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SOURCE ANALYSIS FOR EARTHQUAKE SEQUENCE OCCURRED IN VRANCEA (ROMANIA) REGION ON 6 TO 30 SEPTEMBER 2008

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Abstract. The goal of the paper is to investigate the most recent earthquake sequence (6–30 September 2008) generated in a characteristic seismicity cluster located in the crust, in the north-eastern part of the Vrancea intermediate-depth epicentral area (close to the Vrancioaia seismic station). Seismic source properties are determined using multiple approaches: empirical Green's functions (EGF) deconvolution, spectral ratios technique and acceleration spectra analysis. For EGF and spectral ratios application, we associated to the main event (M_D = 4.4) eight co-located aftershocks ($2.0 \leq M_D \leq 3.6$), selected according to the requirements for empirical Green's functions. The source parameters (seismic moment, corner frequency, rise time, source duration) are estimated as mean values for all the available pairs. In parallel, source parameters are retrieved from the analysis of the accelerometer spectra. The resulted source time functions are similar from one station to the other, suggesting negligible source directivity effects for the study events. The shape of the deconvolved source time function for the main shock of 6 September 2008 indicates a homogeneous rupture process in the focus with rupture duration of 0.24s. The multiple technique approach allows us to test the stability of the obtained parameters.

Key words: source parameters, Vrancea crustal seismicity, empirical Green's functions, spectral ratios, acceleration spectra.

1. INTRODUCTION

Description and analysis of acceleration spectra recorded at earthquakes as well as separation in these spectra forms of different effects is an issue of great interest, playing nowadays an important role in the study of seismic source and strong ground motion prediction.

The seismic source parameters can not be simply retrieved from the ground motion recorded at Earth surface by seismic instruments, since the effects of propagation on the way between hypocenter and seismic station and the effects induced by the local structure beneath the observatory site are severely disturbing the initial source signal The correction of seismogram for these effects and the appropriate interpretation are essential for a proper understanding of the physical process of rupture. Corrections and analysis are more difficult at high frequencies, where the processes and structural heterogeneity at small scale predominate and are more difficult to be controlled. For this reason, most of the source studies are limited to low frequencies and sufficiently large scale, so that the detailed processes in source and small wavelength heterogeneities can be disregarded. This restriction allows us to get acceptable source and structure modeling, but with relatively low resolution. However, the contribution of high frequencies to ground motion is of first concern for civil engineers and seismic microzonation. Any step that extends the frequency range to higher values represents, from this point of view, a challenge for seismologists because the difficulty increases tenfold as the frequency value is higher.

Several techniques have been introduced in seismological research in order to separate the source, propagation and local response factors from the recorded seismogram. The relative methods, spectral ratios and deconvolution with empirical Green's functions, are commonly used methods in analysis of acceleration spectra. In essence, the methods are based on data from earthquake pairs with close hypocenters recorded by common stations, assuming in this case that the propagation effects can be neglected. The method is suitable for seismic sequences, characterized by clusters of events grouped in time and space, which are typical for the given region.

A well defined cluster of earthquakes is located at intermediate depth in the Vrancea region, Romania, at a triple contact between East European, Intra-Alpine and Moesian plates. Seismicity is generated persistently in a very narrow active volume, with 2-3 shocks of magnitude above 7 each century. This concentrated seismic activity is sharply contrasting the seismic activity in the overlying crust, where only sporadic, small-size events (M_w < 5.5) are recorded. Apparently the subcrustal and crustal seismicities are decoupled, but this aspect is still controversial despite the efforts deployed to monitor the seismicity and any possible related parameter in the Vrancea overlying crust [1, 5, 10, 11, 12, 19].

A cluster of earthquakes characteristic for the shallow seismicity in the Vrancea region is located close to the Vrancioaia seismic station. The last sequence of earthquakes occurred here in 6 – 30 September 2008. The purpose of the present paper is to investigate the seismic source properties for this sequence using relative deconvolution methods and spectral analysis of the recorded accelerograms.

2. THE SEISMIC SEQUENCE OF 6 TO 30 SEPTEMBER 2008

The area located at the sharp bend of the South-Eastern Carpathians (Vrancea region) is the place where three tectonic units, East European, Intra-Alpine and Moesian plates, come into contact. The seismicity associated with the complex geodynamics in the region consists of clusters of earthquakes generated both in the crust and in the upper mantle. The earthquakes at intermediate depths are confined in a narrow vertical volume extended down to about 170 km depth. Shocks as large as $M_w = 7$ or larger are reported 2-3 times per century. The seismic activity in the overlaying crust is significantly lower as radiated energy ($M_w < 5.5$). Two significant clusters of earthquakes generated in the Vrancea crustal domain are located close to Vrancioaia and Ramnicu Sarat sites. The epicenters of the most recent sequences recorded in the Vrancioaia cluster (September 2008) and Ramnicu Sarat cluster (29 November to 3 December 2007) are represented in Fig. 1.

The earthquakes in the Vrancioaia region are frequently generated in sequences of small to moderate magnitudes [20, 15]. The last sequence occurred in the region in September 2008 (Fig. 1) was triggered by the main shock on 6 September ($M_D = 4.4$), followed by 41 aftershocks that could be identified until 30 September ($1.6 \leq M_D \leq 3.4$). After an interval of about one month of quiescence, another event occurred on 25 October (M_D 3.6) and located close to the main event (Table 1) is assumed to belong to the same sequence (a sort of delayed aftershock). The records belonging to the Romania real-time network were used to identify and locate the events.

