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EARTH PHYSICS

THE FOCAL MECHANISM OF LOW MAGNITUDE SUBCRUSTAL EARTHQUAKES OF VRANCEA RETRIEVED BY HIGH FREQUENCY WAVEFORM INVERSION

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Abstract. The goal of this work is to test the capability of high frequency local waveform inversion to retrieve the source of low magnitude intermediate depth earthquakes of Vrancea region. Following a similar procedure to that previously developed to analyze the weak shallow events from the Eastern Carpathians bending zone, we obtain a fairly robust estimate of the orientation of the double couple component of the seismic moment tensor. The resolution of the resolved fault plane solution allows correlations with the stress field in the area; this opens perspectives to using the small subcrustal earthquakes, frequently recorded, to obtain detailed information on the process taking place in the Vrancea focal region.

Key words: Vrancea seismic region, low magnitude subcrustal earthquakes, high frequency waveform inversion, seismic moment tensor, fault plane solution.

1. INTRODUCTION

The significant progress in the study of the seismic source during the passed decades is mainly due to the development of the methods for waveform inversion.

At present, the waveform inversion for the seismic moment tensor became a routine for teleseismic records [1–2] and long period regional data (*e.g.* [3–8]). The application to short period local and regional data is less frequent, due to the problems with the construction of reliable Green's functions (*e.g.* [9–11]). However, the high frequency waveform modeling is of great interest in the case of weak events with small number of records, or with noisy records, where the traditional approaches to retrieve the focal mechanism (inversion of polarities, amplitudes) may fail.

Several techniques were developed to estimate the source of low magnitude earthquakes recorded at few stations, by inversion of dominant phases of the wave trains (*e.g.* [12–14]). The uncertainty of the resolved seismic moment tensor was also investigated by a series of theoretical studies, simulating imperfect location of the hypocentre [15], mismodeling of the inhomogeneity of the velocity structure of the crust [16], neglect of anisotropy of the crust [17–18], neglect of a free surface nearby the hypocentre [19]. The results evidenced the vulnerability of the non-double couple components of the moment tensor to all the types of mismodeling mentioned, and, by contrast, the good resolution of the orientation of its deviatoric part – the fault plane solution.

The inversion of high frequency local waveforms has been applied to analyse the crustal earthquakes with local magnitude around 3.0 occurred in the seismogenic zone from the Eastern Carpathians bend (*e.g.* [20–21]). The implemented methodology – INPAR (INdirect PARameterization) algorithm [13], complemented with a bootstrap procedure [21–22] – resulted in robust estimates of the fault plane solutions by using at least five high quality records (with high signal/noise ratio) [21–24]. The stability tests [22], [25–27] proved that the resolution of the orientation of the principal axes of the moment tensor allows correlations with the stress field in the area.

Contrary to the shallow events, the low magnitude subcrustal earthquakes of Vrancea region have been less approached by now [20–21], [24] due to increased difficulties encountered in the forward modeling, related to availability of reliable structural models down to about 200 km, appropriate space distribution of recording stations, numerical problems in generating Green's functions for deep sources (depths greater than 60 km).

The recent progress in modeling the P- and S-wave velocity distribution in crust and Upper Mantle beneath the Vrancea region and surrounding area, the large number of permanent seismic stations equipped with high quality digital instruments installed during the past decade, as well as late numerical developments and our wide experience with crustal earthquakes afford at present the study of the source of weak intermediate depth events of Vrancea by high frequency waveform inversion. The goal of this paper is to show that the inversion procedure previously developed to investigate the Vrancea shallow earthquakes can be successfully extended to subcrustal events, yielding fairly robust estimates of the focal mechanism and its uncertainty.

2. METHOD

The inversion scheme INPAR (INdirect PARameterization) developed by [13] for high frequency waveform data is a 2 steps algorithm which implements the indirect parameterization of the point source: instead of determining directly the moment tensor and source time function as traditional approaches do (*e.g.* [12],

[14]), it involves 6 independent time functions representing the time derivatives of the components of the seismic moment tensor. The first step is a linear inversion – very rapid – which determines the 6 moment tensor rate functions by taking advantage of the linear relation between them and the components of the ground displacement. The second step is a non-linear inversion, by which the 6 independent functions (involving a mechanism varying in time – unreasonable assumption for the weak events) are reduced to a common time function (the source time function) and a constant mechanism. The inverted moment tensor is decomposed afterwards into its isotropic component and deviatoric part, separated in the double couple and compensated linear vector dipole components.

