SOURCE OF VRANCEA (ROMANIA) INTERMEDIATE-DEPTH EARTHQUAKES: PARAMETER VARIABILITY TEST USING A SMALL-APERTURE ARRAY

EMILIA POPESCU, MIRCEA RADULIAN, MIHAELA POPA,
ANCA O. PLĂCINTĂ, BOGDAN GRECU

Institutul Naţional de Cercetare-Dezvoltare pentru Fizica Pământului
C. P. MG-2, 077125, Bucureşti

La source des tremblements de terre de profondeur moyenne de Vrancea (Roumanie): le test du paramètre variabilité en utilisant un réseau à petite aperture. Le réseau sismique de Bucovine (BURAR) est un réseau à petite aperture installé en 2002 en coopération avec les États-Unis dans la partie septentrionale de la Roumanie, dans les Carpates Orientales, à une distance d'environ 250 km nord de l'aire épicentrale de Vrancea. Le réseau est formé de 10 stations (neuf instruments de courte période et un de large bande) distribuées sur une aire de 5×5 km^2. L'intention est d'analyser la capabilité de BURAR de contraindre les paramètres de la source des tremblements de terre de profondeur moyenne de Vrancea comme une station de type *stand alone*. Dans ce but, on a appliqué les techniques de déconvolution relative, comme les techniques des rapports spectraux (SR) et de la fonction empirique de Green (EGF), sur un nombre de données de 36 séismes de profondeur moyenne de Vrancea ($3.4 \le M_W \le 6.0$) produits entre 2002 et 2005 et deux événements récents, en plus, qui sont les meilleurs enregistrements jamais faits sur le territoire roumain: le 27 septembre 2004 (45.70°N, 26.45°E, h = 166 km, $M_w = 4.7$) et le 27 octobre 2004 (45.84°N, 26.63°E, h = 105 km, $M_w = 6.0$). On démontre, de même, l'exactité des paramètres résultés par ces techniques, en utilisant la possibilité de comparer les enregistrements de plusieurs stations du réseau BURAR. Finalement, pour les tremblements de terre de Vrancea, les relations de calibrage et de calage, en utilisant les enregistrements de la station BURAR, sont déterminantes. Les relations de calage, évaluées sur les paramètres de source résultés, mettent en évidence un comportement lié au comportement typique pour d'autres aires de source à une dépendence significative de la chute de contrainte du moment sismique (le modèle de la source variable de la chute de contrainte). Bien que BURAR soit situé assez loin de l'aire épicentrale de Vrancea et le chemin particulier entre le focus de profondeur moyenne et le site montre de puissantes inhomogénités latérales, l'étude met en évidence que les enregistrements de ce réseau constituent des instruments fiables et utiles pour contraindre efficacement la source des paramètres et les propriétés de calage de la source.

Key words: seismic array, Vrancea earthquakes, spectral ratios, empirical Green's function method.

Rev. Roum. GÉOPHYSIQUE, **51**, p. 15–34, 2007, Bucureşti

INTRODUCTION

Seismic arrays are specific configurations of seismic stations installed over relatively small areas which allow a significant enhancement of the coherent signal *vs*. the ambient noise. A few specialized techniques, based on multiple signal processing, have been proposed to extract and handle from the signal recorded by these arrays the true information on seismic source or path effects. They follow a simple principle: the source and path contributions in the recorded seismograms are coherent, while the noise is incoherent, therefore the summation of seismograms will improve the signal/noise ratio.

The Bucovina array (BURAR) was installed in July 2002 in the northern part of Romania, in the Eastern Carpathians Mountains (Fig. 1). The array is operated and maintained in the framework of a bilateral cooperation program between the American Air Force Technical Applications Center (AFTAC) and the Romanian National Institute for Earth Physics (NIEP). The array consists of nine short period vertical sensors (model Geotech Instruments GS-21) and one broadband three-component sensor (model Geotech Instruments KS-54000), distributed in a 5 × 5 km^2 area as shown in Fig. 1. A study of the detection and signal processing capabilities of the BURAR array for Vrancea earthquakes can be found in Ghica *et al.* (2004).