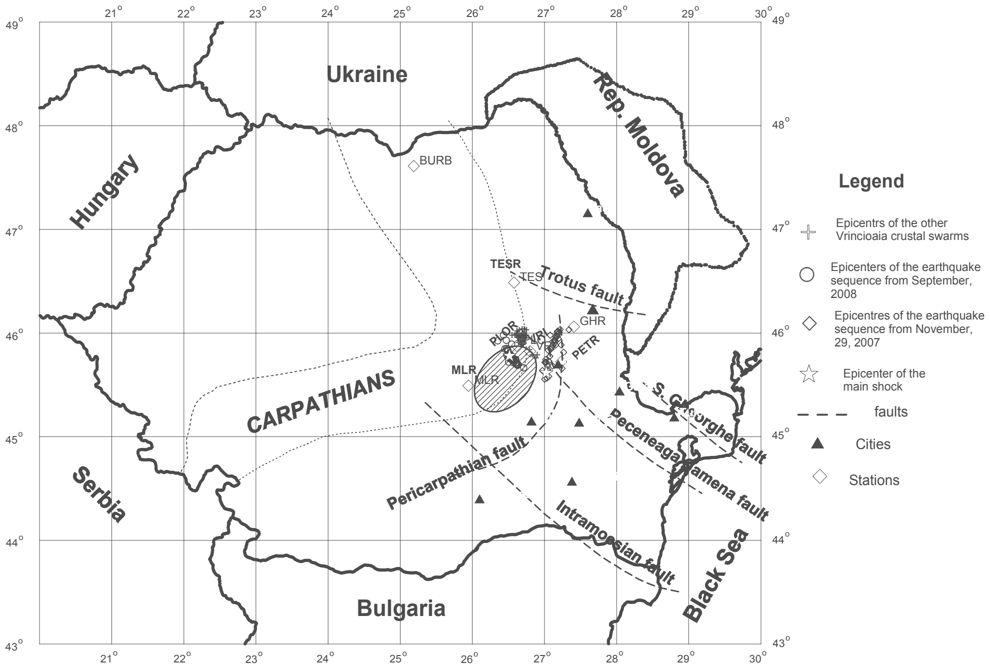


Fig. 1 – Distribution of earthquake epicenters for the most recent sequences occurred in Vrancioaia and Ramnicu Sarat regions. The study sequence is plotted with empty circles. The Vrancioaia sequence of August-September 1989 is plotted with crosses. The most recent sequence in the Ramnicu Sarat region is plotted with empty diamonds. Dashed ellipsis defines roughly the epicentral area of the Vrancea intermediate-depth earthquakes.

Table 1

Vrancioaia sequence located events

Nr.	Year/month/day	hh:mm:ss	Latitude (°N)	Longitude (°E)	h (km)	M_D
1	**2008/09/06**	**19:48:01.63**	**45.80**	**26.51**	**13**	**4.4**
2	2008/09/06	19:57:08.03	45.76	26.50	5	2.0
3	2008/09/06	20:01:17.43	45.85	26.45	15	2.1
4	2008/09/06	20:35:48.49	45.74	26.54	5	1.9
5	2008/09/06	20:47:52.99	45.79	26.50	4	2.1
6	2008/09/06	21:11:26.48	45.78	26.49	4	3.1
7	2008/09/06	22:52:33.12	45.98	26.43	4	2.3
8	2008/09/06	23:32:25.52	45.71	26.60	10	2.1
9	2008/09/06	23:47:58.79	45.76	26.50	5	2.7
10	2008/09/07	00:03:53.85	45.79	26.53	13	2.9
11	2008/09/07	21:56:06.53	45.79	26.48	2	2.3
12	2008/09/07	22:41:14.22	45.77	26.52	11	3.4
13	2008/09/08	00:08:16.17	45.74	26.55	5	1.9
14	2008/09/08	02:00:05.37	45.76	26.52	3	2.4
15	2008/09/08	02:16:08.27	45.93	26.35	5	1.8
16	2008/09/08	19:52:43.04	45.75	26.60	5	1.7
17	2008/09/09	17:19:39.86	45.84	26.48	11	2.0
18	2008/09/09	21:00:47.93	45.73	26.58	5	1.7
19	2008/09/10	15:03:05.25	45.89	26.55	51	1.8
20	2008/09/10	16:43:36.01	45.83	26.50	10	1.9
21	2008/09/10	20:44:15.12	45.75	26.58	5	1.6
22	2008/09/10	21:38:27.98	45.79	26.53	10	1.6
23	2008/09/11	21:54:28.04	45.70	26.62	5	2.1
24	2008/09/12	11:09:23.71	45.66	26.71	5	2.2
25	2008/09/12	11:09:53.02	45.93	26.47	1	2.1
26	2008/09/12	12:25:06.53	45.70	26.63	5	2.1
27	2008/09/13	15:36:41.57	45.71	26.60	9	2.0
28	2008/09/14	12:27:33.05	45.71	26.60	3	2.2
29	2008/09/15	07:58:19.53	45.74	26.56	5	2.2
30	2008/09/16	09:58:23.97	45.76	26.52	5	1.9
31	2008/09/17	04:33:21.39	45.77	26.55	8	3.2
32	2008/09/19	22:48:19.95	45.78	26.54	9	3.1
33	2008/09/21	07:33:53.42	45.74	26.59	5	2.0
34	2008/09/22	04:50:10.61	45.85	26.48	10	2.1
35	2008/09/23	08:37:35.36	45.69	26.63	5	2.1
36	2008/09/28	07:58:44.35	45.71	26.61	6	2.5
37	2008/09/28	10:46:40.41	45.71	26.57	5	1.9
38	2008/09/28	18:36:54.75	45.70	26.61	5	2.5
39	2008/09/28	19:52:41.52	45.72	26.50	5	1.7
40	2008/09/29	07:08:40.08	45.72	26.59	5	2.1
41	2008/09/29	22:58:00.82	45.71	26.60	5	2.1
42	2008/09/30	03:32:12.43	45.74	26.58	9	2.4
43	2008/10/25	20:31:11.31	45.78	26.51	10	3.6

The hypocenter coordinates are determined with a joint hypocenter determination algorithm [4], using the station corrections calibrated on a set of 50 crustal earthquakes occurred in the Ramnicu Sarat region. The event of October 25, 2008 was selected as reference event. This way, the locations are performed with acceptable accuracy (Table 1). The distribution of epicenters is represented in Figs. 1 and 2.

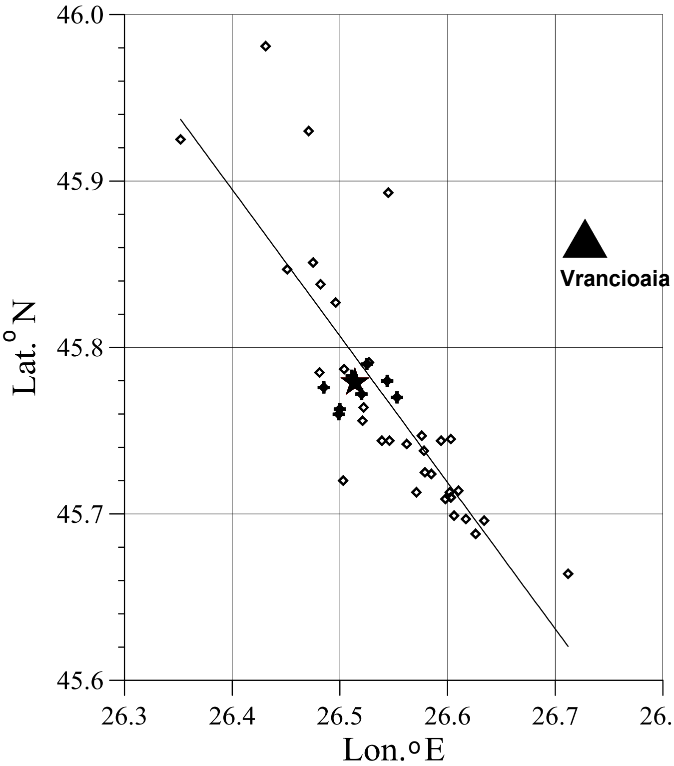


Fig. 2 – Epicentral distribution for the sequence of 6 to 30 September 2008. Star – main shock; diamonds – aftershock epicenters; black crosses – events used as empirical Green's functions; black triangle – seismic station. The line represents the large axis of the ellipse associated with epicenter distribution, oriented N36°W.

