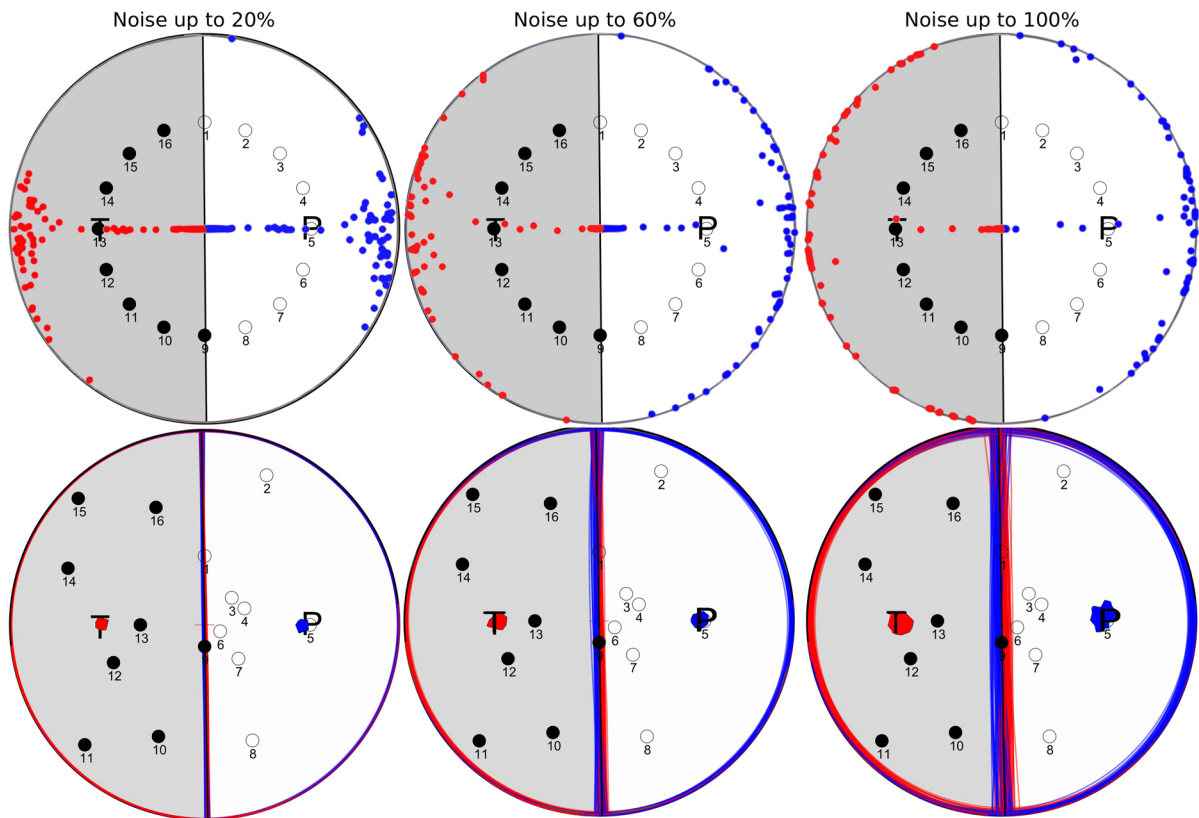


Figure 5

Full MT results of the bootstrap amplitude resampling test. *Upper row* represents the results of tests for network configuration with the uniform take-off angle on all azimuths. The *lower row* represents network configuration with the different take-off angles. *Blue and red dots* represent tension and pressure axes, respectively. On the *lower row* the nodal planes are also denoted, while on the *upper row* there are only principal axes shown due to the very small DC part of the solutions

The nodal plane orientation stability for full (Fig. 5), deviatoric (Fig. 7), and DC (Fig. 8) solutions was tested. The stability of nodal plane orientation was very bad in case of full MT inversion for poor focal sphere coverage even when small amount of noise was contaminating the input data (Fig. 5, upper row). It is connected with negligible DC part of the solution in most of the cases. The deviatoric (Fig. 7) and DC (Fig. 8) solutions were much more stable in obtaining of the proper nodal plane orientation, the difference between strike of the assumed fault planes and resulting ones were not higher than 10 degrees. In case of good focal sphere coverage the stability of the nodal plane is good for all types of solutions and wasn't influenced much by noise.