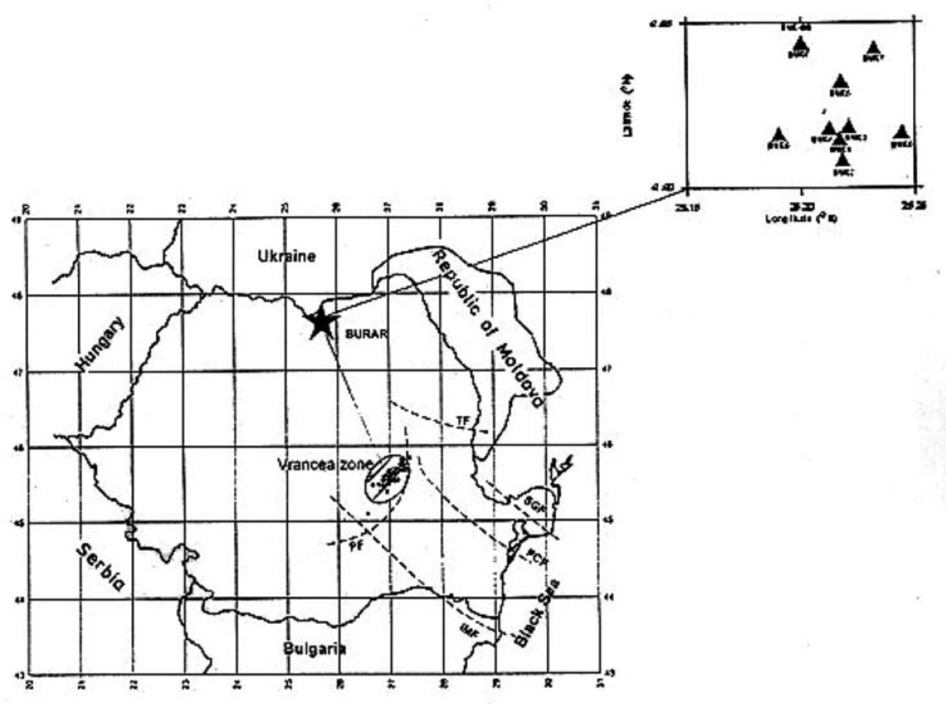

Fig. 1 – Configuration of the BURAR array. BURB is equipped with a broadband instrument, while BUR1, 2, …9 are equipped with short-period instruments.

The purpose of this paper is to analyze the capability of the BURAR small-aperture array to constrain the source parameters of the Vrancea intermediate-depth earthquakes as a stand alone station. To this purpose, relative deconvolution techniques will be applied, such as spectral ratios (SR) and empirical Green's function (EGF) techniques. At the same time, we shall show how accurate the parameters resulted from these techniques are, using the possibility to compare multiple station recordings from the BURAR array. Finally, calibration and scaling relations for the Vrancea earthquakes using the BURAR array recordings will be determined.

The relative deconvolution techniques were applied several times in case of Vrancea intermediate-depth earthquakes to retrieve the source parameters (Radulian, Popa, 1993; Popa, Radulian, 2000; Popescu *et al.*, 2003). All these studies were based on data provided by the Romanian national network and mostly on short-period seismograms. The new data coming from the recent installed BURAR array offer an excellent opportunity to extend this analysis and to test the stability and accuracy of the source parameter assessment by relative techniques.

OBSERVATION DATA

For the present study we selected 36 earthquakes occurred after 2002 in the Vrancea seismic region at intermediate depths ($87 \le h \le 166$ km) with moderate magnitudes ($3.4 \le M_w \le 6.0$). For this magnitude range the signal/noise ratio as recorded at BURAR stations is acceptable for our purpose. The VELEST algorithm was applied to locate the events: the hypocentre parameters are given in Table 1. The VELEST is an inversion routine to solve the coupled inverse problem of hypocenter location and structure determination by a trial-and-error procedure using different initial velocity models, initial hypocenters and control parameters (*e.g.*, damping parameter) (Kissling *et al.*, 1995). The progressive iterative procedure stops when a minimum average RMS value is obtained for the whole set of earthquakes.

In order to apply relative deconvolution techniques we need main events (11 events in Table 1, marked by bolded characters) and EGF events (26 events in Table 1). Each main event is accompanied by at least one EGF event with the hypocentre approximately located in the same place as the main event and the size sufficiently smaller than the size of the main event. Note that in Table 1 an EGF can appear several times associated with different main earthquakes.

Table 1

List of the selected earthquakes for this study*

Event nr.	**Date**	**hh:mm**	**Lat.** (°N)	**Lon.** (°E)	**h** (km)	**M**$_w$
1	2002/08/27	06:46	45.61	26.41	148	4.0
2	**2002/11/30**	**08:15**	**45.68**	**26.49**	**173**	**4.7**
3	2002/12/15	13:37	45.79	26.69	106	3.6
4	2002/12/23	19:32	45.57	26.41	113	3.5
5	2002/12/30	15:41	45.69	26.54	150	4.1
6	2003/04/05	16:26	45.77	26.61	115	3.5
7	2003/05/02	20:34	45.64	26.44	148	3.7
8	2003/05/19	08:38	45.67	26.48	150	3.9
9	2003/07/18	02:45	45.64	26.46	145	3.6
10	2003/08/02	01:32	45.62	26.44	149	4.1
11	2003/08/27	13:15	45.61	26.41	149	3.8
12	2003/09/16	09:25	45.70	26.61	88	3.8
13	**2003/10/05**	**21:38**	**45.62**	**26.36**	**152**	**4.6**
14	2003/11/20	12:59	45.72	26.68	135	3.6
15	**2004/01/21**	**05:49**	**45.54**	**26.41**	**119**	**4.1**
16	**2004/02/07**	**11:58**	**45.73**	**26.61**	**143**	**4.4**
17	2004/03/14	05:26	45.76	26.71	126	3.8
18	**2004/04/04**	**06:41**	**45.66**	**26.46**	**144**	**4.3**
19	2004/04/06	22:35	45.64	26.55	141	3.8
20	2004/04/24	13:00	45.53	26.61	116	3.7
21	2004/06/16	15:46	45.48	26.29	113	3.5
22	2004/07/02	01:38	45.68	26.81	108	3.8
23	**2004/07/10**	**00:34**	**45.71**	**26.54**	**150**	**4.3**
24	**2004/07/22**	**17:09**	**45.59**	**26.34**	**147**	**4.2**
25	2004/08/13	00:47	45.70	26.60	89	3.4
26	2004/09/12	04:26	45.51	26.32	140	3.8
27	**2004/09/27**	**09:16**	**45.65**	**26.46**	**152**	**4.7**
28	**2004/10/24**	**19:56**	**45.50**	**26.37**	**163**	**4.3**
29	**2004/10/27**	**20:34**	**45.80**	**26.65**	**97**	**6.0**
30	2004/10/30	05:20	45.60	26.36	150	3.8
31	2004/11/23	18:33	45.75	26.73	122	3.9
32	2005/03/06	22:32	45.65	26.48	153	4.2
33	2005/04/04	18:59	45.40	26.36	129	4.0
34	2005/05/09	06:53	45.50	26.28	143	4.1
35	**2005/05/14**	**01:53**	**45.66**	**26.52**	**146**	**5.1**
36	2005/05/14	06:36	45.65	26.49	147	4.2

*The main events are written with bolded characters. One EGF event can be associated to one or more main events when they comply with the collocation requirements.