During its first step, INPAR performs also a dynamic relocation of the hypocenter, and a simple optimization of the structural model simultaneously with the determination of the 6 moment tensor rate functions. The Green's functions are constructed in several levels around the hypocenter depth and interpolated during an iterative search. Similarly, iterations are performed on the continuous scale between two extreme structure models with the aim to select the best-fitting one.

The Green's functions needed to extract the moment tensor rate functions from the observed seismograms are computed using the multimodal summation method in layered anelastic media [28–29]. The method allows to solve in an exact and complete way the full wave equation in a preassigned interval of frequencies and phase velocities; the synthetic signals incorporate the contribution of all the rays which propagate with phase velocity less than a maximum value, given by the S-wave velocity assigned to the half space used to terminate the structure at depth.

To obtain reliable source parameters and estimate roughly their errors, the inversion scheme is complemented with a bootstrap procedure [21–22]; it consists in inverting subsets of the complete data set (instead of processing the available records altogether), combined with rejection of obvious outliers – solutions which deviate strongly from the average. The outliers are specified using the criterion of a "distance": the difference in the orientation of the principal axes of the moment tensor – calculated as the sum of deviations of the individual principal axes (tension, null vector and pressure) – should exceed a given threshold.

3. DATA

The subcrustal event selected for this pilot analysis is presented in Table 1.

Table 1

The study earthquake

Date	*Origin time*	*Lat.* [°N]	*Lon.* [°E]	*Depth* [km]	*Local magnitude*
11 November 1997	23: 06: 06	45.77	26.97	71	3.6

The use of modal summation in the forward modeling, a method based on the complete wavefield synthesis, very advantageous in the inversion of complex high frequency waveforms where the identification of phases may be difficult and rather uncertain, restrains the number of suitable source – station configurations.

The modal summation allows us to describe all the rays propagating with phase velocity less than a maximum value – which is the S-wave velocity assigned to the half space (*e.g.* [30]) – therefore the method can be successfully applied only for epicentral distances reached by these rays; these distances depend on both structural model and source depth, and are, generally, comparable or greater than the hypocentral depth.

This constraint limits the number of eligible stations in the case of subcrustal sources, as the records from locations close to the epicenter become unusable for the inversion.

Nevertheless, the present development of the permanent seismic networks operating in Romania allows the successful investigation of the Vrancea intermediate depth earthquakes by the methodology for high frequency waveform modeling described above. The network of 30 stations equipped with K2 accelerometers, with acceleration and velocity channels (broadband and short period sensors), installed in the period 1996–1999, and the automatic seismic array installed in 2002 in Bucovina, together with the older telemetered network of 15 stations with short period instruments, working since 1981, cover a wide area around Vrancea focal zone and provide a large amount of high quality digital data.

The observed waveforms used in this study are collected by 7 stations belonging to the K2 accelerometer network (Table 2). Fig. 1 shows their location. The rough data – vertical component velocity records, sampled with 200 sps – are displayed in Fig. 2.

Table 2

The coordinates of the seismic stations and the characteristics of their instruments

Seismic station	*Latitude* [°N]	*Longitude* [°E]	*Elevation* [m]	*Natural frequency* [Hz]	*Damping coefficient*
Bucureşti-Măgurele (BMG)	44.35	26.03	118	0.700	0.700
Fulga (FUL)	44.89	26.44	117	0.480	0.999
Luciu (LUC)	44.97	27.10	120	0.470	0.768
Mangalia (MAN)	43.85	28.51	94	0.700	0.799
Muntele Roşu (MLR)	45.49	25.94	1392	0.450	0.947
Tescani (TES)	46.51	26.65	465	0.010	0.700
Vârlezi (VAR)	45.88	27.86	195	0.730	0.679

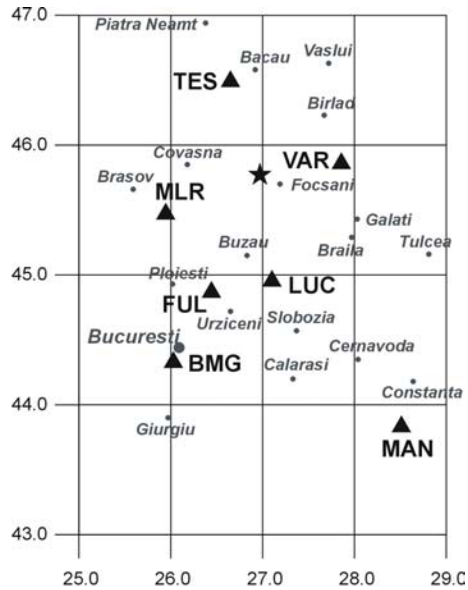

Fig. 1 – Location of epicenter (star) and seismic stations (full triangles).

