Effects of 1-D versus 3-D velocity models on moment tensor inversion in the Dobrá Voda locality at the Little Carpathians region, Slovakia

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Summary

To retrieve the parameters of a seismic source from seismograms means to deconvolve the response of the medium from the seismic records. Thus, in general, source parameters are determined from both the seismograms and the Green function describing the properties of the medium in which the earthquake focus is buried. The quality of each of these two data sets is equally significant for a successful determination of the source characteristics. As a rule, both the sets are subject to contamination by effects, which decrease the resolution of the source parameters. Seismic records are usually contaminated by noise which appears as a spurious signal not related to the source. Error in the Green function is usually caused by the use of an improper model of the medium due to generally common poor knowledge of the seismic velocity of the area under study. Then, the phenomena of the structure which are not modelled in the Green function are assigned to the source where they distort the source mechanism.

To demonstrate these effects, we performed a synthetic case study simulating seismic observations in Dobrá Voda locality at Little Carpathians region, Slovakia. A simplified 1-D and 3-D laterally inhomogeneous structural models were constructed, and the synthetic data were calculated in the 3-D model. We then used both the models during moment tensor inversion. The synthetic data were contaminated by a random noise up to 10% and 20% of maximum signal amplitude. We compared the influence of these two effects on retrieving moment tensors. It turned out that a poor structural model could be compensated by a high quality data, and, in similar way, a lack of data could be compensated by a detailed model of the medium. As an example, five local events from Dobrá Voda locality were processed.

Keywords

Ray tracing, 3-D velocity model, earthquake mechanism, amplitude inversion.

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1. Introduction and motivation

The mountain region of Little Carpathians in western Slovakia, especially the zone around Dobrá Voda, suffers from moderate seismicity and is one of the most seismically active zones on the territory of Slovakia in the present days. Major known earthquake at the Dobrá Voda area was felt on January 9, 1906 with intensity I_0 = VIII-IX according to EMS98 (magnitude M ~ 5.7) and was followed by an aftershock with almost the same magnitude (M ~ 5.1). From historical data (Kárník, 1968) we obtain an evidence of another felt earthquakes in 1890 (M ~ 4.5), 1914 (M ~ 5.1), 1964 (M ~ 4.2), 1976 (M ~ 4.7). The local seismic network Malé Karpaty (MKNET) operated by ProgSeis has monitored the seismic activity instrumentally in this region since 1985. The strongest earthquake recorded by network MKNET occurred on March 13, 2006 with a magnitude of 3.4.

The Little Carpathians are situated in the transition zone between the Eastern Alps and the Western Carpathians. They border on the Danube Basin in the south-east, which is characterized by thick sediments deposited on a thinned crust. The dominant brittle structures of the Dobrá Voda area are ENE–WSW trending fault zones. The Brezová fault zone forms the northern margin of the Brezová elevation, while its southern border with the Dobrá Voda depression is represented by the distinctive Dobrá Voda fault zone (e.g. Marko *et al.*, 1991).

The study of the earthquake mechanisms in the complete moment tensor description is a useful tool for the identification of the active fault systems and for the determination of the tectonic stress. The moment tensors are sensitive to a mislocation of the hypocenters, low signal-to-noise ratios, insufficient focal sphere coverage, and especially to a quality of structural model (Jechumtálová & Šílený, 2005; Šílený, 2009). It is very common that a detailed 3-D laterally inhomogeneous model of the medium in the hypocenter area is not available, and it is thus usually substituted by simplified 1-D model.

Fojtíková *et al.* (2010) studied the double-couple focal mechanisms and complete moment tensors of selected earthquakes that occurred in the Dobrá Voda area in the period 2001–2009. They applied three methods for moment tensor inversion and compared them with respect to their accuracy and stability. 1-D structural model was used in all the three methods. As the first method they chose the Focmec code (Snoke, 2003) which inverts for double-couple focal mechanisms employing the P wave polarities. If we intend to study also non-double-couple components of moment tensor, the Focmec code cannot be used. The second method calculated the complete moment tensors from the vertical P wave amplitudes using the AMT computer code (Vavryčuk, 2009). AMT seems to be the most reliable of the three methods, but requires good focal sphere coverage. Unfortunately, for many of the events located in the Dobrá Voda region the coverage is not sufficient. Finally, Fojtíková *et al.* (2010) performed waveform inversion using the ISOLA computer code (Sokos & Zahradník, 2009). In contrary to AMT, ISOLA is not sensitive to focal sphere coverage and can be used with only few stations. On the other hand, it is very sensitive to the structural model. To obtain reliable results, 3-D structural model is needed, 1-D model is insufficient in the case of the Dobrá Voda region.

In view of the fact that the velocity data available for the Dobrá Voda locality (Geofyzika Brno, 1985) enable to construct such a 3-D structural model, we can study the effects of using 1-D or 3-D models on the resulting moment tensors. In this paper, available velocity data are shown, and the process of building the 1-D and 3-D velocity models of the locality is described. We then perform synthetic tests of moment tensor inversion in order to show possible distortions of the resulting moment tensors caused by using a 1-D velocity model for calculating the response of the medium instead of using the true 3-D model. The effect of inverting P- and S-wave amplitudes together, as compared to inverting P-wave amplitudes only, and the influence of noise contamination of the data are investigated as well. The ability to resolve non-shear components is also analyzed during the synthetic tests.

Subsequently, we perform moment tensor inversion of five real earthquakes occurred in the Dobrá Voda locality since 2009 and strong enough allowing reliable determination of source parameters. We compare the results obtained using the 1-D or the 3-D velocity models, and we conclude that the mechanisms obtained using the 3-D model are closer to the pure shear-slips than the mechanisms obtained using the 1-D model.

2. Methodology

2.1. Smoothing velocity models for ray tracing

As described above, one of the steps of the MT inversion method applied is the modelling of Green functions from the earthquake hypocenters to the stations of the seismic network. In order to calculate the Green function, the construction of a velocity model of the locality is the first step. We use the ray-theory Green function in our algorithm. In such a case, if the discrete values of velocity are known, we need to fit them by a continuous velocity model. In order to successfully perform ray tracing, proper smoothing of the velocity model is a key issue. We use the method of the construction of a velocity model by fitting the given values of velocity while minimizing the Sobolev norm of the model composed of second velocity derivatives (Bulant, 2002). The velocity in the constructed model is interpolated by B-splines. The values of velocity in the prescribed spline points of the constructed model are calculated during smoothing, based on the given velocity data and on the applied amount of smoothing.