RELATIVE DECONVOLUTION METHODS

The basic hypothesis of the relative deconvolution methods is the removal of the path and site effects using pairs of collocated events. The SR and EGF techniques differ in two important aspects: *(i)* the first method is applied in the spectral domain, while the second method is applied in the time domain; *(ii)* the condition of a minimum size difference between the main and EGF events is not compulsory for the SR technique.

The SR method was developed and applied in different seismic zones after 1985 (Mueller, 1985; Frankel *et al.*, 1986, Mori, Frankel, 1990; Hough *et al.*, 1991). The method proved to be particularly efficient for broadband recordings (Lindley, 1994). One advantage of the method is the possibility to simultaneously retrieve the source parameters for both the main and the associated collocated event. One essential condition is to have available an extended frequency band of the seismic instrument and the signal/noise ratio for the smaller event to be high enough.

If the source model represents a simple, uniform rupture process and the high-frequency spectral decay is like ω^{-2}, the spectral ratio is given by the theoretical function:

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

where Ω_0^P, Ω_0^G are the low-frequency levels of the displacement amplitude spectra of main and Green's function events, while f_c^P, f_c^G are the corresponding corner frequencies.

A procedure of nonlinear regression is applied to fit the observed spectral ratios to the function (1), taking as free parameters the ratio of the seismic moments and the two corner frequencies f_c^P and f_c^G. The corner frequency is directly related to the dimension of the rupture area (Brune, 1970):

$$r = 0.28\, v_s/f_c \quad (2)$$

where r is the equivalent source radius. The ratio of the seismic moments (nominated as *a*) and the corner frequencies for a given pair are estimated as an average for the stations of the BURAR array (10 stations in general). The method is relative and therefore does not allow the computation of the absolute seismic moment values. To determine absolute values we need the value of one of the seismic moments obtained by another method.

After estimating seismic moments and corner frequencies we compute the source radius with (2) and the stress drop using Brune's relation:

$$\Delta\sigma_B = \frac{7M_0}{16r^3} \quad (3)$$

In parallel we applied the EGF deconvolution for the same earthquake pairs. The result of deconvolving the Green's function from the main event is the apparent source time function (STF). For a simple rupture process the STF is a single pulse, more or less symmetric. The width of the pulse, τ, is a measure of the source duration and can be used to estimate the source radius (Boatwright, 1980):

$$r = (\tau_{1/2} v)/(1 - v/\alpha \sin\theta) \quad (4)$$

where $\tau_{1/2}$ is the rise time, and in a first approximation can be taken as half of the pulse width, v is the rupture velocity ($v = 0.9\beta$, β is the shear wave velocity at the source depth), α is the longitudinal wave propagation velocity and θ is the emergence angle of the longitudinal waves relative to the normal to the fault plane. We assume an average estimation of $\theta = 15^{o}$ corresponding to a fault plane solution with a rupture plane oriented approximately N45^{o}E and dipping vertically, which is predominantly observed for the Vrancea earthquakes. For the average shear wave velocity at source depth we consider $\beta = 3.5$ km/s for the entire intermediate-depth domain. Likewise the estimations from spectral ratios, the source parameters deduced from EGF technique are averages using all the array recordings for a given earthquake pair. The final values are estimated using both results from SP and EGF methods.

DECONVOLUTION ANALYSIS

The relative deconvolution methods are applied for each main event of Table 1 in order to determine the source parameters. In each case, we make use of all possible co-located events which can be considered as empirical Green's functions. An example of waveforms of main event and associated empirical Green's event is given in Fig. 2 for the main shock recorded on 14 May 2005, 01:53 and the aftershock recorded after about 5 hours in the same day (14 May 2005, 06:36). To simplify the image we represent only the broadband seismograms (station B10).

Note the deficit of S-wave radiation for the smaller event when compared with the larger event. This feature is not observed for P waves and should be related to a specific frequency dependent attenuation or site effect. Since it is present in all cases considered by our study, the effect should be caused by propagation and not by source properties. At the same time, it should be very sensitive to frequency content in order to explain the relative difference between the waveforms for such small magnitude variation (about 1 unit of magnitude or even less). This is also the reason why we did not use S wave in our deconvolution analysis (due to the low S/N ratio for the smaller events).

The spectral ratios and the fit function (1) obtained using P waves are represented in Fig. 3 and the source time functions resulted after applying the EGF deconvolution are given in Fig. 4. We represent as example the case of the main event of 27 September 2004, 09:16 and the collocated event of 6 April 2004, 22:35.

The analysis of the spectral ratios allows the estimation of the corner frequencies and the ratio of seismic moments for the main and EGF events, while the analysis of the source time function provides the measure of the source duration for the main event. These parameters are obtained using different stations of the array and different EGF events for a given main event. Since they refer to source, they should be similar. Thus, our combined procedure offers the possibility to have a measure of the dispersion of the source parameters determination. Similar shapes like in Figs. 2, 3 and 4 are obtained for all the combinations of main and EGF earthquakes we considered.