These results indicate that the Jarocin 2012 earthquake full MT solution was not reliable due to poor focal sphere coverage and noise. On the

contrary the 2007 Jarocin event was much more reliable, because the azimuthal and focal sphere coverage was good. The difference comes from the availability of local stations from PASSEQ epicentral distance of which varies from 40 to 150 km. In such case the ray tracing in the local velocity model was possible and produced good range of the take-off angles to cover well the focal sphere. Moreover, the closer stations have usually higher signal-to-noise ratio, which means lower noise contamination of the data. The 2012 event analysis was limited to the regional stations with the epicentral distance from 110 to 430 km, which did not allow us to use local velocity models in reliable way. The regional variation of the global model used in ray tracing procedure produced almost the same take-off angles for all stations within the epicentral distance from 100 to 500 km. Therefore, in case of the MT

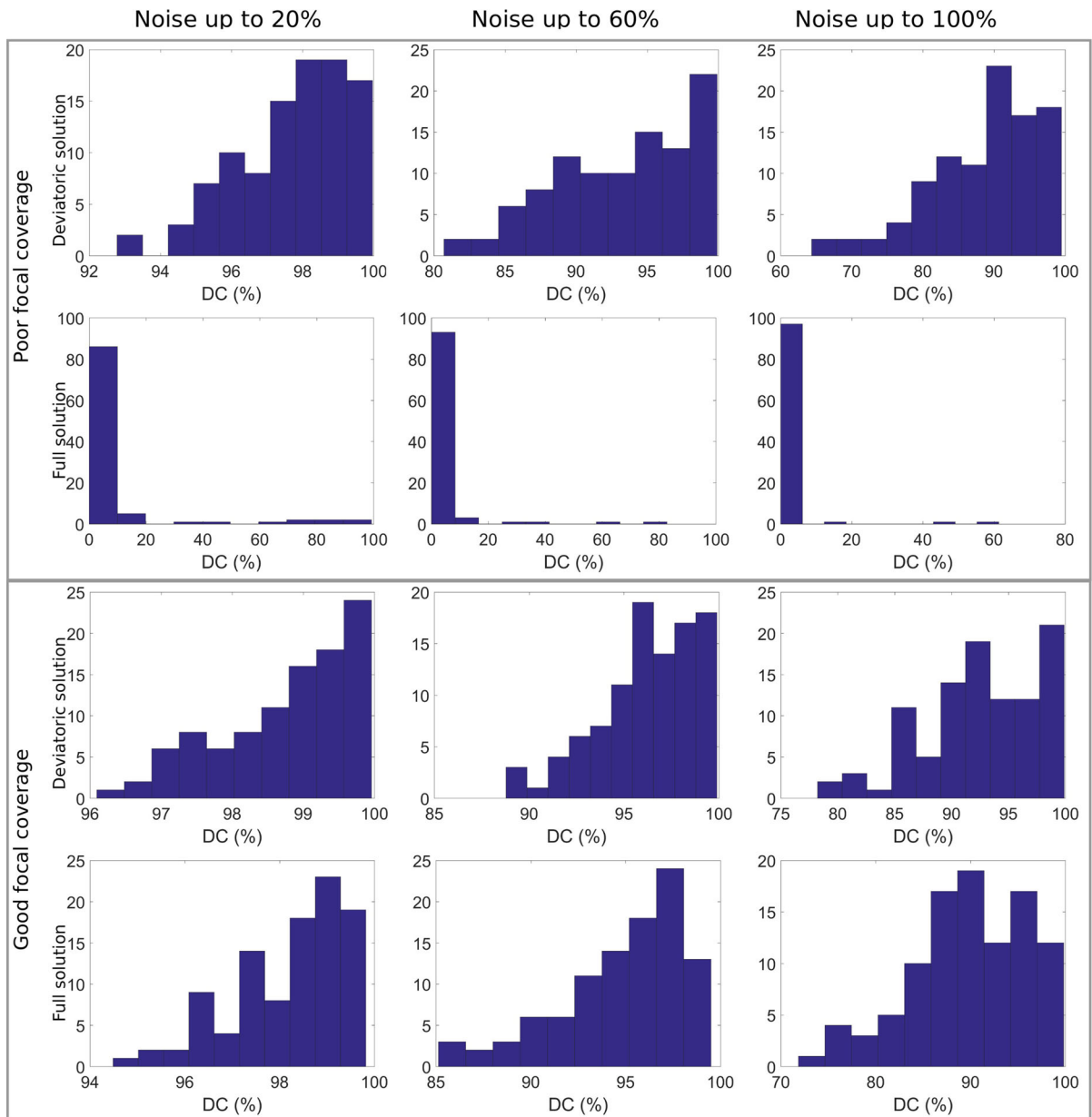


Figure 6

Histograms of the DC component of full and deviatoric MT solutions for all inversions carried out during bootstrap amplitude resampling test

inversion of small earthquakes and distant stations the results should be carefully interpreted and tested for the inconsistency between the full MT and null-trace solutions. On the other hand, the deviatoric and DC solutions are usually stable and reliable in terms of the nodal planes orientations and seismic moment component values.