2.2. Moment tensor inversion

The description of an earthquake mechanism by a complete moment tensor (MT) allows us to search for general dipole sources, i.e. not only for a double couple (DC), and at the same time the MT inversion remains linear. The MT could be retrieved from complete waveforms (e.g. Šílený *et al.*, 1992, 1996), amplitudes of seismic waves (e.g. Šílený & Milev, 2008) or even from their ratios (e.g. Snoke, 2003; Jechumtálová & Šílený, 2005). If the structural model is not detailed enough, the waveforms may not be correctly modelled by the synthetic seismograms, and the result of the waveform inversion may be significantly biased. The impact of uncertainty about the medium may be partly reduced by using only amplitudes instead of complete waveforms, as demonstrated by Šílený & Milev (2008). Therefore we employed amplitude inversion. The response of the medium to elementary dipole excitation, i.e. the Green functions, with regard to the amplitude of direct P and S waves was constructed by means of the ray method using the software packages MODEL and CRT (Červený, Klimeš & Pšenčík, 1988). To solve the linear system of equations in the MT inversion, we use the singular value decomposition method and apply the library routine from Numeric Recipes by Press et al. (1992).

The complete MT is commonly split into the volumetric component that can be either explosive or implosive and deviatoric component. The decomposition of the latter part is not unique, traditionally it is split into a double-couple (DC) and compensated linear-vector dipole that can be oriented either along a tension axis (T-axis) or a pressure axis (P-axis). In this paper we apply the evaluation of the percentage of individual components defined by Vavryčuk (2001).

In parallel to the MT solution, we search also for a pure DC source. Contrary to the MT inversion, which is linear, description of the pure DC source implies a nonlinear inversion. We seek for the dip, strike, and rake angles and the scalar moment in a grid search: through the full definition range with a step of 3° for the three orientation angles and within (0; $2M_0$) with a step of 0:05M_0 for the scalar moment, M_0 being the value determined in the search for the MT solution.

The MT solution has two degrees of freedom more than the pure DC solution, and thus can fit the data better. As the noise in the data, mismodeling of the Green's function, and other uncertainties of the MT inversion manifest themselves mostly in the non-DC part of the MT solution, we need to estimate the significance of the non-DC components retrieved in the particular configuration of the inverse task and reveal weather the better match of the synthetics to the data for the MT model than for a DC model is not achieved by chance. We quantify the confidence of the MT model with respect to the pure DC one in an F-test by comparing the fits achieved by unconstrained MT and pure DC models. The value of 100% shows the same confidence of these two solutions. If the probability in the F-test drops below 50%, the MT solution is less confident than the pure DC one.

The F-test is based on the assumption that observational errors are uncorrelated and random with a normal distribution. We invert amplitudes of direct P and S waves, not the waveforms, so we need not take into account the data correlation as we should do when inverting filtered waveforms. The normal distribution is however the issue: it may be well satisfied concerning the ambient noise, but the errors due to hypocenter mislocation and velocity mismodeling probably violate the assumption. Then, the applicability of the F-test is limited.

3. 1-D and 3-D velocity models of the Dobrá Voda locality

3.1. Data for the P and S-wave velocity

For the Dobrá Voda locality, the P-wave and S-wave velocity data are available in the form of a very sparsely sampled 3-D model created by Geofyzika Brno (1985), consisting of 7 x 8 x 8 discrete values of P and S-wave velocity. The data grid is rectangular but irregular, namely in the vertical direction where 6 grid points are available for depths from 0 km to 4.8 km, with two remaining grid points in depths 25 km and 50 km. The values at depths 0 to 4.8 km display lateral variation of the velocity, whereas the velocity at the remaining two depth levels is laterally invariant, see Figure 1. Vertically the data consist of two very different parts, the upper densely sampled part with a strong velocity gradient and strong lateral variation, and the lower sparsely sampled part with a weak gradient.

3.2. 1-D model of Dobrá Voda locality

Using the algorithm of the velocity model construction described above, and properly selecting the amount of smoothing, the optimum 1-D P-wave velocity model of the Dobrá Voda locality was prepared by Bulant (2010). In a very similar way, the 1-D S-wave velocity model was constructed, see Figure 1.