The source radius is estimated using both corner frequency (eq. (2)) and source duration (eq. (4)). The seismic moment is deduced from the spectral ratio low frequency level and stress drop is subsequently computed using eq. (3). The source parameters inferred as average using all the values per station and for different empirical Green's functions are given in Table 2. For the largest earthquake of our dataset (27 October 2004) we could not find appropriate EGF and therefore we could not recover a well-defined and reliable STF. Possibly, this event occurred in a sort of gap (unruptured zone) of the Vrancea active volume, and for this reason we could not find co-located earthquakes. Another explanation could be the particularity of the rupture process for this earthquake, with a relatively long nucleation phase (Radulian *et al.*, 2005). Therefore, for the October 2004 event, only the spectral determinations (SR) are applied since they are not so sensitive to differences in location of source process among main and Green's events.

Table 2

Source parameters of the main events of Table 1 retrieved as average values

Ev.	$\langle f_c \rangle$ (Hz)	$\langle r_s \rangle$ (m)	$\langle \tau_{1/2} \rangle$ (s)	$\langle r_t \rangle$ (m)	$\langle \Delta\sigma_s \rangle$ (MPa)	$\langle \Delta\sigma_t \rangle$ (MPa)	$\langle M_o \rangle$ (Nm)
2002/11/30	1.67±0.38	1001±230	0.195±0.036	1274±233	94	46	2.15×10^{17}
2003/10/05	3.82±0.30	417±35	0.092±0.023	584±122	65	264	1.20×10^{17}
2004/01/21*	3.89±0.85	424±94	0.157±0.017	1024±112	6	0.4	9.50×10^{14}
2004/02/07*	3.81±0.03	416 ± 3	0.137±0.036	897±237	26	3	4.20×10^{15}
2004/04/04	2.60±0.34	624±104	0.101±0.010	662±75	3	2	1.40×10^{15}
2004/07/10*	2.15±0.10	738±34	0.156±0.016	1016±106	3	1	2.80×10^{15}
2004/07/22	3.93±0.64	411±71	0.108±0.017	704±110	18	4	2.90×10^{15}
2004/09/27	2.37±0.39	688 ±124	0.110±0.020	735±108	54	44	4.00×10^{16}
2004/10/24	3.08±0.66	533±102	0.096±0.014	627±98	75	46	2.59×10^{16}
2004/10/27	1.37±0.28	1205±231	–	–	135	–	5.40×10^{17}
2005/05/14*	1.87±0.44	904±251	0.235±0.030	1533±195	30	6	5.00×10^{16}

* Complex sources.

The subscript 's' indicates spectral estimation and 't', time estimation.