4. Moment tensor solutions of anthropogenic earthquakes

Anthropogenic seismicity is the main feature of the overall seismic activity in Poland. There are several tens of moment tensor mechanisms calculated for events recorded locally in underground mines

Table 4

Results of bootstrap tests of noise influence on P-wave amplitude MT inversion

	Double-couple solution		Null-trace solution			Full solution			
	RMS	DC (%)	RMS	DC (%)	CLVD (%)	RMS	DC (%)	CLVD (%)	ISO (%)
Poor focal coverage (up to 20 % noise)	0.02–0.06	100	0.01–0.05	92.8–100	–7.2 to 7.2	0.01–0.04	0.02–99.9	–67.9 to 67.9	–32.1 to 32.1
Good focal coverage (up to 20 % noise)	0.02–0.06	100	0.01–0.05	96.1–100	–3.5 to 3.9	0.01–0.05	94.5–100	–3.5 to 4	–1.2 to 1.5
Poor focal coverage (up to 60 % noise)	0.05–0.2	100	0.04–0.2	80.7–100	–13.9 to 19.3	0.04–0.1	0.07–99.9	–67.8 to 67.8	–32.2 to 32.1
Good focal coverage (up to 60 % noise)	0.04–0.2	100	0.04–0.2	88.8–100	–11.2 to 10.8	0.04–0.1	85.1–100	–11.1 to 11	–3.4 to 4.9
Poor focal coverage (up to 100 % noise)	0.1–0.3	100	0.07–0.2	64.4–100	–35.6 to 27.6	0.07–0.2	0.02–99.9	–67.9 to 67.8	–32.3 to 32.2
Good focal coverage (up to 100 % noise)	0.01–0.3	100	0.06–0.2	78.2–100	–19.8 to 21.8	0.06–0.2	71.9–100	–19.3 to 21.5	–6.8 to 8.9