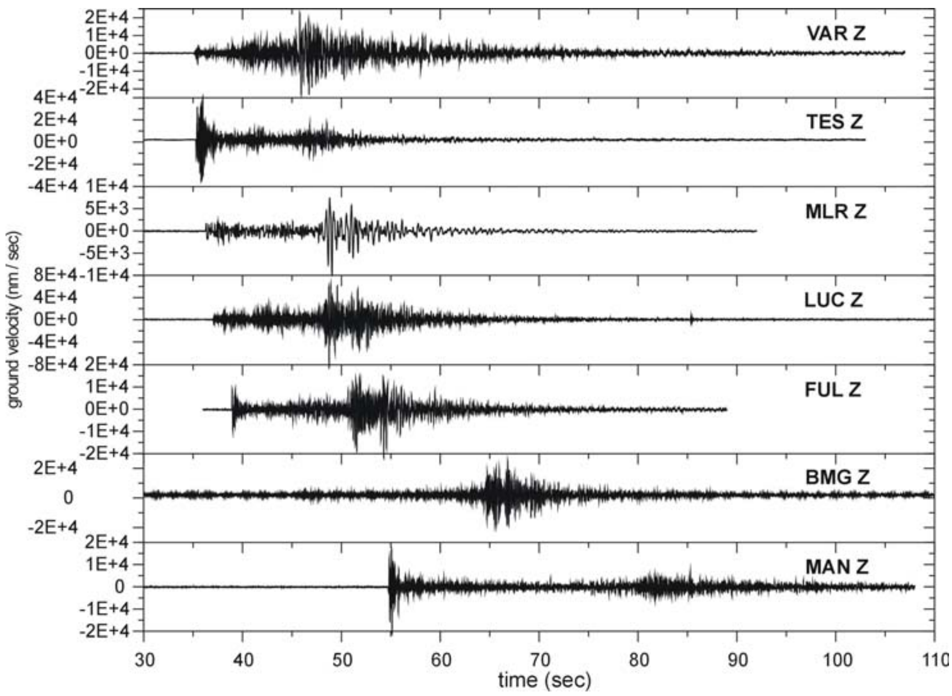

Fig. 2 – The observed waveforms - rough data; epicentral distances: VAR station – 70 km, TES station – 86 km, MLR station – 86 km, LUC station – 89 km, FUL station – 106 km, BMG station – 175 km, MAN station – 245 km.

4. STRUCTURAL MODELS

A 3-D inhomogeneous model capable to describe accurately the complex structure of the medium beneath the area from the Eastern Carpathians bend is not available yet. Its construction being a long term objective, simpler alternatives have to be accepted to simulate the prominent lateral variations of the structure in the Vrancea region.

In the present work, we adopt specific 1-D models for each source-to-station path, to approach roughly the dependence on azimuth. Similar approximation was successfully used in the inversion of high frequency data from crustal earthquakes (*e.g.* [21–22]).

The structures are constructed as realistically as possible, by integrating data available from geological and seismological measurements and studies (Figs. 3–9).

The models for the sedimentary cover approximate the local structure for an area of a few km^2 around the recording stations. The thickness of layers and P-wave velocities are determined from geological cross-sections, seismic reflection and refraction profiles [31], 3-D tomographic inversion [32]. The S-wave velocity is derived from seismic refraction profiles [33] or from P-wave velocity, using v_P/v_S ratios from literature, appropriate for the corresponding rock types [34–37].

The values of thickness and P- and S-wave velocities in the crystalline crust are assigned from deep seismic sounding [38–40] and travel time curves of earthquake data [41].

Source of information on the subcrustal distribution of the P- and S-wave velocities were body-wave tomography studies carried out using local, teleseismic and global travel time data [42–44], as well as surface waves tomographic analyses [45].

The density was obtained by laboratory measurements of rock samples from boreholes or adopted from literature, in correlation with the P-wave velocity and rock type [46–49].