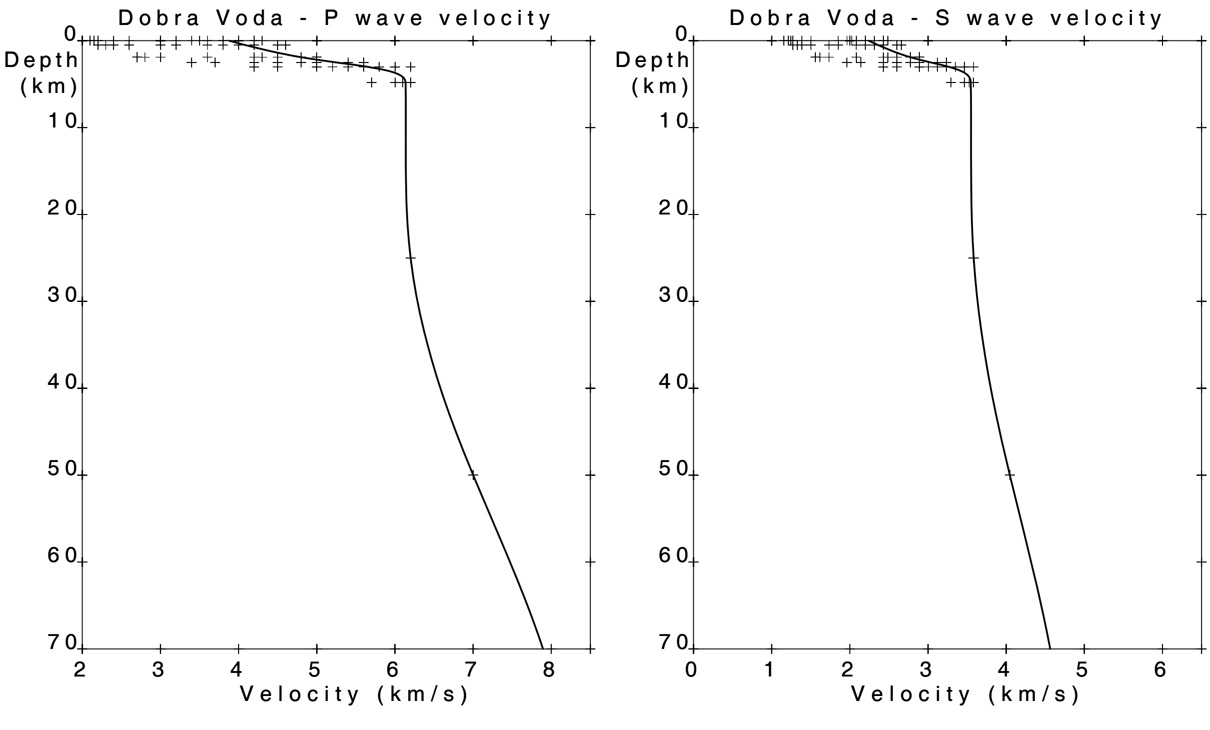

Figure 1: 1-D P-wave (left plot) and S-wave (right plot) velocity models of Dobrá Voda locality. The vertical axis is the depth, horizontal axis is the P-wave or S-wave velocity. The crosses show the values of the velocity in the data points. The solid line shows the velocity in the constructed smooth 1-D velocity models.

3.3. 3-D model of Dobrá Voda locality

Construction of the 3-D smooth velocity model using the above described method of fitting the given values of velocity while minimizing the Sobolev norm of the model composed of second velocity derivatives should be, in principle, very similar to the construction of the 1-D model. However, in the case of Dobrá Voda locality, due to the fact that the data consist of two very different parts, the construction of the 3-D model based on the velocity data only was not possible. This is mainly due to the abrupt change in the vertical velocity gradient in the data at the depth of 4.8 km combined with the lack of the data in the depths under 4.8 km. This lack of the data causes appearance of unacceptable low and high velocity channels in the depth around 12 km, as already indicated by Bulant (2010, Chapter 5).

The velocity data were thus completed with the values of velocities obtained from the 1-D velocity model in the depths of 5 to 45 km, and a 3-D model was created. Completing of the data may be justified by the fact, that the original data below 4.8 km are available only at two depths of 25 and 50 km, and are laterally invariant. Forcing the 3-D model to be similar to 1-D model under 4.8 km thus seems to be reasonable.

Several sections through the resulting 3-D P-wave velocity model are shown in Figure 2. The basic features of the locality, like higher velocities at the Little Carpathians Mountains and lower velocities at the sedimentary basin around river Váh, are nicely described by the model. Two-point rays calculated from one of the hypocentres of the earthquakes to the stations of the seismic network are displayed in Figure 2, and they illustrate that the 3-D model is suitable for calculation of ray-theory Green functions for the purposes of the moment tensor inversion.

The 3-D S-wave velocity model was constructed analogously to the construction of the 3-D P-wave velocity model, and it displays in general similar behaviour to the 3-D P-wave velocity model.