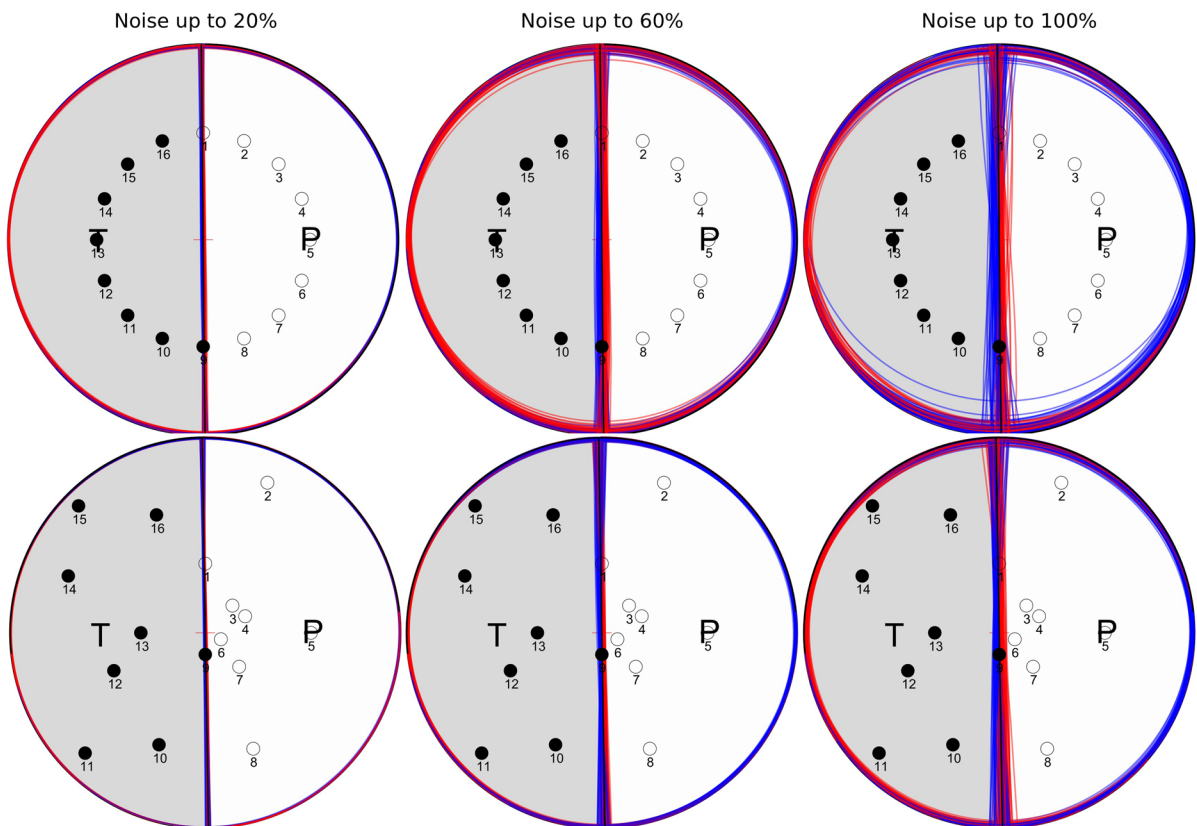


Figure 7

Null-trace MT results of the bootstrap amplitude resampling test. *Upper row* represents the results of tests for network configuration with the uniform take-off angle on all azimuths. The *lower row* represents network configuration with the different take-off angles