The quality factor of the medium is the less certain structural parameter. Most of the studies focused on the attenuation of the seismic waves in the area do not provide direct estimates of Q (*e.g.* [50–53]), or yield average Q-values for the whole ray path (*e.g.* [54–57]). Works investigating the depth dependence of the quality factor in Vrancea region are sparse (*e.g.* [58–60]. Therefore, for each focus-to-observation point path we propose several reasonable 1-D models for Q, with values adopted from literature and correlated with the seismic wave velocities in each layer (see Figs. 3–9).

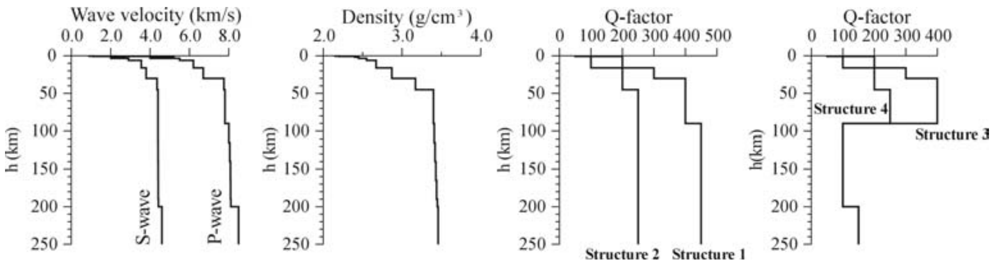

Fig. 3 – The structural models for the source – BMG station ray path.

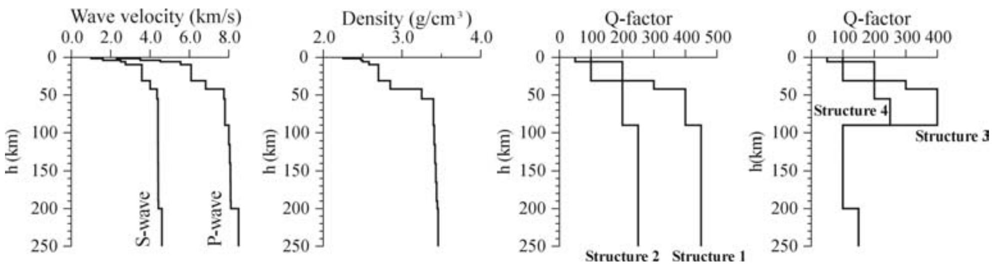

Fig. 4 – The structural models for the source – FUL station ray path.

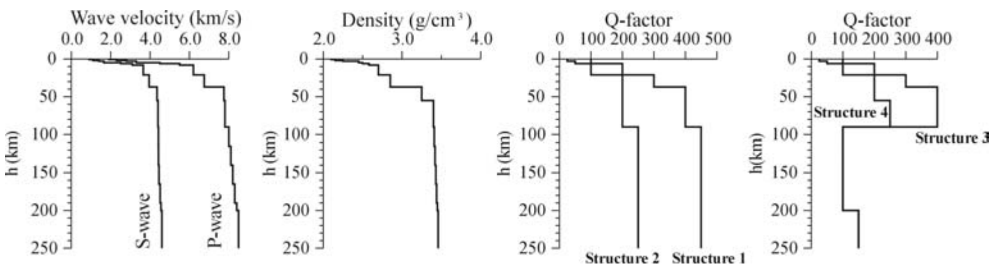

Fig. 5 – The structural models for the source – LUC station ray path.

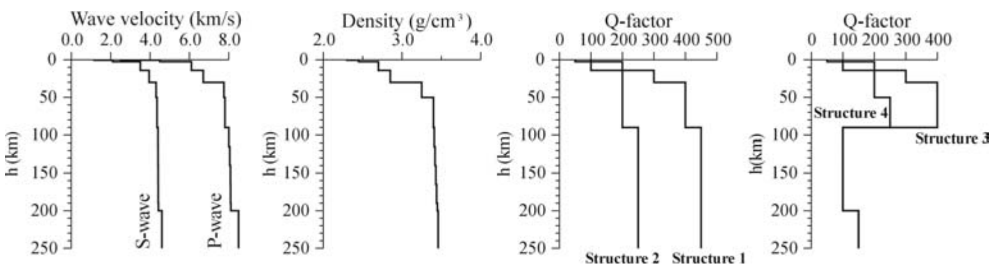

Fig. 6 – The structural models for the source – MAN station ray path.