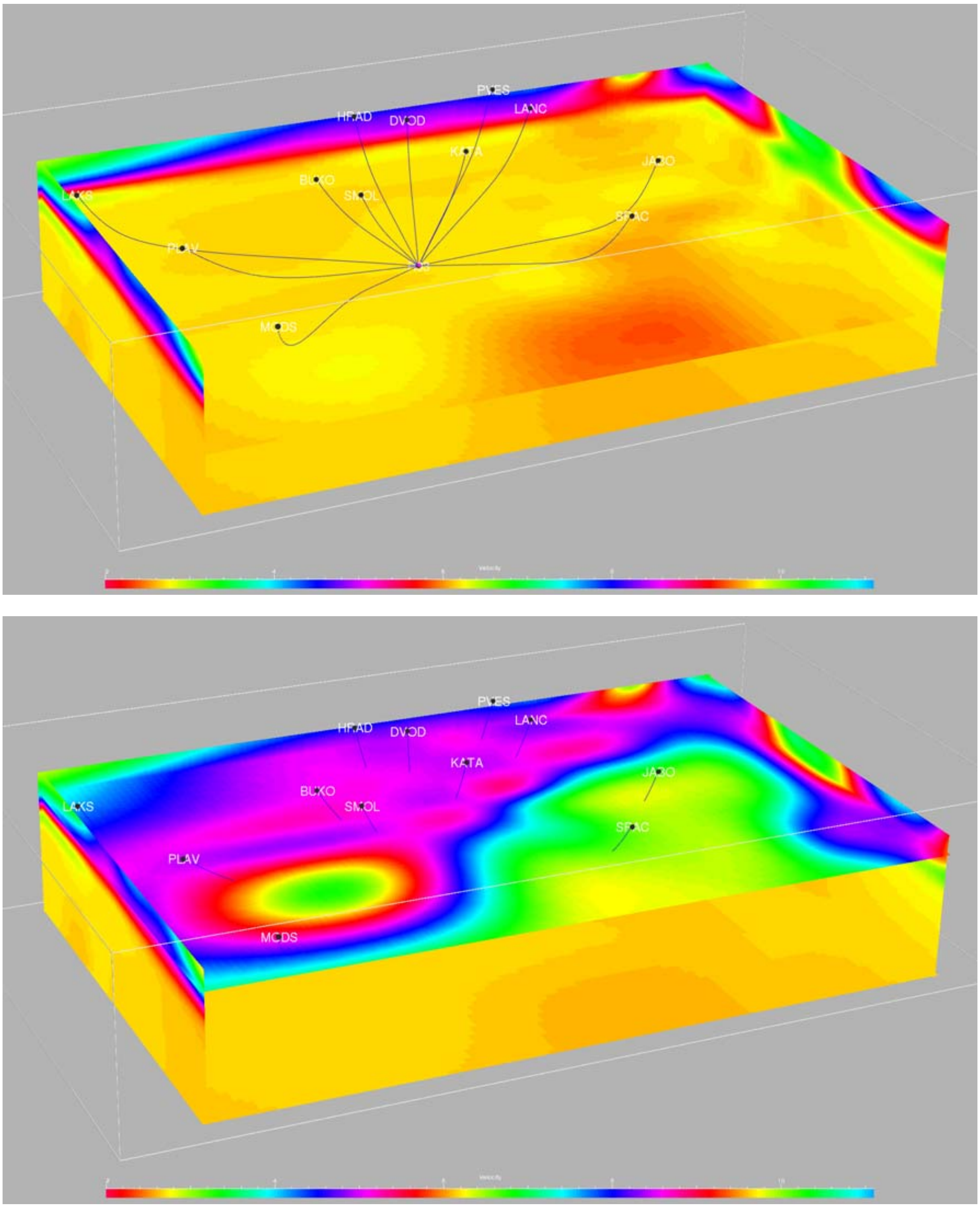

Figure 2: 3-D P-wave velocity model of the Dobrá Voda locality. Velocity sections at the west (left), north (back), east (right), and bottom side of the model are shown in both plots. The upper plot shows also horizontal velocity section at the depth of 23 km, the lower plot shows the section at 5 km depth. Positions of seismic stations are marked by black dots with station names shown in white. Two-point rays calculated from the hypocenter of one of the earthquakes to the seismic stations are also shown.

The velocity at the bottom of the model shown in brown color is approximately 6.2 km/s, the velocity under the station JABO in the lower plot shown in yellow is approximately 2.8 km/s; the velocity scales in the bottoms of the plots range from 2 to 12 km/s. The model nicely fits the basic features of the locality, like the low velocity in the sedimentary river basin in the area of stations SPAC and JABO, or the higher velocities in the area of Little Carpathians mountains in the SW-NE direction from station MODS to station PVES. However, also some probably artificial artefacts like an extremely high velocity spot between stations MODS, PLAV and SMOL appear too.

4. Synthetic tests of moment tensor inversion

To assess the resolution power of the monitoring network, it is reasonable to perform synthetic experiments. We designed a series of synthetic tests simulating the real configuration of the seismic network MKNET, with the aim to test the importance of structural model used. For a tectonic event, i.e. pure double-couple source mechanism, with dip 43°, strike 80° and rake 10°, (Figure 3), synthetic three-component P- and S-wave amplitudes are computed for 3-D structural model. These amplitudes are then contaminated by artificial random white noise with the maximum amplitude equal to 10, and 20% of the respective amplitude in order to study the importance of the quality of the data. A total of 100 data sets are generated for each level of noise. Then, all P- and S-wave amplitude datasets, P-wave amplitude datasets and vertical P-wave amplitude only datasets are inverted using the Green functions calculated in both 3-D and 1-D structural models, respectively. We checked the resolution of DC orientation and especially of the DC/non-DC contents, which is known to be sensitive to inexact modeling of the velocity in the crust.

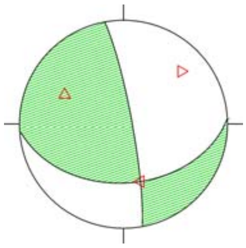

Figure 3: Source model of tectonic event for synthetic experiment. The mechanism in traditional fault plane solution, i.e. equal area projection of the lower hemisphere; black lines - nodal lines of the DC part; triangle up - T axis, triangle right - P axis, triangle left - N axis; green zone - compressions.

The results of the synthetic test, where we inverted 3-D input data using Green functions computed for 3-D structural model, i.e. the correct one, are displayed at Figure 4. The moment tensors obtained by inverting the noise free data are depicted in the traditional fault plane solutions. The resultant mechanisms of noisy data are split into two separated pictures, the first one for displaying the shear component and the second one for non-shear components. The shear part of the derived source mechanism is shown by using the principal T, P and N axes in equal-area, lower-hemisphere projection. The source type plot (Hudson et al., 1989) is used to distinguish between shear and non-shear components of moment tensor. This plot, shaped like a diamond, is a two-dimensional equal-area graphical display showing the relative position of the source mechanism to the positions of the fundamental source types. The pure-shear is located in the middle of the diamond, whereas the volumetric (V) source is displayed on top (expansion) or bottom (implosion). The cracks, dipoles and compensated linear-vector dipole (CLVD) are situated on straight lines crossing the centre of the diamond.

Not surprisingly, we obtained exact seismic source for noise free input data. At this case we observe only the effect of network configuration here, which is very good and, thus, the distortion of the reconstructed MTs is negligible. The orientation of double-couple part of the mechanism was retrieved well also for noisy input data. We can observe bigger uncertainty in the orientation of T, P and N axes only in the case when random noise up to 20% of maximum amplitude was added to the both P & S wave amplitudes. As for the DC/non-DC contents of resulting MTs, rather large distortion however appears. The decompositions of complete moment tensor are summarised in Table 1. For noisy datasets the average values for each component together with their standard deviations are given. We know that components of MT are not independent of each other, but this expression gives at least any estimation of statistical scatter.

The noise is converted mostly into the CLVD component and, considerably less, into the V component. If only P-wave amplitudes are inverted, the ratio between CLVD and V components is even higher. It implies that, in the case of noisy or insufficient data, in an effort to fit the data the procedure creates spurious non-double-couple components of the unconstrained MT. The decomposition of the moment tensor is retrieved more precisely using P-wave amplitudes only than using both P- and S-wave amplitudes. This is however a consequence of the fact the noise was constructed as a percentage of the maximum amplitude within the dataset. Since S-waves are usually stronger than P, the noise amplitudes are related to the percentage from the S-waves, thus the noise contamination of P-waves is larger in the case P- and S-waves are inverted together than if P-waves are treated alone. It means that the noise experiments incorporating both P- and S-waves on one hand and experiments with P-waves only are not fully comparable. Obviously, the noisier the data, the more uncertain is the decomposition of the MT.

The results of the synthetic test, where we inverted 3-D input data using 1-D structural model, i.e. the simplified one, are exhibited in Figure 5. We do not obtained exact seismic source for noise free input data now. The orientation of double-couple part of the mechanism was slightly shifted and some non-shear components appeared. The decomposition of resulting MTs is expressed in percentages in Table 2. For noisy datasets the average values for each component together with their standard deviations are given again. The effect of noise contamination has similar character like in the previous case, when the correct structural model was used, but we can observe much big statistical scatter.