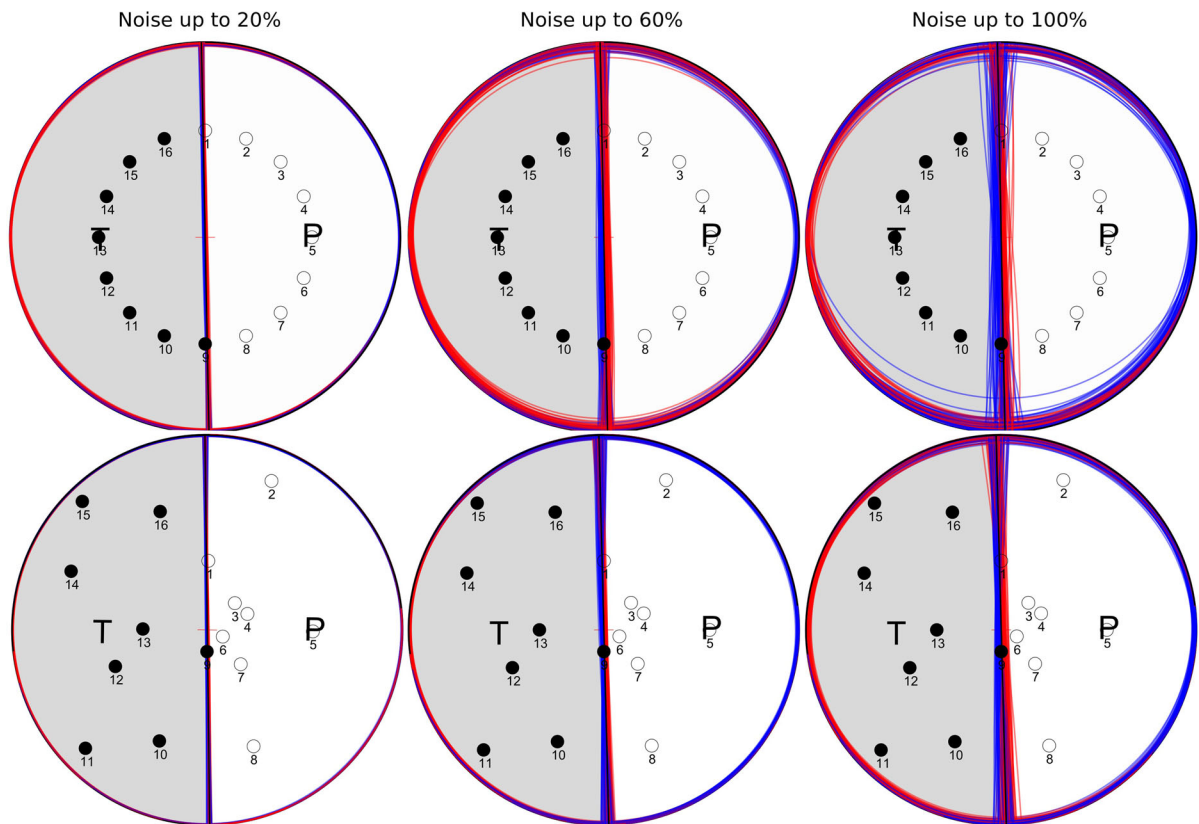


Figure 8

DC MT results of the bootstrap amplitude resampling test. *Upper row* represents the results of tests for network configuration with the uniform take-off angle on all azimuths. The *lower row* represents network configuration with the different take-off angles

(e.g., Lizurek and Wiejacz 2011; Stec 2007) and several for events near Czorsztyn reservoir. The basic mechanism solution description will be introduced below with the examples of events.

USCB underground mining has a long, over 200 years, history. Currently, exploitation is performed with longwall system on various depths from 300 to 1100 m on more than 20 mines (IS-EPOS 2016). The studies of mining-induced seismicity showed two groups of events in USCB mines: first connected directly with mining operations and second with events connected with large discontinuities (e.g., Kijko et al. 1987; Idziak et al. 1991; Gibowicz and Kijko 1994; Gibowicz and Lasocki 2001). This bimodal character may result with complex and multimodal magnitude distribution of mining seismic events (Lasocki 2001). Stec (2007) called the first group “mining” events and second “mining-

tectonic” according to full MT solutions. In nomenclature used in this work after the definition of Dahm et al. (2013) the first group is called induced seismicity, while the second one is an example of triggered seismicity. Induced events in USCB are characterized by small shearing component in full MT solution of about 10–20 % and very high non-DC components with isotropic component from 20 to 50 %. The rupture orientations rarely follow any preexisting local faults but are mainly connected with excavation geometry and mining front orientation. Location of these events was usually close to the mining front and the magnitude is rarely above $M_L = 3$. The triggered events are characterized with about 70 % of the shearing component in full MT solution and the location of these events was close to the tectonic discontinuities and usually far below the mining level. The mechanism was mostly normal

faulting with some strike-slip component involved and the nodal planes were in accord with the local faults (Stec 2007 and literature therein).