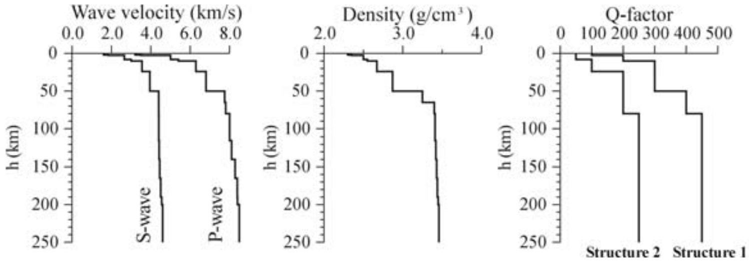

Fig. 7 – The structural models for the source – MLR station ray path.

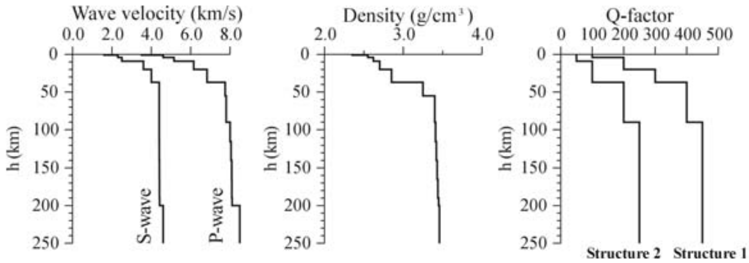

Fig. 8 – The structural models for the source – TES station ray path.

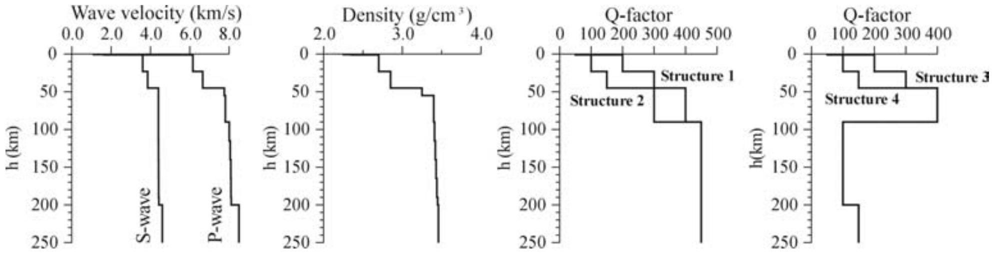

Fig. 9 – The structural models for the source – VAR station ray path.

5. WAVEFORM INVERSION

The spectral analysis of the short period records of Vrancea low magnitude earthquakes reveals low energy of the waveforms for frequencies below 1 Hz. Therefore, using a maximum frequency of 1 Hz in the inversion for source parameters as previous studies do (*e.g.* [20–21]) seems rather inadequate, as a significant amount of information contained in the wave trains may be lost. On the other hand, a high frequency content of the waveforms to be inverted increases the vulnerability of the reconstructed source parameters to the mismodeling of the medium structure.

Taking into account our experience with crustal sources [21–22], [24] we adopt the maximum frequency of 5 Hz for the present analysis.

The Green's functions are generated by modal summation up to 5 Hz; the number of modes of oscillation needed to synthesize the complete seismograms exceeds 140 for all the structures (Table 3).

The velocity records are also filtered by low-pass with cut-off frequency at 5Hz. The most energetic part of the observed signals is selected for the inversion; the truncation procedure is illustrated in Fig. 10.

Table 3

The number of modes of oscillation needed to compute the complete seismograms for the maximum frequency of 5 Hz

Seismic station		*Number of modes*
București-Măgurele (BMG)	Structure 1	149
	Structure 2	149
	Structure 3	148
	Structure 4	148
Fulga (FUL)	Structure 1	182
	Structure 2	182
	Structure 3	181
	Structure 4	180
Luciu (LUC)	Structure 1	158
	Structure 2	155
	Structure 3	179
	Structure 4	178
Mangalia (MAN)	Structure 1	143
	Structure 2	142
	Structure 3	142
	Structure 4	141
Muntele Roșu (MLR)	Structure 1	146
	Structure 2	146
Tescani (TES)	Structure 1	151
	Structure 2	150
Vârlezi (VAR)	Structure 1	151
	Structure 2	150
	Structure 3	151
	Structure 4	150

The INPAR algorithm performs during its first step a simple optimization in the sense of selecting the best-fitting Green's function on the continuous scale between two structural models. However, this is not an inversion for the structure, as we cannot pass beyond the extreme models *a priori* chosen.