The distribution of the epicenters given in Fig. 2 can be approximated by an ellipsis N36°W oriented. Here, pronounced diapirism areas are highlighted at a depth of 5.5 km, with a heterogeneous structure of surface layers, which may explain quasi-permanent microseismicity of this region.

Fault plane solutions are calculated from inversion of the first arrivals of P waves for the main earthquake and for the aftershocks of September 6, 2008, 21: 11, M_D = 3.1, September 7, 2008, 22: 41, M_D = 3.4 and for the singular co-located event of October 25, 2008, 20:31, M_D = 3.6 (Table 2).

Table 2

Parameters of the fault plane solutions in case of four earthquakes which had been analyzed

Year	Mo	Day	hh:mm	Plane A			Plane B			P-axis		B-axis		T-axis	
				az	dip	slip	az	dip	slip	az	pl	az	pl	az	pl
2008	9	6	19:48	138	11	-22	249	86	-100	149	48	250	10	349	40
2008	9	6	21:11	78	56	-23	181	71	-144	44	38	205	50	307	10
2008	9	7	22:41	125	35	0	35	90	125	95	35	215	35	335	35
2008	10	25	20:31	316	57	20	215	73	145	268	10	12	52	180	36

Fault plane solution for the main shock, obtained using 28 P-wave first arrival signs by SEISAN algorithm [7], correlates well with the geometry of the epicentral distribution of the aftershocks (Fig. 2, Fig. 3). Note the preferential direction of migration, NW-SE, that we associate with the rupture plane direction. The relative position of the main shock indicates a bilateral fracture.

The solution of the aftershock of 7 September 2008 22: 41 obtained using 17 P-wave first arrivals signs, is similar to the fault plane solution of the main shock mechanism (Fig. 3c). For the other two aftershocks we used 11 P-wave first arrivals signs (6 September 2008) and 16 P-wave first arrivals signs (25 October 2008), respectively (Fig. 3d).

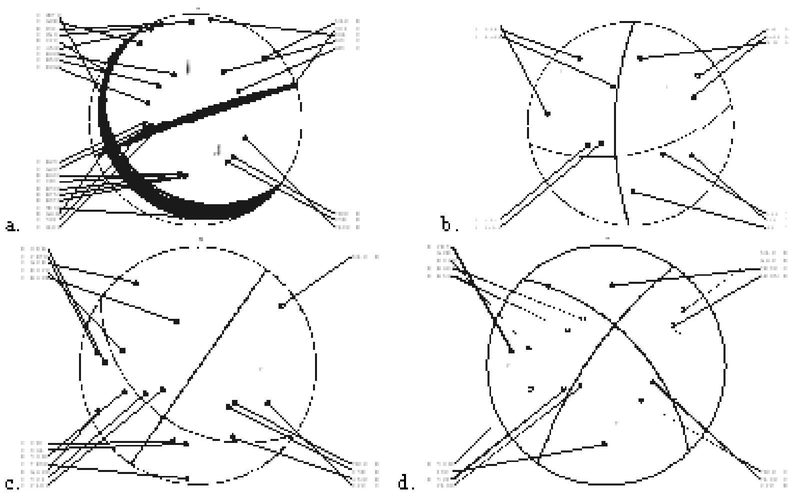


Fig. 3 – Fault plane solutions: a) the main shock of 6 September 2008, b) the aftershock of 6 September 2008, at 21:11, $M_D = 3.1$, c) the aftershock of 7 September 2008 at 22: 41, $M_D = 3.4$, d) the event of 25 October 2008 at 20: 31, $M_D = 3.6$.

The focal mechanism of the main earthquake of the sequence represents normal faulting with the rupture plane dipping SW and oriented approximately N48^{o}W. The compression axis is E-W oriented, while the dilatation axis is N-S oriented. The number of the available polarities (28) is relatively large and consequently the solution is reasonably well constrained. The fault plane solution for the aftershock of September 7, 2008 is close to the main shock solution. The focal mechanism of the aftershock of September 6, 2008 (Fig. 3b) is of strike-slip type with normal faulting component. The focal mechanism of the earthquake of October 25, 2008 is of strike-slip type with a reverse faulting component.

Although the orientation of the rupture plane is persistent, as suggested by the spatial distribution of aftershocks, the strain field is complex in the vicinity of the Carpathian Arc bend and shows a transition zone between a compressional regime characteristic the Vrancea subcrustal domain and an extensional regime, characteristic for the entire Moesian platform [21].

To test the relative methods efficiency in parameterization of seismic source we used the database of the Vrancioaia crustal sequence earthquakes recorded by Romania real-time network stations, which provides waveforms with sufficient signal-to-noise ratio for the application of spectral analysis. We selected 9 crustal earthquakes of the 2008 sequence ($4 \le h \le 13$ km) with magnitudes in the range $2.0 \le M_D \le 4.4$.

3. THE RELATIVE DECONVOLUTION METHODS TO DETERMINE SOURCE PARAMETERS

The relative deconvolution methods (spectral ratios and empirical Green's function deconvolution) are widely used in analyzing ground motion spectra in order to retrieve source parameters (seismic moment, source radius, rupture duration, rise time and stress drop). Typically for this class of methods, the path, site and instrument effects are efficiently removed by deconvolving the waveform of a lower magnitude event from the main event waveform, when the two events are co-located. The conditions to be satisfied by the main shock and the associated empirical Green's function are:

– hypocenters located close each other,

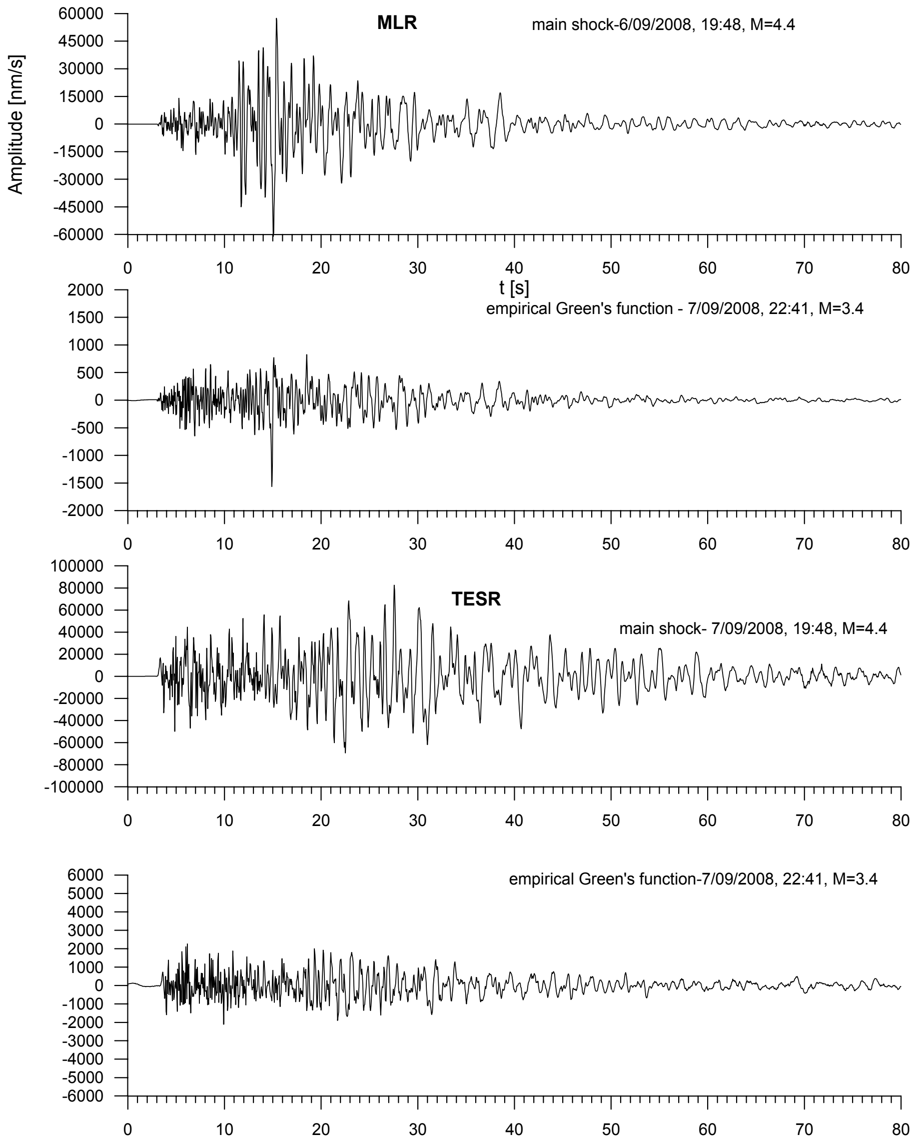
– similar waveforms, therefore similar focal mechanisms,

– the magnitude difference between the main event and the associated Green's function has to be at least one unit.

Mathematically, when the pulse width of empirical Green's function is sufficiently small as compared with the pulse width of the main earthquake, then it can be approximated by a delta function and consequently, its waveform approximates the response of the medium between the focus and measuring site.

Spectral ratios method has been developed after 80's in seismology and has been applied in a number of seismic zones of the world [14, 6, 13, 8]. The method is very efficient in obtaining the source parameters when we select pairs of earthquakes having close hypocenters recorded by common broadband stations [9]. Spectral ratios depend essentially only on source when the selection of earthquakes pairs is properly done, and in this case it is not necessary to apply path, local and instrument response corrections. Another advantage of the method is the possibility to simultaneously determine the source for both earthquakes from selected pair, as long as the instrument is broadband and signal-to-noise ratio is high enough in the frequency of interest.

An example of main event-empirical Green's function pair is given in Fig. 4. The main event is the main shock of 6 September 2008 and the empirical Green's function is the aftershock of 7 September 2008, at 22:41. Common recordings at Antelope stations VRI, PLOR, MLR, TESR, GHRR and BURB are available (see Fig. 1 for the location of the stations used in this paper).



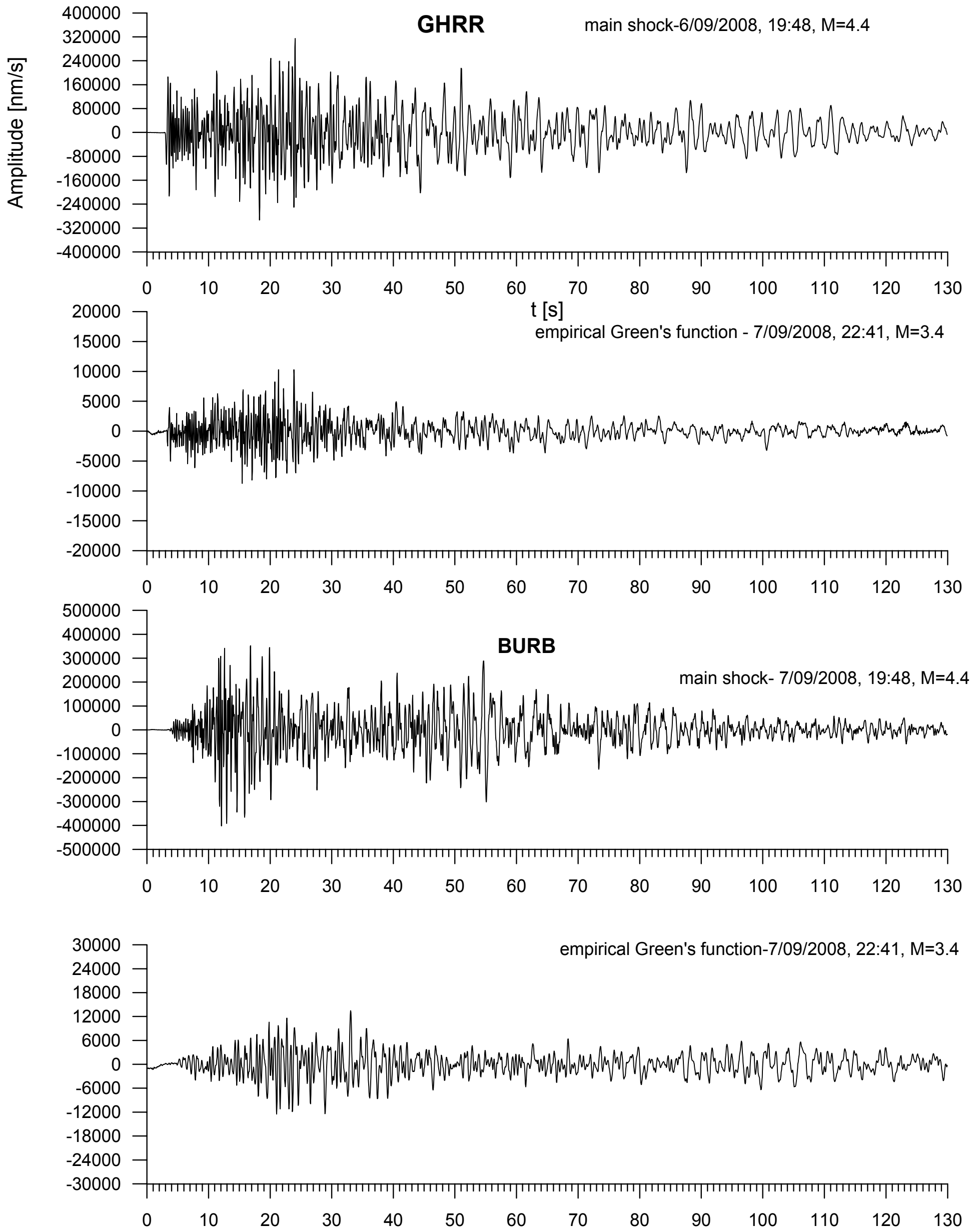


Fig. 4 – Examples of waveforms of the main event of 6 September 2008 and the empirical Green's function of 7 September 2008, at 22:41 at MLR, TESR, GHRR and BURB seismic stations.