These synthetic experiments with correct and simplified velocity models demonstrated that the more exact structural model we have the more accurate results we obtain. Thus, we can determine source parameters reliably even for smaller events provided that we are able to construct Green’s functions in the 3-D laterally inhomogeneous model.

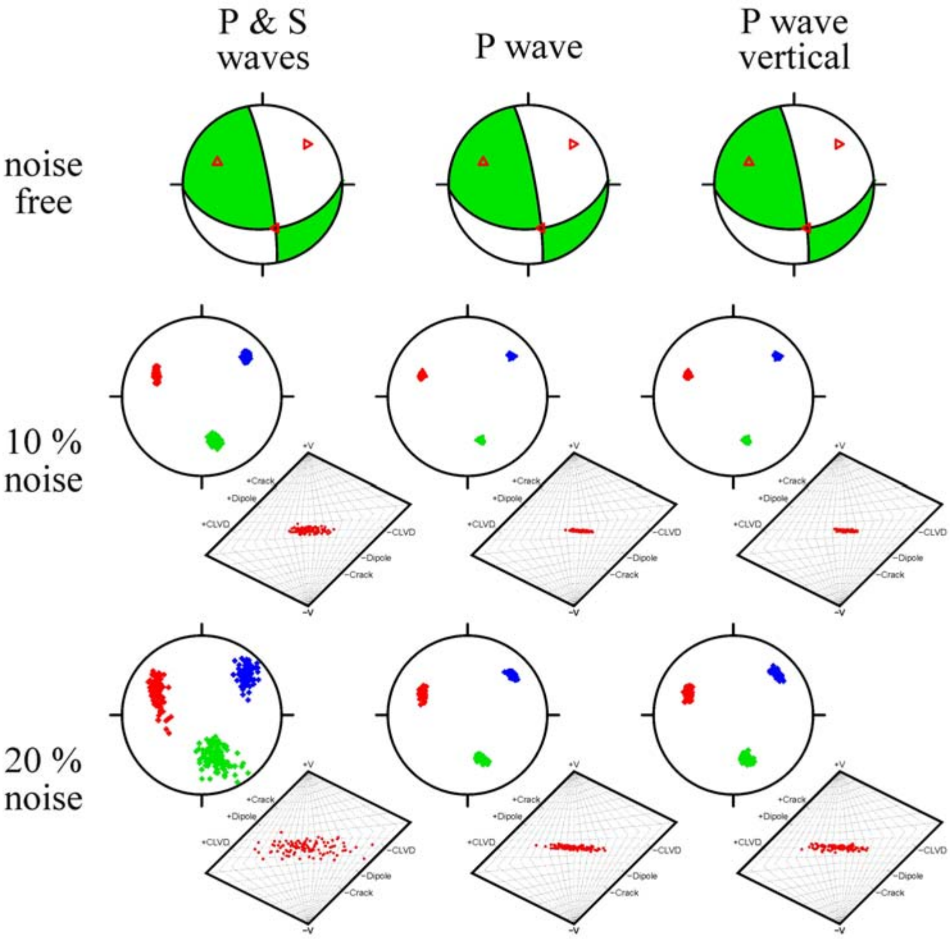

Figure 4: Synthetic experiment of moment tensor inversion using correct velocity model for calculation of responses of the medium. Upper row – noise free input data, middle row – random noise up to 10% of maximum amplitude added to the input data, bottom row – random noise up to 20% of maximum amplitude added to the input data. Columns from left to right: inversion of P together with S wave amplitude, inversion of P wave amplitude, inversion of vertical P wave amplitude only. MT of the noise free data - displayed in the traditional fault plane solutions. MT of noisy data - displayed in two ways: the shear part is shown using the principal T (red), P (blue) and N (green) axes in equal-area, lower-hemisphere projection and the non-shear part is shown using Hudson plot.

	P & S waves	P wave	P wave vertical
noise free	DC 100.0% V 0.0% CLVD 0.0%	DC 100.0% V 0.0% CLVD 0.0%	DC 100.0% V 0.0% CLVD 0.0%
10% noise	DC 88.0±7.6% V -0.7±2.7% CLVD -1.7±12.1%	DC 90.1±6.2% V -1.5±0.8% CLVD -7.7±6.7%	DC 88.4±6.4% V -1.2±1.0% CLVD -9.7±7.1%
20% noise	DC 70.6±18.2% V 0.0±7.3% CLVD 2.6±29.1%	DC 84.4±10.7% V 0.2±2.0% CLVD 0.9±17.3%	DC 82.4±11.1% V 0.1±2.5% CLVD 0.1±18.9%

Table 1: The decomposition of the moment tensors of the synthetic test with correct velocity model into the percentage of the double-couple (DC), volumetric component (positive for explosion and negative for implosion) and the compensated linear-vector dipole (positive if oriented along the tension and negative if oriented along the pressure axis).