Another site of the extensive underground mining is LGCD, Southwestern Poland, where the copper ore underground exploitation is carried out in three mines: “Rudna”, “Polkowice-Sieroszowice”, and “Lubin”. The ore bearing strata exploitation depth ranges from 400 m in “Lubin” mine to 1250 in “Rudna” mine. Exploitation is performed in several mining panels with pillar-chamber mining method. (KGHM 2016). The three biggest events from LGCD took place in 1977 $M_L = 4.5$ (Gibowicz et al. 1979), in 1987 event with $M_L = 4.3$ (Gibowicz et al. 1989) and 2013 with $M_L = 4.2$ (Lizurek et al. 2015). The moment tensor studies of LGCD events have been carried out since early 1990’s (Król et al. 1991; Wiejacz 1992).

There are several hundred MT solutions from various mines published since then, showing common feature of high non-DC components in the solutions of focal mechanisms of mining induced events from LGCD (e.g., Gibowicz and Kijko 1994 and literature therein). Mechanisms with implosive or explosive component were reported for LGCD mines but usually no dominant fault plane was observed (e.g., Wiejacz 1992; Lizurek and Wiejacz 2011). Significant multidimensional clustering of the smaller events before the large seismic event with high non-DC components was detected by Lizurek and Lasocki (2014) within the chosen mining panel of “Rudna”

mine. The significant role of the non-DC mechanisms on the ground effects was also studied and proved by Orlecka et al. (2014). Unlike USCB, all the seismicity reported in the LGCD region is considered as a direct mining-induced seismicity (Gibowicz and Kijko 1994). Even in case of 2013, $M_L = 4.2$ event, which occurred on the preexisting fault within the mine, tectonic stress role in the seismogenic process cannot be confirmed (Lizurek et al. 2015). In the following study, Rudziński et al. (2016) showed that the complex rupture of such large mining seismic event started on the fault, which acted as a weak zone rather than a preexisting fault plane. The examples of obtained tensors of main event and biggest aftershocks are presented in Table 5. The dominance of non-DC components in both aftershocks and main shock supports the mining-induced origin of these events.

The last anthropogenic seismic activity in Poland is linked to the impoundment of Czorsztyn artificial lake created on Dunajec river in south of Poland. It’s filling ended in 1997. The reservoir of 234.5 million cubic meters capacity is shallow, on average between 20 to 50 m of water column. Between 1995 and 2011 there were 60 events recorded in this area (1 event per 3 months in average), but since November 2011 seismic activity has increased up to about several events per month. This region is tectonically active. Czorsztyn Lake is situated in a border zone of Inner and Outer Carpathians. Niedzica dam is located at the eastern border of Orawa–Nowy Targ Basin, which is

Table 5

Examples of full MT solutions of March 19, 2013 $M_L = 4.2$ Rudna Mine events and three of the largest aftershocks (Lizurek et al. 2015)

Event	March 19, 2013 21:09 UTC	March 19, 2013 21:13 UTC	March 19, 2013 22:05 UTC	March 19, 2013 23:15 UTC
Magnitude M_W	3.7	1.9	2.1	2.3
MT components (Nm)				
M_{11}	-1.26×10^{14}	-1.23×10^{11}	-3.59×10^{11}	-8.74×10^{11}
M_{22}	-7.10×10^{13}	-2.08×10^{11}	-1.99×10^{11}	-9.75×10^{11}
M_{33}	4.46×10^{14}	9.52×10^{11}	1.70×10^{12}	3.15×10^{12}
M_{12}	-6.76×10^{13}	-2.88×10^{10}	-1.40×10^{10}	2.02×10^{11}
M_{13}	4.49×10^{12}	1.22×10^{11}	4.95×10^{11}	4.14×10^{11}
M_{23}	-7.10×10^{13}	1.19×10^{11}	2.56×10^{11}	1.18×10^{11}
RMS	0.1	0.12	0.1	0.5
MT decomposition				
ISO (%)	25	21	21	13
CLVD (%)	33	67	64	75
DC (%)	42	12	15	12