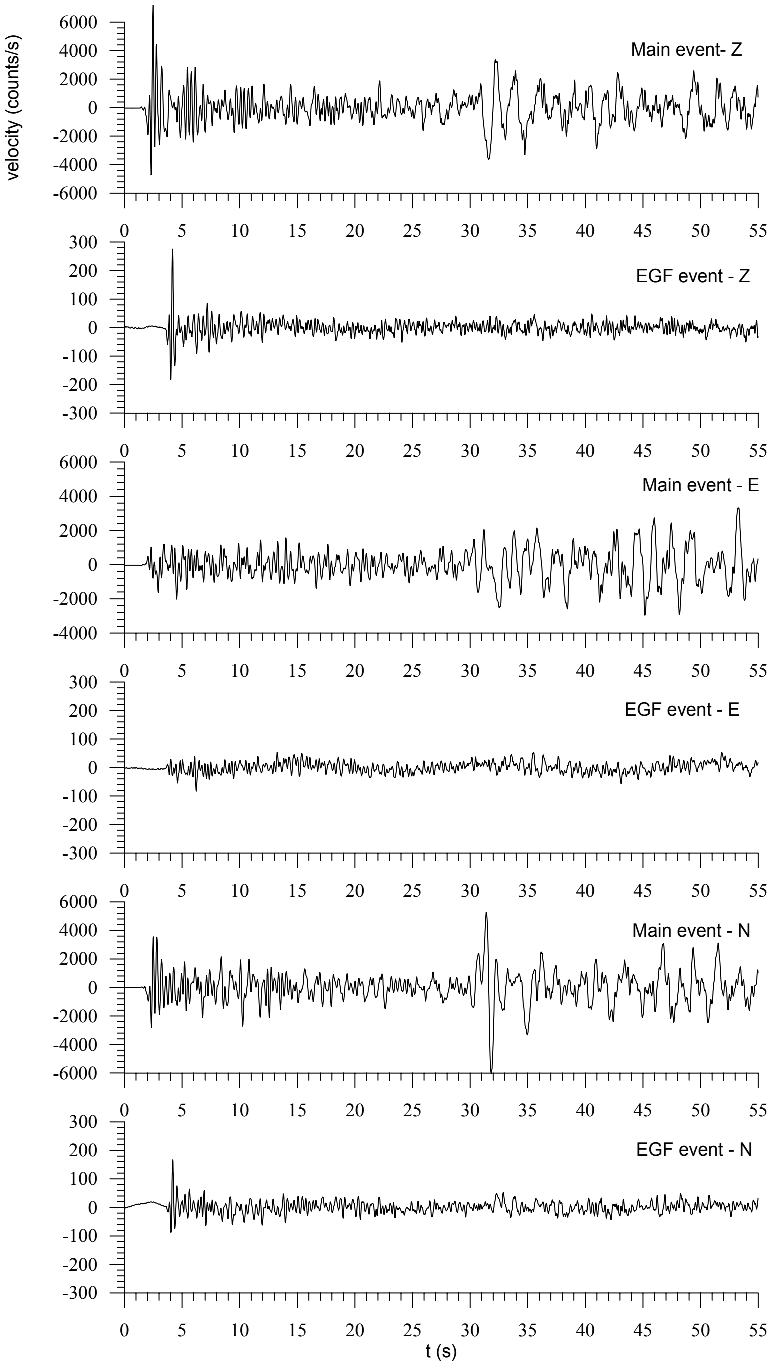

Fig. 2 – Example of waveforms recorded at station B10 (velocity in counts) for the main event of 14 May 2005, 01:53 and the associated collocated event of 14 May 2005, 06:36.

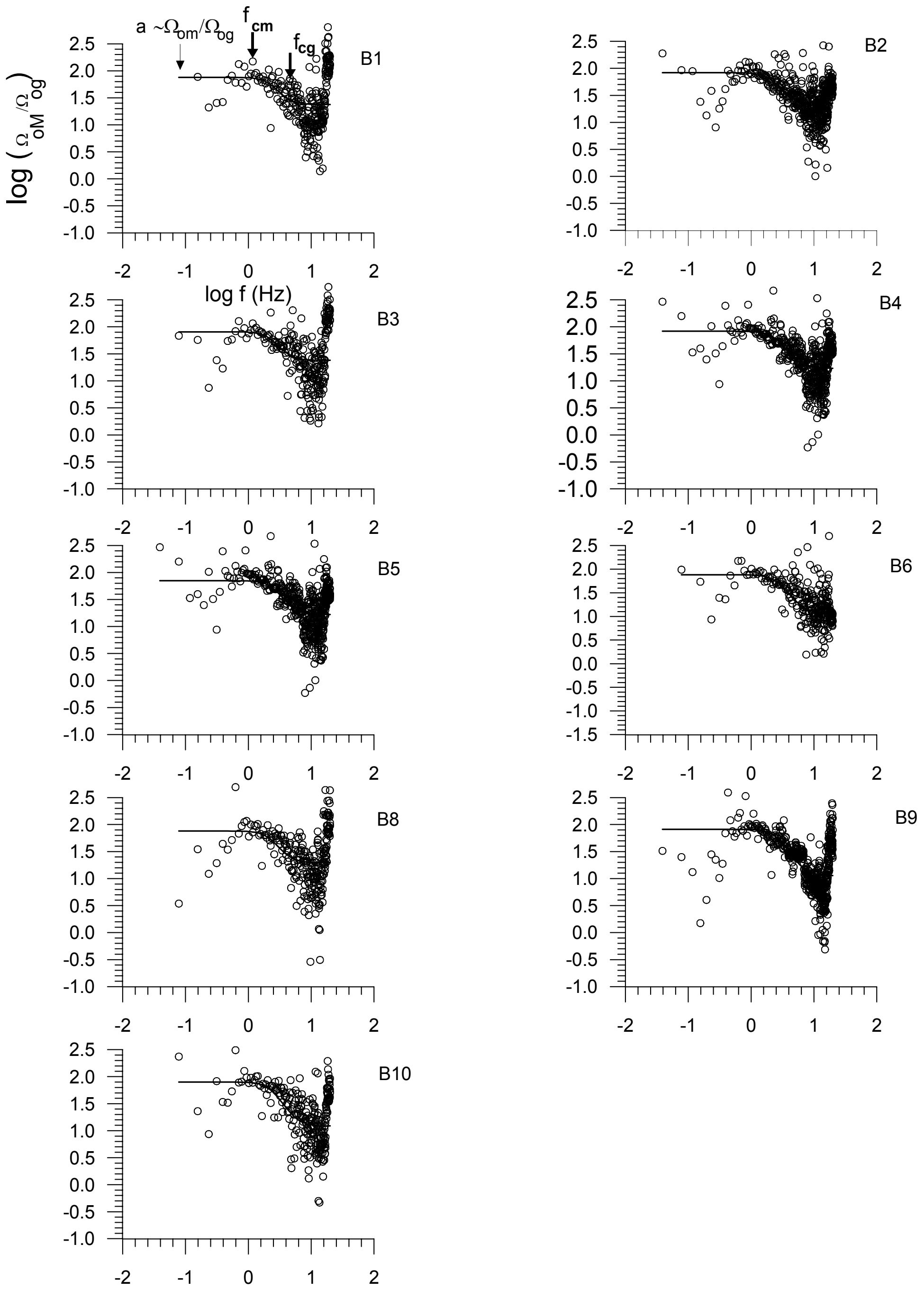

Fig. 3 – Spectral ratios for the main event of 27 September 2004, 09:16 and the associated collocated event of 6 April 2004, 22:35.