In this study the two alternative structures differ only by the quality factor: from the *Q*-models initially proposed we select the optimal pair to be used in the inversion by comparing the fit between the resulted Green's functions and observed seismograms (see Fig. 10). It is worthy to mention that the structures with low attenuation in the subcrustal segment are more appropriate to reproduce the data, for all the investigated rays.

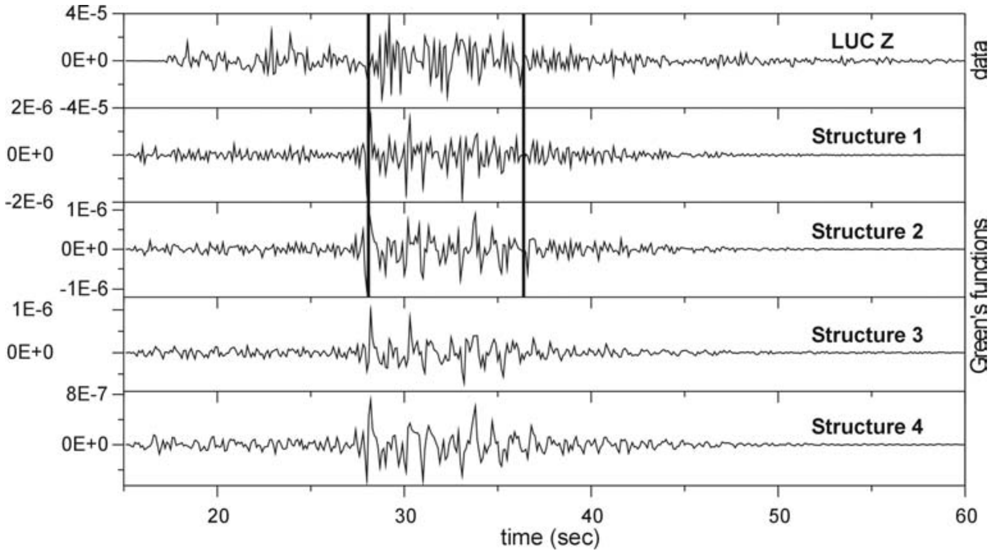

Fig. 10 – The selection of the time window. The observed data (m/s) are plotted together with the elementary seismograms (m/s), computed for several models for *Q*-factor. Elementary seismograms correspond to an instantaneous point source located in the hypocenter of the study earthquake, having the scalar moment $M_0 = 10^{15}$ Nm, and based on a moment tensor with M_{11} the only nonzero component. Vertical bars indicate the time window used in the inversion.

The 1-D models designed to reflect the average medium properties along the selected ray paths represent only gross approximations of the real structure, consequently they may result in inexact Green's functions which deteriorate the quality of the inversion solution. To cope with the uncertainty from the structural modeling we apply a bootstrap procedure – a similar approach to that followed in the analysis of shallow events.

The data sets selected for bootstrap trials have to fulfil the requirement of the minimum number of stations needed to determine the moment tensor, and also the requirement of a reasonable azimuthal coverage with the stations currently chosen. Based on the experience with crustal earthquake data processing [22, 24], we accept subsets of 4 vertical records (where the dominant part of the wave train is formed by S- and Rayleigh waves), from recording stations displaying a sector greater than 100°.

As outliers we classify the individual moment tensors with fault plane solution differing by more than 180° from the average.

Fig. 11 shows the fit of the synthetics to the seismograms for an individual station subset.

The pattern of fault plane solutions obtained by bootstrap approach can be observed in Fig. 12. The double couple percentage varies across the subsets, but the double couple orientation is fairly stable (Table 4). The average mechanism

(Table 5, Fig. 13a) is consistent with the distribution of the available P-wave polarities. The volumetric component of the average moment tensor is negligible (0.1% of the total moment), the retrieved source being purely deviatoric. The compensated linear vector dipole component is rather large (36% of the the total moment), but most probably it is an artifact of the inaccurate modeling of the medium structure.