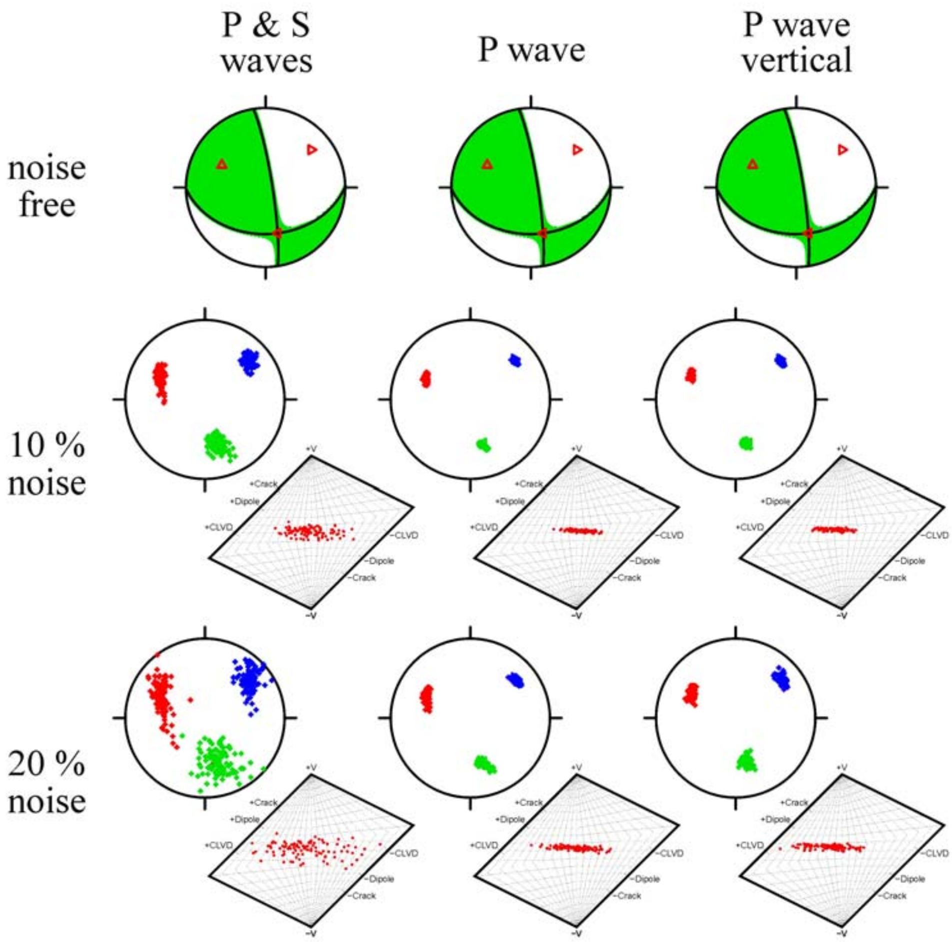

Figure 5: Synthetic experiment of moment tensor inversion using incorrect velocity model: 1-D model for calculation of responses of the medium, while the synthetic data correspond to 3-D model. For details see caption of Figure 4.

	P & S waves		P wave		P wave vertical	
noise free	DC	94.7%	DC	94.7%	DC	94.7%
	V	3.6%	V	3.6%	V	3.6%
	CLVD	1.7%	CLVD	1.7%	CLVD	1.7%
10% noise	DC	77.8±12.7%	DC	86.9±7.5%	DC	83.0±10.8%
	V	1.3±5.0%	V	2.5±1.4%	V	4.1±1.5%
	CLVD	1.4±21.7%	CLVD	-4.8±12.2%	CLVD	9.6±13.5%
20% noise	DC	64.3±19.9%	DC	79.5±12.7%	DC	72.5±18.6%
	V	1.6±9.2%	V	3.6±2.3%	V	5.0±2.4%
	CLVD	6.6±33.5%	CLVD	2.4±20.7%	CLVD	17.6±22.8%

Table 2: The decomposition of the moment tensors of the synthetic test exploring incorrect velocity modelling into the percentage of the double-couple (DC), volumetric component (positive for explosion and negative for implosion) and the compensated linear-vector dipole (positive if oriented along the tension and negative if oriented along the pressure axis).

5. Dobrá Voda sample events

At the beginning of year 2011, the MKNET network was significantly innovated. Since that time several microearthquakes have occurred in the mountain region of Little Carpathians. The five strongest events (see Table 3) that have been recorded by sufficient number of stations were suitable for moment tensor inversion.

Date	Origin time	Latitude	Longitude	Depth	M_L
20.7.2011	18:30:58,0	48.620	17.870	16.0	2.1
21.10.2011	15:58:39,3	48.530	17.170	8.0	2.5
5.3.2012	22:56:57,1	48.550	17.186	14.0	3.1
18.11.2012	21:23:31,0	48.582	17.605	5.2	1.9
16.3.2013	09:38:38,9	48.540	17.569	9.8	1.5

Table 3: The catalogue of events suitable for MT inversion. Data provided by ProgSeis.

The seismograms allow reliable estimation of P and sometimes also S wave amplitudes, which contributes to the confidence of the reconstructed MTs as we demonstrated in the synthetic modelling. When available, advantageously we inverted ground-displacement peak amplitudes of both P and S waves to retrieve the moment tensors of selected microearthquakes together with pure DC sources (Figure 6). For each event we inverted for both the full MT model and the pure DC model using 1-D and also 3-D structural model for calculation of responses of the medium. The decompositions of MTs are presented in Table 4. The resultant MTs indicate the dominance of the DC components almost in all cases, the non-DC part remaining low. Moreover, it is smaller for the inversion by using the 3-D velocity model than for the 1-D, the effect is well pronounced especially concerning the compensated linear-vector dipole (CLVD) component. Reminding the sensitivity of the non-DC to noise contamination, mislocation, irregular focal sphere coverage and the accuracy of the structural modelling demonstrated in the synthetic experiments, it suggests that they are probably insignificant here. The positions of event locations and positions of seismic stations of the MKNET network are displayed in Figure 7, which shows also the moment tensors retrieved using the 3-D model for calculation of responses of the medium. The mechanisms retrieved are in good agreement with the maximum compression in the Dobrá Voda area determined by Fojtíková *et al*. (2010) which has an azimuth of 210–220°NE and lies along the strike of the Malé Karpaty Mts.