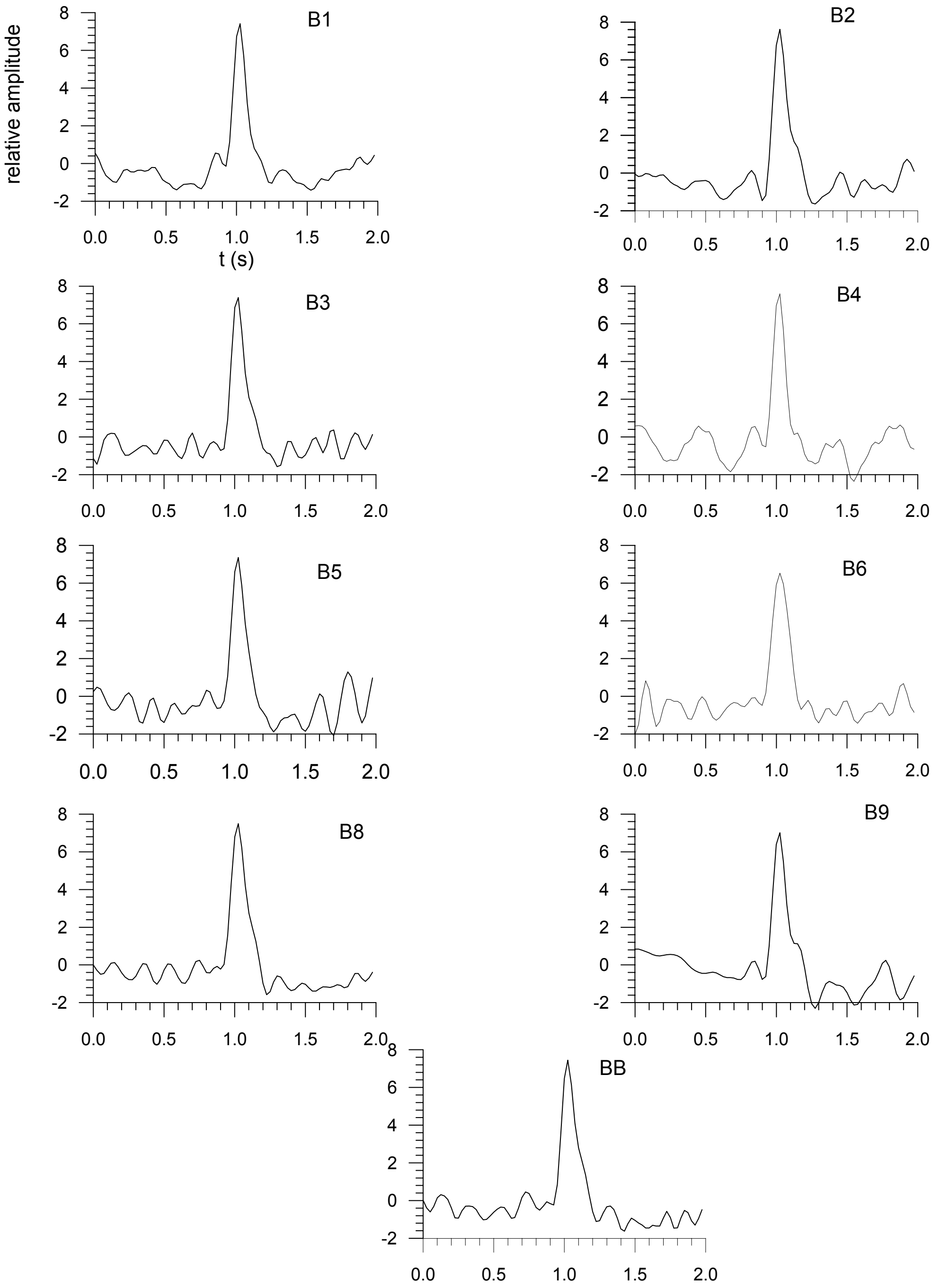

Fig. 4 – Source time function of the main event of 27 September 2004, 09:16 retrieved by deconvolution with the EGF of 6 April 2004, 22:35.

The measure of scattering is given by the standard deviation (Table 3). The relative errors are in the range of [3, 30%]; the smallest characterize the low-frequency level in spectral ratios, a ~ $\Omega_{om}/\ \Omega_{og}$ (3-4%), while the largest characterize the EGF events corner frequencies by spectral ratios method (30%).

Table 3

Standard deviations for the source parameter estimations of the main shocks

Events	Ds % (a)	Ds % (f_{cm})	Ds% (r_{MRS})	Ds % ($\tau_{1/2}$)	Ds % (r_{RTM})
2002/11/30	8–10	23 (45)	23 (45)	18 (40)	18 (40)
2003/10/05	3(3)	8 (3)	8(3)	25 (29)	25 (29)
2004/01/21*	10	22(5)	22(5)	12 (5)	12 (5)
2004/02/07*	7	1(2)	1(2)	26(10)	26(10)
2004/04/04	3–6	17 (21)	17 (21)	11 (30)	11 (30)
2004/07/10*	2 (2)	5(2)	5(2)	10(10)	10(10)
2004/07/22	7 (2)	16 (2)	16 (2)	16(9)	16(9)
2004/09/27	1–4	20 (64)	23 (64)	15 (59)	15(59)
2004/10/24	3–4	17 (21)	17 (21)	11 (30)	11 (30)
2004/10/27	2–5	20 (54)	19 (54)	–	–
2005/05/14*	2–5	24 (60)	28(60)	13 (37)	13 (37)

The number of observations for average estimate is given within parentheses.