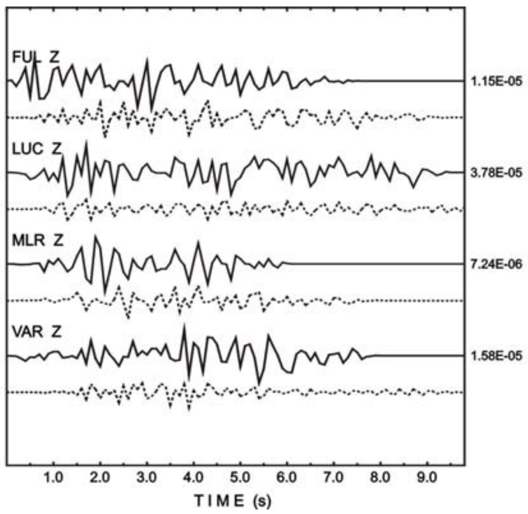

Fig. 11 – Observed data (solid lines) and synthetic seismograms (dashed lines). The numbers in the right-hand side represent the maximum amplitude (in m/s) for the particular station.

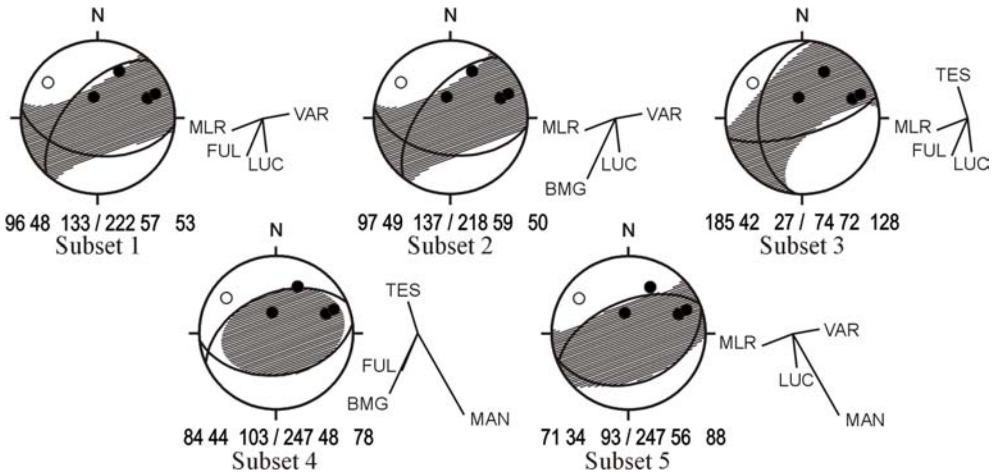

Fig. 12 – Fault plane solutions (shaded area – compressions, white area – dilatations) determined using individual station subsets. Observed P-wave polarities: dilatation – open circles, compression – full circles.

Table 4

Individual bootstrap solutions

Station subset	*Plane 1*			*Plane 2*			*T-axis*		*N-axis*		*P-axis*	
	strike	*dip*	*rake*	*strike*	*dip*	*rake*	*strike*	*dip*	*strike*	*dip*	*strike*	*dip*
1. FUL, LUC, MLR, VAR	96	48	133	222	57	53	76	59	245	30	337	5
2. BMG, LUC, MLR, VAR	97	49	137	218	59	50	74	56	242	33	335	6
3. FUL, LUC, MLR, TES	74	72	128	185	42	27	25	48	240	36	136	18
4. BMG, FUL, MAN, TES	84	44	103	247	48	78	88	81	255	9	345	2
5. LUC, MAN, MLR, VAR	71	34	93	247	56	88	148	79	248	2	339	11

Table 5

The average fault plane solution

Plane 1			*Plane 2*			*T-axis*		*N-axis*		*P-axis*	
strike	*dip*	*rake*	*strike*	*dip*	*rake*	*strike*	*dip*	*strike*	*dip*	*strike*	*dip*
98	50	127	228	52	54	75	62	252	28	343	1