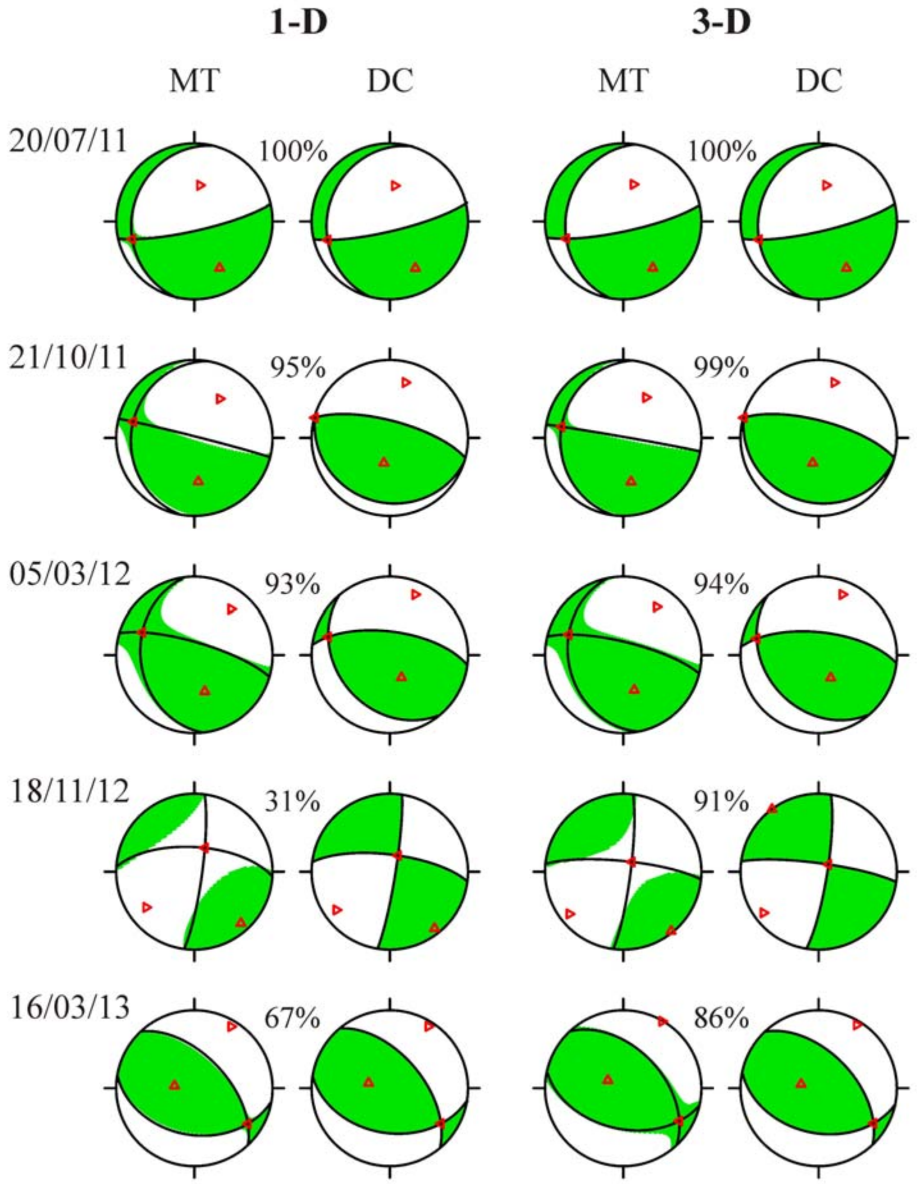

Figure 6: Full MT model and pure DC model inversion of sample events from Dobrá Voda. Left columns – 1-D model used for calculation of responses of the medium, right columns – 3-D model used for calculation of responses of the medium. Each row represents different seismic event from the mountain region of Little Carpathians. For each case the probability that the MT model is significant is displayed in percents. The probability was obtained in the F-test comparing the unconstrained MT and pure DC model.

	20/07/11	21/10/11	05/03/12	18/11/12	16/03/13
1-D model	DC 95.9% V -0.5% CLVD -3.6%	DC 64.2% V -8.2% CLVD -27.6%	DC 75.9% V 6.2% CLVD -17.9%	DC 23.6% V -10.1% CLVD 66.3%	DC 77.8% V -6.9% CLVD -15.3%
3-D model	DC 99.5% V -0.1% CLVD 0.4%	DC 75.2% V -6.9% CLVD -17.9%	DC 86.9% V 7.1% CLVD -6.0%	DC 59.4% V -3.4% CLVD 37.2%	DC 88.5% V 2.5% CLVD 9.0%

Table 4: Decomposition of the moment tensors of sample events from Dobrá Voda into the percentage of the double-couple (DC), volumetric component (V, positive for explosion and negative for implosion) and the compensated linear-vector dipole (CLVD, positive if oriented along the tension and negative if oriented along the pressure axis).

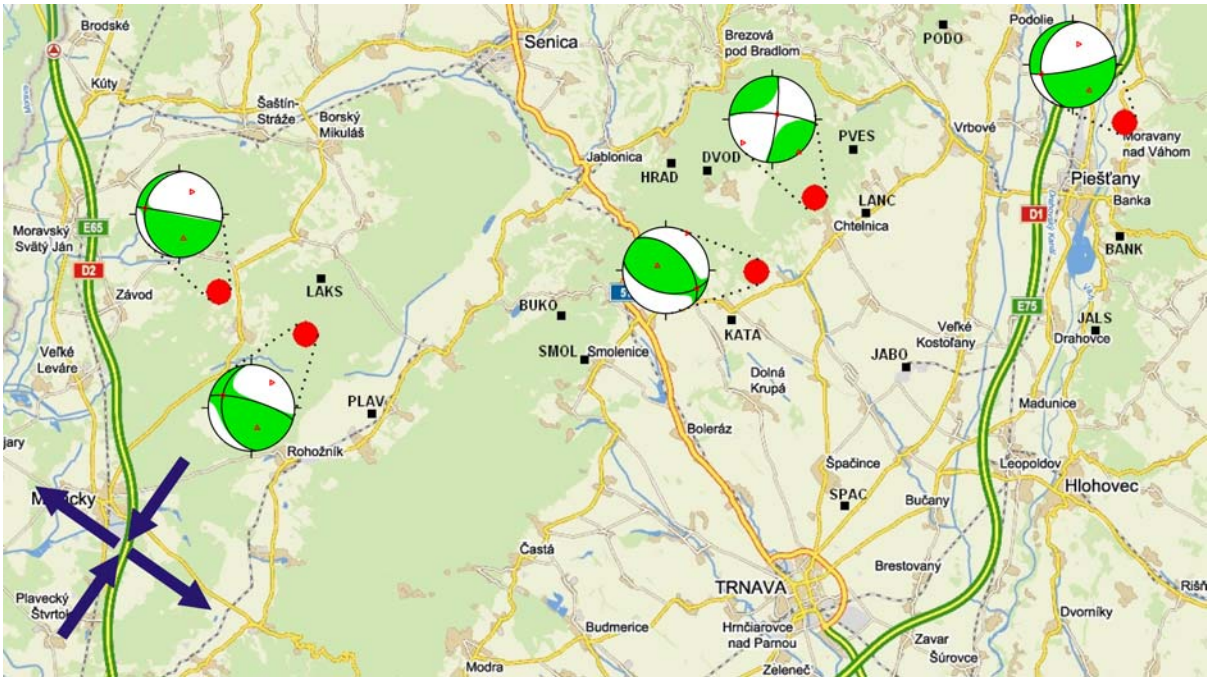

Figure 7: Locations of sample events from Dobrá Voda (red dots) and positions of seismic stations of the MKNET network (black squares) are shown together with the fault plane solutions of the full moment tensor inversions using 3-D model for calculation of responses of the medium. Blue arrows show the direction of the maximum compression and the maximum extension in the Dobrá Voda area according to Fojtíková *et al*. (2010).