For a source model with uniform rupture and $\omega^{-\gamma}$ spectral fall-off at high frequencies, the spectral ratios can be approximated by the theoretical function:

$$R(f) = \frac{\Omega_0^M \left[1 + \left(f / f_c^G\right)^{2\gamma}\right]^{1/2}}{\Omega_0^G \left[1 + \left(f / f_c^M\right)^{2\gamma}\right]^{1/2}}, \tag{1}$$

where $\Omega_0{}^M$, $\Omega_0{}^G$ are the low-frequency asymptotes of amplitude spectra of principal and Green's earthquakes, f_c^M, f_c^G are the corresponding corner frequencies and γ is the coefficient of the spectral fall-off at high frequency.

The function of type (1) that best approximates the observed spectral ratios is obtained trough a nonlinear regression procedure. Free parameters are: the ratio of seismic moments (proportional to the ratio of low-frequency asymptotes of the displacement spectrum of collocated events) and the corner frequencies. The size of the rupture area is directly related to the corner frequency [3]:

$$r = 0.28 V_s / f_c, \tag{2}$$

r representing the equivalent radius of the source. With relationship (2) we determine the source radius for the main event ($r_{sr}{}^M$) and Green's function ($r_{sr}{}^G$).

We applied spectral ratios method for the pairs of main event and empirical Green's functions given in Table 3. Actually, only one main event is selected with 8 co-located aftershocks as Green's functions.

Table 3

Hypocentral parameters of the main shock and the associated empirical Green's functions

Nr.	year/month/day	hh:mm:ss	Lat (°N)	Lon (°E)	*h* (km)	M_D
M	**2008/09/06**	**19:48:01.63**	**45.78**	**26.51**	**13**	**4.4**
1	2008/09/06	19:57:08.03	45.76	26.50	5	2.0
2	2008/09/06	21:11:26.48	45.78	26.49	4	3.1
3	2008/09/06	23:47:58.79	45.76	26.50	4	2.7
4	2008/09/07	00:03:53.85	45.79	26.53	13	2.9
5	2008/09/07	22:41:14.22	45.77	26.52	11	3.4
6	2008/09/17	04:33:21.39	45.77	26.55	8	3.2
7	2008/09/19	22:48:19.95	45.78	26.54	9	3.1
8	2008/10/25	20:31:11.31	45.78	26.51	10	3.6

The corner frequency (radius respectively) and the ratio of low-frequency asymptotes in logarithmic scale (A) are estimated as average over all particular values for available stations. Since the method is relative, it does not allow simultaneous estimation of seismic moment absolute values for both co-located earthquakes in a pair. Therefore, it is necessary to know the independent seismic moment for one of the two earthquakes. We use the seismic moment value estimated from spectral analysis [16, 17, 18] for the main shock. From corner frequencies determined for the main event and for the Green's functions through the spectral ratios method the source radii r_{rs} are estimated using equation (2). Source parameters estimated by the spectral ratios method and the deconvolution with empirical Green's functions are found in Tables 4.1–4.8. A is the logarithm of the spectral ratio.

Table 4.1

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/06, at 19:57, $M = 2.0$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	r^G_{sr} (m)	r^M_{sr} (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
PLOR	3.32	6.14	2.73	134	329	0.110	232
VRI	3.29	5.95	3.13	138	287	0.115	242
Average	3.31±0.02	6.05±0.13	2.93±0.28	136±3	308± 30	0.113±0.004	237±7

Table 4.2

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/06, at 21:11, $M = 3.1$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	r^G_{sr} (m)	r^M_{sr} (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
MLR	2.12	5.85	2.20	140	409	0.130	274
TESR	2.13	4.44	2.04	185	441	0.150	316
VRI	1.97	5.14	2.08	160	432	0.147	311
Average	2.07±0.09	5.143±0.705	2.11±0.08	162±23	427± 17	0.142 ±0.011	300±23

Table 4.3

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/06, at 23:47, $M = 2.7$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	r^G_{sr} (m)	r^M_{sr} (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
MLR	2.54	5.00	3.00	164	300	0.120	253
PLOR	2.69	6.75	2.37	122	379	0.115	242
VRI	2.57	5.00	2.21	164	407	0.140	295
Average	2.60±0.08	5.58 ±1.01	2.53 ±0.42	150 ±24	362± 55	0.125±0.013	263± 28

Table 4.4

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/07, at 00:03, $M = 2.9$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	$r^G{}_{sr}$ (m)	$r^M{}_{sr}$ (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
MLR	2.28	4.73	2.78	190	323	0.120	250
PETR	-	-	-	-	-	0.115	240
PLOR	2.29	5.96	2.09	151	430	0.120	250
TESR	2.36	6.10	3.33	147	270	0.130	271
VRI	2.34	5.19	1.97	173	456	0.150	313
Average	2.32±0.039	5.50±0.65	2.54±0.63	165±20	370± 88	0.127±0.014	265±29

Table 4.5

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/07, at 22:41, $M = 3.4$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	$r^G{}_{sr}$ (m)	$r^M{}_{sr}$ (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
GHRR	1.71	5.85	2.36	154	380	0.115	240
MLR	1.53	4.80	2.54	187	354	0.125	261
PETR	1.87	3.25	1.69	277	532	-	
PLOR	-	-	-			0.135	282
TESR	-	-	-			0.090	188
Average	1.70±0.17	4.58±1.24	2.19±0.44	206±64	422± 96	0.116±0.019	243±40

Table 4.6

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/17, at 04:33, $M = 3.2$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	$r^G{}_{sr}$ (m)	$r^M{}_{sr}$ (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
BURB	1.55	5.66	2.92	159	308	-	-
MLR	1.51	6.08	2.75	148	326	0.132	275
TESR	2.29	4.47	2.36	201	381	0.086	179
VRI	2.11	3.35	1.8	268	499	-	
Average	1.87±0.39	4.89 ±1.23	2.46±0.50	194 ±54	379± 86	0.109 ±0.033	227± 68