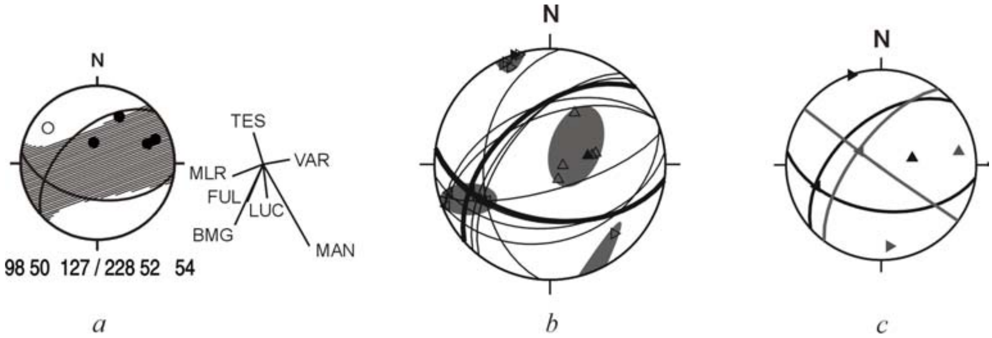

Fig. 13 – a) Average fault plane solution (shaded area – compressions, white area – dilatations). Observed P-wave polarities: dilatation – open circles, compression – full circles. b) Principal axes and nodal lines for the average mechanism (full symbols and thick lines, respectively) and the bootstrap solutions (empty symbols and thin lines). T-axis - triangle up, P-axis - triangle right, N-axis - triangle left. The shaded areas enclose the individual bootstrap axes. c) Principal axes and nodal lines for the mechanism determined by waveform inversion (black symbols and lines) and from P-wave polarities, respectively (grey symbols and lines). T-axis - triangle up, P-axis - triangle right, N-axis - triangle left.

The reliability of the average solution can be roughly estimated from the distribution of the individual fault plane solutions (Fig. 13b). N-axis is the most certain parameter, but also P- and T-axes can be considered as fairly well constrained. The average mechanism indicates a dominant reverse faulting with quasi-vertical T-axis; the compressive axis is quasi-horizontal and roughly oriented NW-SE.

The fault plane solution determined by standard methods – inversion of signs of first arrivals – [61] is displayed in Fig. 13c for comparison. The mechanisms determined by the 2 methodologies differ significantly; both of them point to a reverse faulting, and the P-axes are reasonably clustered, but the N- and T-axes vary largely.

The solution estimated from P-wave polarities was obtained by using no more than 11 observations, therefore its uncertainty is considerable. On the contrary, the mechanism retrieved by inverting 7 high frequency records is more reliable, because the waveform modeling, which implicitly includes many seismic phases, requires only few stations. Moreover, the bootstrap approach we used to evaluate the error in the determination of the double couple component evidences the good resolution of the orientation of the deviatoric part of the resolved moment tensor.

6. CONCLUSIONS

The present work aims to demonstrate the functionality of the high frequency local waveform inversion in investigating the focal mechanism of low magnitude intermediate depth earthquakes from Vrancea region.

The procedure followed in this analysis can be successfully applied due to the recent advancement of knowledge on lithosphere structure beneath the area from the Eastern Carpathians bend, development of recording networks, as well as to the experience gained from shallow earthquake study. The superiority of this approach above the traditional methods based on inversion of polarities or amplitudes is obvious in the case of small earthquakes when few records are available and/or the noise distorts significantly or covers the first arrivals.

The reliability in retrieving the orientation of the principal axes of the moment tensor allows us to exploit the weak subcrustal events, frequently recorded, for a detailed exploration of the stress field in the deep segment of the Vrancea focal zone.

As concerns the fault plane solutions of the strong and moderate-size intermediate depth earthquakes of Vrancea, the reverse faulting with tension axis almost vertical and pressure axis quasi-horizontal characterizes all the major events ($M_w > 6$), and over 90% of the analyzed events disregarding their magnitude [62–65]. Two typical mechanisms were noticed: (i) the fault plane oriented NE-SW, dipping to NW and the compressive axis perpendicular to the Carpathians Arc; (ii) the fault plane oriented NW-SE , dipping to SW and the compression axis parallel to the mountains arc. Both instrumental and macroseismic data available point to type (i) solutions for all the earthquakes with $M_w > 7$, this source mechanism being the most frequent over the whole magnitude range (*e.g.* [62–69]). Only few solutions indicate normal or strike-slip faulting, for events located close to the upper, respectively lower boundary of the seismogenic volume [64–65].

The event considered in this study is located in the upper part of the subcrustal seismogenic zone, where the detachment of the slab from the crust presumably took place; therefore we may expect a more complex stress field in this depth range relative to the deeper part of the slab [69]. However the mechanism retrieved by high frequency waveform inversion complies with the most common pattern of fault plane solutions in the subcrustal domain; the double couple component of the resolved moment tensor displays the characteristics of the most frequent mechanism (type (i)) observed in the Vrancea intermediate depth seismic region.

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