The average source time functions (normalized) for the entire set of main events for the broad band instrument (B10) are represented in Fig. 5. The averaging procedure for a given earthquake is justified since the variability from one individual case to the other (for different Green's events and for different stations) is acceptably small. As a consequence, we can assume weak directivity effects for the moderate size earthquakes considered in this study, which is not always the case for Vrancea earthquakes (see Popa and Radulian, 2000). The inspection of the source time function patterns shows both simple homogeneous and complex rupture processes. Complex rupture is obtained for the earthquakes of November 30, 2002, February 7, 2004, July 10, 2004 and May 14, 2005. In these cases, the source dimension and stress drop are computed using the parameters of the first subevent composing the source.

STABILITY AND ACCURACY TESTS

Since the BURAR array provides recordings from several stations located over a small area relative to the distance to the Vrancea focus, we can test straightforwardly the stability and accuracy of our results. Thus, in Fig. 6 we present comparatively the source time functions for the main event of September 27, 2004 deconvolved using the empirical Green's function of May 2, 2003 for all the short period instruments (B1,….,B9) and the broadband instrument B10.

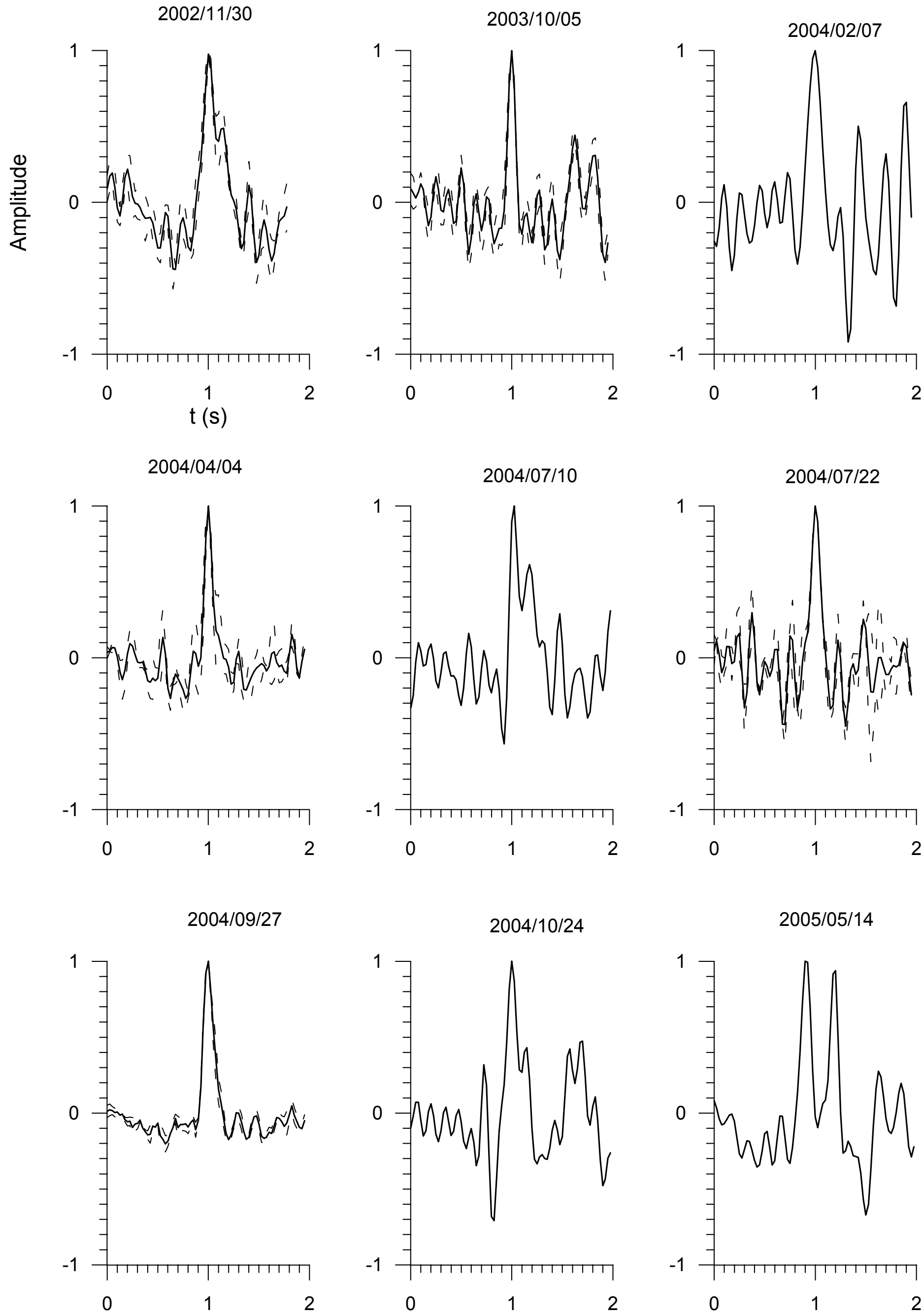

Fig. 5 – Average source time functions of the main events of Table 1 as retrieved using the broadband station (B10). The dashed line is standard deviation. The event of 2004/01/21 is missing since the broadband station was not working in this case.