Table 4.7

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/09/19, at 22:48, $M = 3.1$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	r^G_{sr} (m)	r^M_{sr} (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
PETR	1.89	4.73	2.74	190	328	0.130	271
PLOR	2.25	5.84	2.45	154	367	0.120	250
TESR	1.96	5.25	2.87	171	313	0.110	229
VRI	2.11	5.00	1.77	180	508	-	-
Average	2.05±0.16	5.21 ±0.47	2.46 ±0.49	174 ±15	379± 89	0.120 ±0.010	250±21

Table 4.8

The main event occurred on 2008/09/06 and the associated aftershock occurred on 2008/10/25, at 20:31, $M = 3.6$

Station/ Average	A	f_c^G (Hz)	f_c^M (Hz)	r^G_{sr} (m)	r^M_{sr} (m)	$\tau_{1/2}$ (s)	r_{rt} (m)
BURB	1.25	4.26	2.41	211	373	0.110	229
GHRR	1.19	5.19	2.56	173	351	0.125	261
PLOR	1.48	5.35	2.23	168	403	0.105	219
TESR	1.18	4.66	2.85	193	315	0.115	240
VRI	1.55	3.38	1.48	266	607	-	-
Average	1.33±0.17	4.56±0.79	2.31±0.51	202± 40	410±115	0.114±0.009	237± 18

Examples of spectral ratios calculated for the pair of earthquakes occurred on 6 September 2008 (main event) and one of its aftershocks occurred on 17 September 2008 (empirical Green's function) are represented in Fig. 5.

We applied for the same selected pairs of events the method of deconvolution with empirical Green's functions to obtain the source time function, and then the source radius using formula of [2].

$$R = (\tau_{1/2}\nu)/(1-\nu/\alpha\sin\theta) , \quad (3)$$

where $\tau_{1/2}$ is the rise time (taken as half of pulse width obtained by deconvolution), v is the rupture velocity in the source, considered as $v = 0.9\ \beta$ (with β – S-wave velocity at the seismic source depth), α – P-wave velocity at the source depth, θ – the angle between the fault and the output direction of P waves from hypocenter (in this case was considered $\theta = 45°$).

For each pair of main event and Green's function waveforms at each station, the deconvolution results in a rise time value. Theoretically, all these values should be the same, if source directivity effects are negligible. Practically, we estimate rise time parameter as the mean value for all the available pairs (Table 5). In the case of main event of sequence, eight empirical Green functions were available and the rise time is the average of all values $\tau_{1/2}$ obtained at all stations. In the Table 5 are listed source parameters of the main event of sequence and of the eight empirical Green functions used in this work.

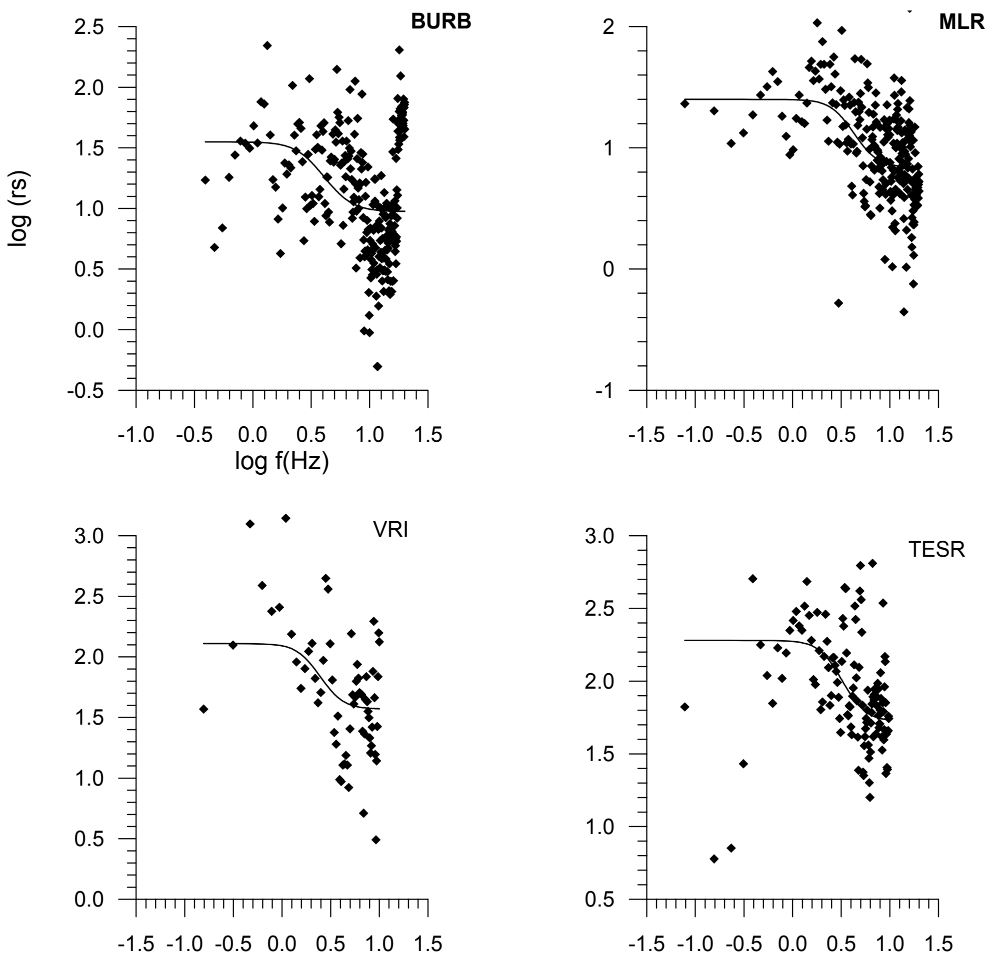


Fig. 5 – Spectral ratios obtained for the pair of earthquakes occurred on 6 September 2008 and empirical Green's function occurred on 17 September 2008, at available stations.

Examples of source time functions (STFs) resulted for the main event (6 September 2008) after deconvolving the waveform of the aftershock of 7 September at 0:03 are shown in Fig. 6. The individual STFs at available stations as well as the average STF with standard errors are plotted.