5. 1. Analysis of the depth of the location of the strongest event

The discrepancy in the depth of the location of the strongest event from 5th March 2012 appeared. Two institutes assessed two different locations. ProgSeis used records from local seismic network MKNET and assigned hypocenter to 48.55N, 17.12E and depth 14 km. The Geophysical Institute of the Slovak Academy of Sciences used stations of Slovak national network and global structural model IASP and assigned hypocenter to 48.55N, 17.16E and depth 5 km. In view of the fact that event location affects significantly the ray paths we computed responses of the medium using 3-D structural model for different hypocenter depths and analyzed impact of depth variations to the moment tensor solutions (Figure 8). Source mechanisms retrieved for different focal depths, MT decomposition and values of normalized residual mean square (NRMS) are presented in Table 5. The fit of the data is improving with increasing focal depth. The orientation of shear part of the MT is changing smoothly. The higher the focal depth, the higher content of DC is included in MT. On the basis of these results we consider the ProgSeis´s location more reliable.

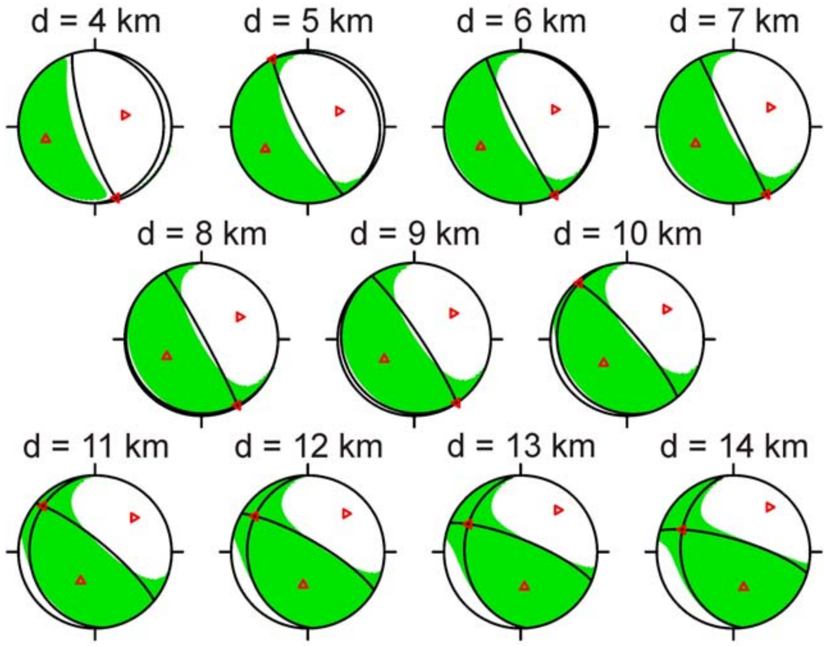

Figure 8: Source mechanisms of real event from 5th March 2012 retrieved using a general moment tensor and different focal depths. The traditional fault-plane solution and principal T, P and N axes are displayed.

depth [km]	NRMS	strike [°]	dip [°]	rake [°]	DC [%]	V [%]	CLVD [%]
4	0.398	163/1	79/11	-94/-72	42.2	-19.9	-37.9
5	0.330	153/329	82/8	-90/-93	44.7	-15.9	-39.4
6	0.284	155/336	86/4	-90/-89	52.6	-12.6	-34.8
7	0.252	154/64	90/2	-92/0	57.9	-10.0	-32.1
8	0.229	331/119	4/87	57/92	61.0	-7.5	-31.5
9	0.215	145/326	6/84	89/90	61.3	-4.8	-33.9
10	0.205	162/319	10/81	112/86	61.1	-1.9	-37.0
11	0.199	173/310	16/79	133/79	62.1	1.0	-36.9
12	0.196	177/300	22/77	145/72	66.1	3.8	-30.1
13	0.195	176/292	28/77	151/66	75.2	6.1	-18.7
14	0.194	174/286	32/77	154/61	86.9	7.1	-6.0

Table 5: Source mechanisms of real event from 5th March 2012 retrieved for different focal depths. Decomposition of the moment tensors of sample events from Dobrá Voda into the percentage of the double-couple (DC), volumetric component (V) and the compensated linear-vector dipole (CLVD).

Conclusions

The quality of the data and the accuracy of the velocity model of the area of interest are the crucial for the moment tensor inversion. The velocity data available for the Dobrá Voda locality enabled both the 1-D and 3-D smooth structural velocity models to be constructed. The models are suitable for ray tracing and enable to calculate the response of the medium which is than used in the MT inversion. The 3-D model realistically describes the basic structural features of the locality.

We performed a synthetic case study simulating seismic observations at Dobrá Voda site to demonstrate the influence of using 1-D approximation of the structure or exact 3-D structural model on the results of MT inversion. We have generated synthetic P and S waves amplitudes in the 3-D model, which were then altered by artificial random white noise with the maximum amplitude equal to 10% and 20% of the maximum amplitude in the dataset. A total of 100 datasets were generated for each level of noise. Then we inverted the data using both the 3-D and 1-D models. We showed that using inexact velocity model generates more spurious non-DC components in the mechanism, which should be taken into account during the interpretation. Using of the exact 3-D model enables to use less data or lower quality data for MT inversion and still obtain reasonable results. Nevertheless, the double-couple component appears to be sufficiently accurate to identify the fault plane orientation properly even from noisy data and with a simple structural model. When a complete reading of P and S wave amplitudes in a high quality is available, a coarse structural model (even 1-D) may be sufficient.

Source mechanisms of five strong enough events observed during last few years were retrieved by unconstrained moment tensor and pure DC inversions of the peak amplitudes of the direct P and S waves, which were extracted from the seismograms of MKNET network. Using the 3-D laterally inhomogeneous model in the MT inversion provides smaller non-DC components of the mechanisms compared to 1-D model. The retrieved mechanisms of the events indicate that all five microearthquakes are nearly pure shear-slips.

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