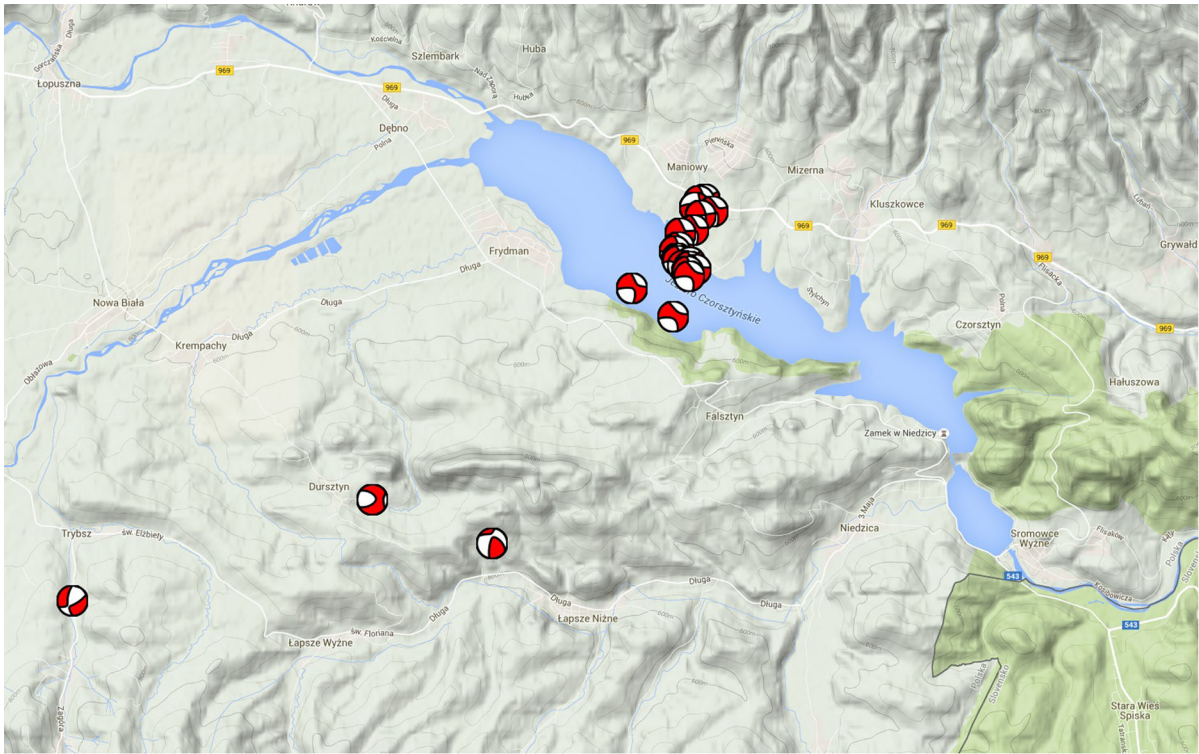


Figure 9
Focal mechanisms of 23 events triggered by Czorsztyn reservoir exploitation

the most seismically active part of Polish Carpathians with several earthquakes reported since 1717 and the strongest events reported in 1990's in the Krynica vicinity with magnitude up to $M_L = 4.0$ and early 2000's in Podhale with the biggest event of $M_L = 4.5$ (Guterch et al. 2005; Plesiewicz and Wiszniowski 2015). The seismicity of the area is considered as the triggered seismicity with delayed response (Białoń et al. 2015). Currently, there are over 150 events located in this area with M_L from -0.6 to 2.4 . There are 23 moment tensor solutions calculated for the events of $0.2 \leq M_L \leq 2.1$, Fig. 9 (IS-EPOS 2016). The MT decomposition results (Fig. 10) confirm the triggering origin of the seismicity in the area of Czorsztyn lake. Shearing component is mostly dominant part of the mechanisms, but the non-DC parts of MT are observed—most of the events have at least 20 % of non-shearing components. This is in agreement with the synthetic test results and suggests that the events were rather triggered than purely induced. This along the tectonic studies and historical seismic