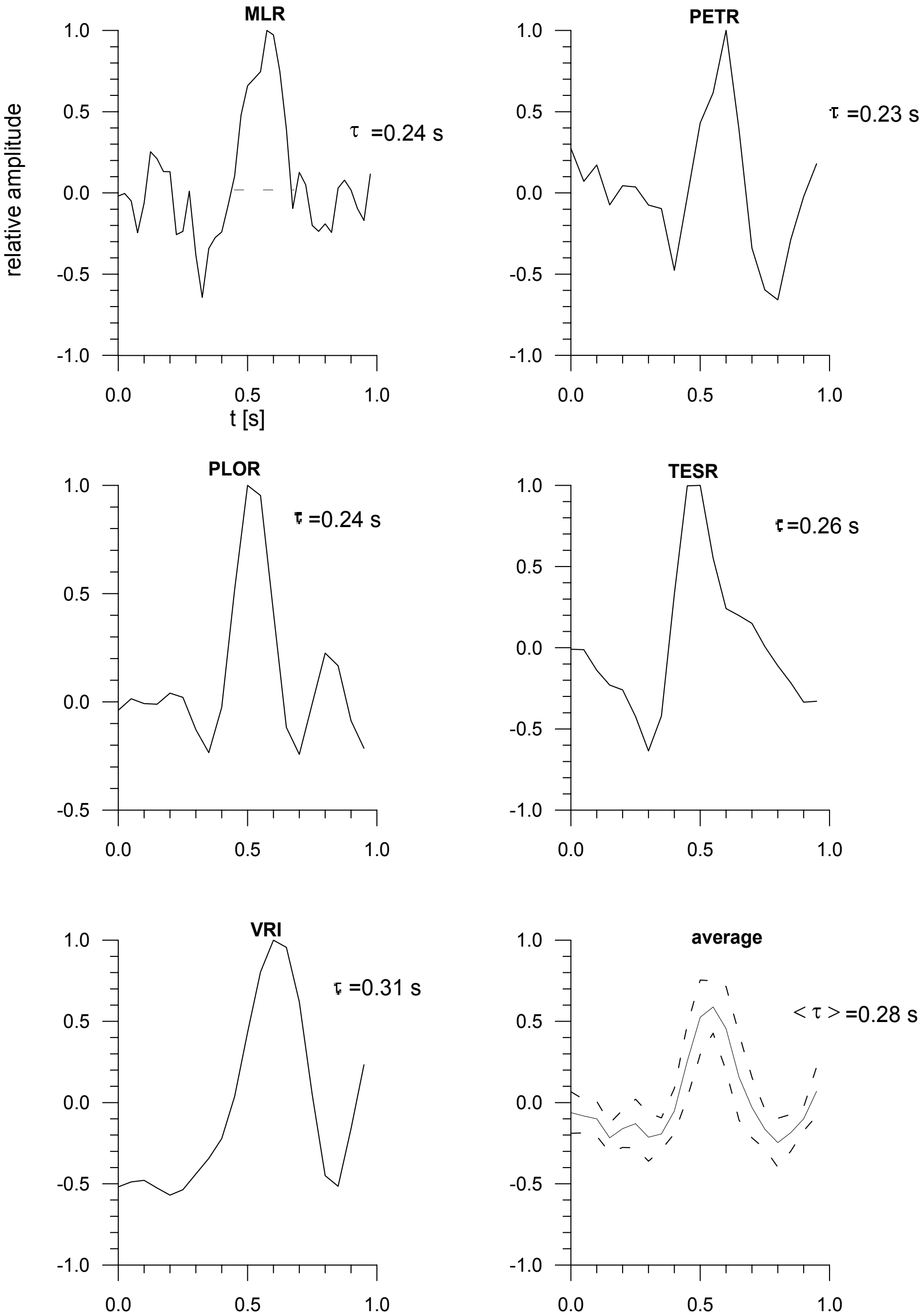


Fig. 6 – Examples of source time functions obtained in case of deconvolution of main event occurred on 6 September 2008 and empirical Green's function of 7 September 2008 at several stations.

Table 5

Source parameters of the main event obtained as means of all deconvolved values and aftershocks used as empirical Green's functions

Event	$\langle f_c^M \rangle$ (Hz)	$\langle r_{rs}^M \rangle$ (m)	$\langle \tau_{1/2} \rangle$ (s)	$\langle r_{rt} \rangle$
2008/09/06	**2.43±0.47**	**386 ±81**	**0.1215±0.0195**	**354±34 (254)**
2008/09/06	6.05±0.13	136 ±3	-	-
2008/09/06	5.14±0.71	162 ±23	-	-
2008/09/06	5.58±1.01	150 ±24	-	-
2008/09/07	5.50±0.65	165 ±20	-	-
2008/09/07	4.58±1.24	206 ±64	-	-
2008/09/17	4.89±1.23	194 ±54	-	-
2008/09/19	5.21±0.47	174 ±15	-	-
2008/10/25	4.56±0.79	202 ±40	-	-

4. SPECTRAL ANALYSIS OF ACCELERATION DATA

Finally, we approximate the acceleration spectra at high frequency using a theoretical model of Brune's source type (such as ω^{-2}):

$$S(f) = \frac{R(\theta,\phi) M_0 (2\bar{u}f)^2}{4\pi\rho r V_s^3 \left[1+(f/f_c)^2\right]} A(f), \tag{4}$$

where $R(\theta, \phi)$ is the source radiation pattern, ρ is density, V_s is the velocity of S waves, r is the hypocentral distance, M_0 is the scalar seismic moment and $A(f)$ is a function of attenuation at high frequencies given by:

$$A(f)=1/[1+(f/f_{\max})^m], \tag{5}$$

where f_{max} is the maximum cut-off frequency in the acceleration spectrum and m is the rate of fall-off at high frequencies. In this case, $S(f)$ is characterized by four parameters: a_0-correlated with low frequency asymptote of the displacement spectrum (or seismic moment), f_c corner frequency and f_{max} and m, as defined above.

The source parameters are estimated by approximating the acceleration spectra of P waves with a theoretical function like that described above. The approximation is made using least square procedure. We analyzed acceleration spectra in case of main event and six aftershocks of the Vrancioaia sequence of 6 September 2008. The observed spectra and the resulted approximations are plotted in Fig. 7. The corresponding source parameters are given in Table 6.

We tested the stability of the obtained parameters in terms of sample dimension (time window), number of stations per event, signal-to-noise ratio, instrument bandwidth.

Comparison of corner frequencies calculated by approximating the observed spectral ratios with a theoretical function of type (1) with corner frequencies estimated through the approximation of acceleration spectra with a function of the form (4) leads to a good correlation between results of the two methods (Fig. 8, equation 6). Correlation coefficient of straight line is r = 0.91 and the standard error σ = 0.57 which means that results are reliable.

$$f_c^{\mathrm{acc}} = (1.01 \pm 0.21) f_c^{\mathrm{sr}} - (0.10 \pm 1.01), \tag{6}$$

for r = 0.91 and σ = 0.57.