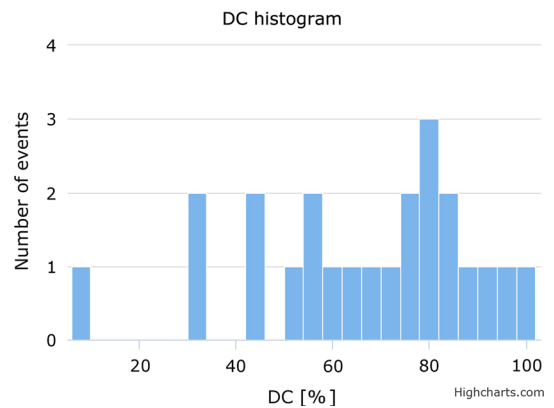


Figure 10
Histogram of DC component of full MT solutions for events near Czorsztyn lake

activity of the broader vicinity in Orawa–Nowy Targ Basin confirms hypothesis of the triggered seismicity type.

5. Conclusions

Full MT inversion is a practical tool for discriminating natural and anthropogenic seismicity especially for distinguishing triggered from purely induced earthquakes. However, the method has some limitations. The main limitation of the full MT inversion with use of the first arrival P-wave displacement amplitude comes from the focal sphere coverage and its sensitivity to noisy data. In the case of poor azimuthal and take-off angle coverage, the results may become unreliable due to the high influence of noise (Fig. 6; Table 4). This was the case of the full MT decomposition of the 2012 Jarocin earthquake, where non-DC components dominated the solution (Table 1). Therefore, the inversion for the full MT should be compared with the null-trace inversion for consistency. If a significant discrepancy is discovered, additional tests for data quality should be performed. Moreover, the interpretations of the results should be taken with caution and should be based on knowledge about tectonics and seismicity of the area. There are also other than full MT models, which may be more useful in obtaining more stable results in case of small earthquakes such as the shear-tensile crack model. This model works better in retrieval of the DC vs non-DC content of the mechanism in case of the noisy data and poor focal coverage (e.g., Šílený 2009; Šílený et al. 2014). In case of complex rupture, the proper full MT decomposition may also be crucial as it was proposed by Rudziński et al. (2016) for the Rudna mine exceptionally large event. The poor focal sphere coverage is a by-product of the velocity model of the studied area and the seismological network configuration. Sites of the sparse seismicity may suffer due to both: too approximate velocity model and sparse seismic network. This is rather rare in case of the anthropogenic seismicity, which is usually well covered by seismic stations. In Polish underground mines both the USCB and LGCD seismic networks are rather dense (e.g., Stec 2007; Lizurek et al. 2015) and allow to get proper focal sphere coverage with use of the local velocity model. It is more complicated in case of the surface networks. Rudziński et al. (2016) and Cesca et al. (2013) proved usefulness of the local and regional surface networks in obtaining full MT with

the full waveform inversion. Regional surface networks were also proved to be robust for non-DC component determination (e.g., Stierle et al. 2014b). However, very dense networks of both short period and broadband sensors with high quality recordings and reasonably detailed velocity model including the shallow subsurface layers are needed (Sen et al. 2013). The P-wave amplitude inversion was also proved to be the more robust than the waveform inversion method of the non-DC component calculation in case of surface sparse networks. The most accurate values of the non-DC components were obtained from the P-wave amplitude inversion (Fojtikowa et al. 2010). The work of Białoń et al. (2015) and the catalog of MT solutions of the events from the Czorsztyn Lake area (IS-EPOS 2016) show that the amplitude inversion of first P-wave pulses may also be a robust tool in case of surface network recordings. Even having in mind the limitations of the method the obtained results seem to be a good first approximation of the full MT.

This work confirmed the Dahm et al. (2013) recommendation, that full MT solutions should be used whenever it is possible in studies aiming at discrimination of anthropogenic (including recognition of induced and triggered types) and natural seismicity. Following the results of the MT inversions of the human-related and tectonic earthquakes from Poland, the full MT analysis should be a significant part of the discrimination workflow, but it cannot be treated as the main and only input for such discrimination.

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