Table 6

Source spectral parameters obtained in case of Vrancioaia region for the main event of the sequence and for selected empirical Green's functions

No.	Event	h (km)	M	A_0	f_c (Hz)	f_{max} (Hz)	m
1.	**2008/09/06**	**13**	**4.4**	**5.77±0.05**	**2.61±0.29**	**6.77±1.00**	**3.48±0.33**
2	2008/09/06	4	3.1	3.56	5.40	6.80	3.7
3	2008/09/06	4	2.7	3.10	6.01	6.73	3.8
4	2008/09/07	13	2.9	3.31	5.88	7.47	3.5
5	2008/09/07	11	3.4	4.23	4.41	6.09	3.3
6	2008/09/17	8	3.2	4.49	4.02	6.13	3.6
7	2008/10/25	10	3.6	4.40	3.92	4.90	3.1

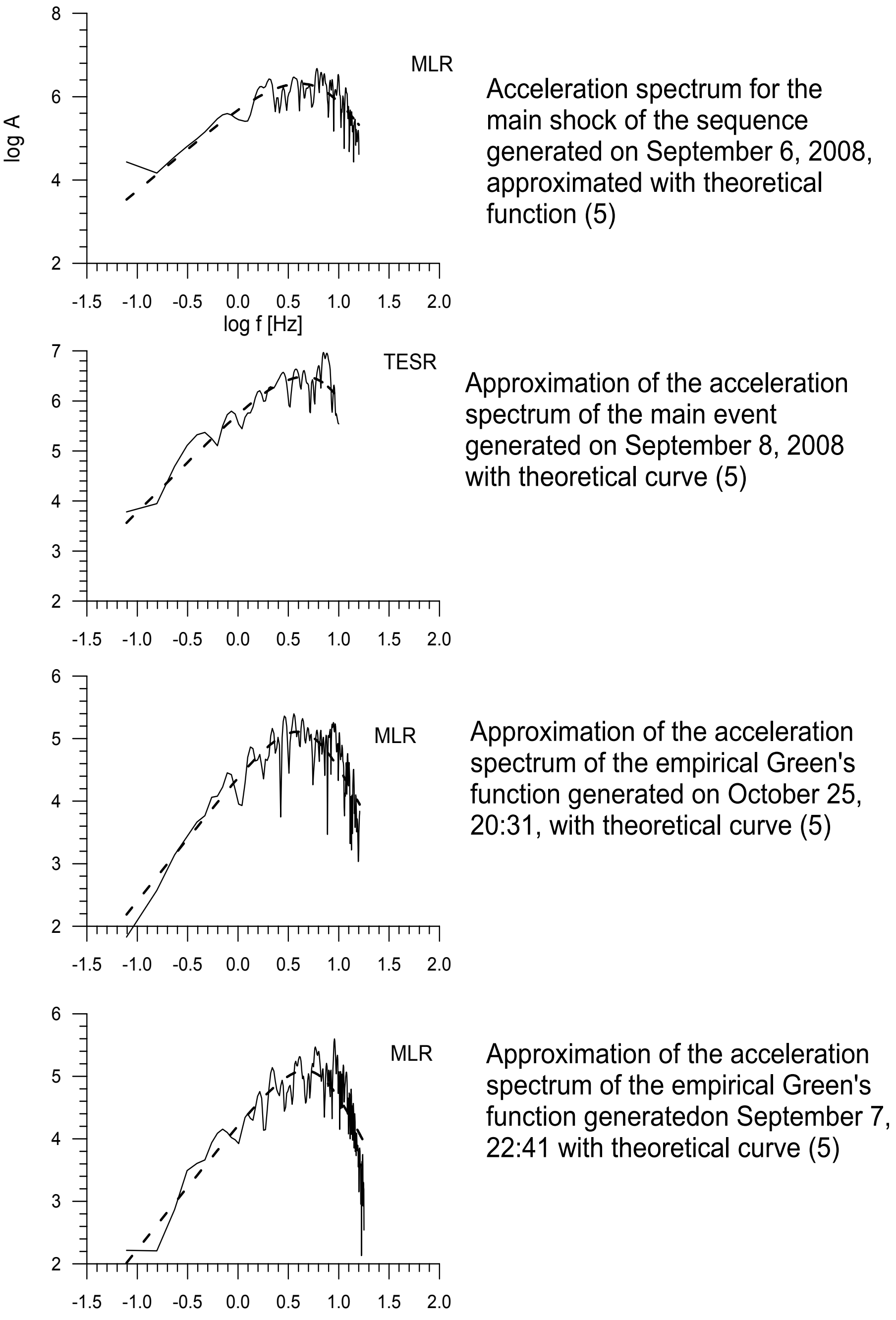


Fig. 7 – Examples of approximation in case of acceleration spectra with theoretical functions of the form (5).

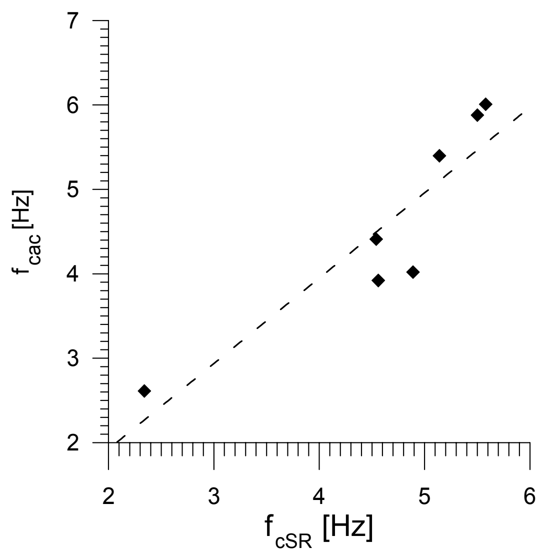


Fig. 8 – Correlation between the values of corner frequencies estimated by spectral ratios method and those obtained from the acceleration spectra analysis.

5. CONCLUSIONS

While a distinctive feature of sequences generated in front of the Carpathians Arc (Ramnicu Sarat region) is the rupture plane orientation parallel to the mountain line (on a SW-NE direction), the configuration of the sequence in Vrancioaia area shows a different, roughly perpendicular orientation (Fig. 1). This orientation coincides with the migration of epicenters (approximately along N36^{o}W direction) and is compatible with the fault plane solution of the main event of 6 September sequence (Fig. 3), with the assumed rupture plane oriented on N48^{o}W direction. Typically, the rupture propagates unilaterally in the Ramnicu Sarat region [15], while for the Vrancioaia sequences apparently bilateral rupture propagation is more common.

The source time function and associated source parameters (corner frequency, seismic moment, source duration, rise time) are determined using both relative deconvolution techniques (spectral ratios, empirical Green's functions) and spectral analysis. The shape of the deconvolved source time function for the main shock of 6 September 2008 indicates a homogeneous rupture process in the focus with a duration of $\tau = 0.24$s (Fig. 6).

The source parameters are retrieved from acceleration spectra by comparing the recorded spectrum with a theoretical spectrum model for a Brune's type source (ω^{-2} source). The corner frequency obtained in this way correlates well with the value resulted from spectral ratios analysis.

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