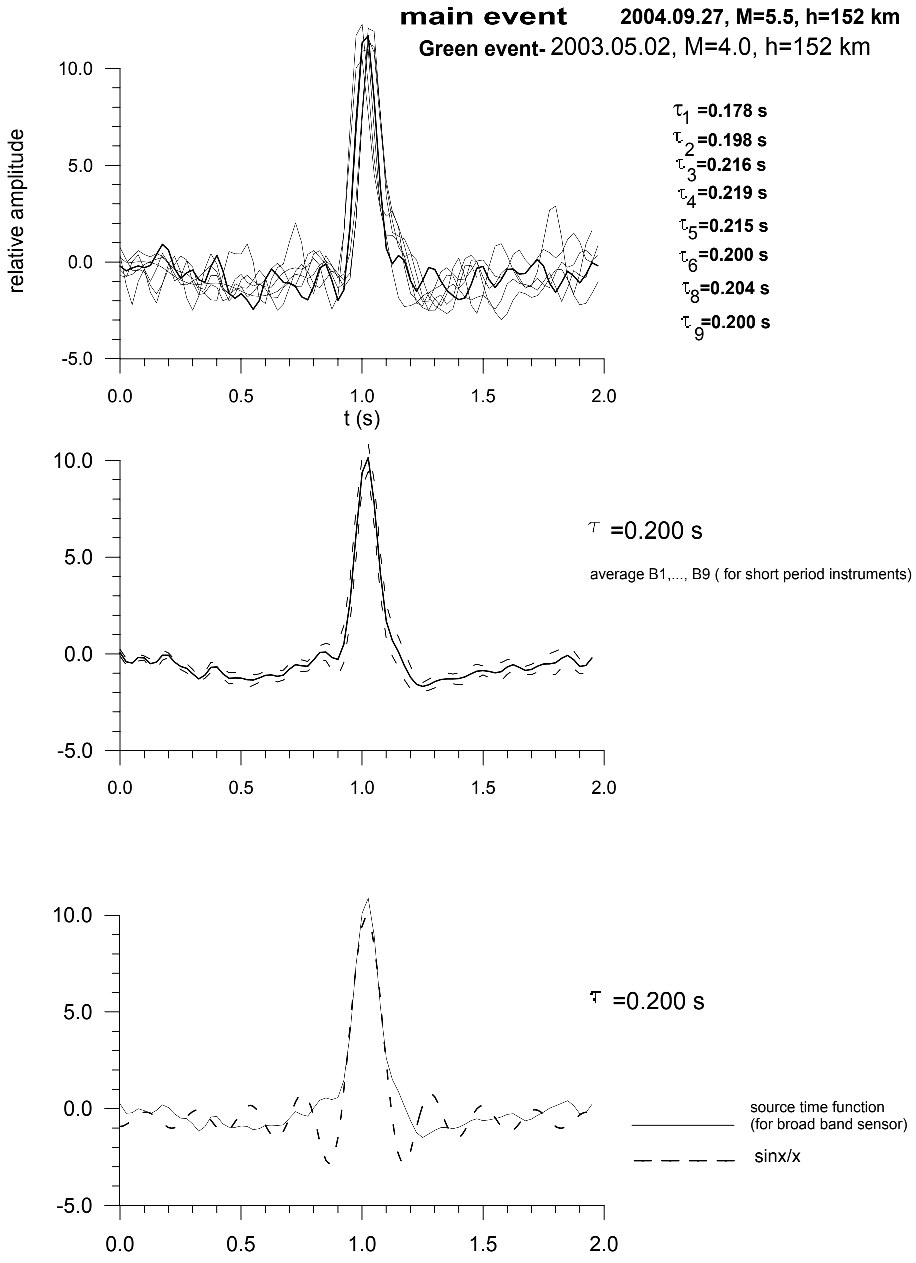

Fig. 6 – Test of stability of the source time function of earthquake of 27 September 2004 obtained by deconvolution using the empirical Green's event of 2 May 2003. Upper slide: STF obtained from short-period instruments; middle slide: STF obtained from the broadband instrument B10 (dashed line) compared with the STF obtained from the short-period instrument located in the same site (B8); lower slide: average STF and a fit function of the type sinx/x (dashed line).

The differences in the STF pulse amplitude are less than 19%, while in the pulse width they are less than 11% (for the case represented in Fig. 6 the rupture duration varies between 0.04 and 0.22s). If we analyze the stability of the deconvolution results considering all the possible EGF events, the accuracy is below 19% for amplitude and 11% for source duration. The errors are caused by differences in local site effects from one site to another and differences in the location of main and associated EGF events.

If we consider the entire set of main and EGF earthquakes, except the events with complex rupture, the accuracy of the STF pulse width is between 11% and 26%. Having in mind the intrinsic instability of the deconvolution procedure, these accuracy bounds are reasonable. The comparison of the STF resulted from short-period instrument (B8) and the broadband instrument (B10), both located in the same place, shows no influence of the instrument frequency response upon the deconvolved functions.

The variability of the spectral ratios obtained for a given main earthquake is tested also using the set of available recordings for different array stations and collocated Green's events. As example, we represent in Fig. 7 the test of variability for the main event of 27 September 2004 and the collocated event of 6 April 2004. The influence of the instrument frequency bandwidth is checked as well: the average of the spectral ratio obtained using short-period recordings is very close to the spectral ratio obtained from broadband data (middle slide of the figure).

The low-frequency level and the corner frequency of the main event are better constrained, as expected, as compared with the high-frequency level and the corner frequency of the associated EGF event. The standard deviation for the low-frequency level varies between ± 1% (for the event of 2004/09/27) and ± 10% (for the event of 2002/11/30 and 2004/01/21). For the corner frequency of the main event the standard deviation is between ± 1% (for the event of 2004/02/07) and ± 24% (for the event of 2005/05/14). The errors are significantly larger for the corner frequency of the EGF event.

SCALING RELATIONSHIPS FOR THE VRANCEA SEISMIC SOURCE

One of the main objectives of this paper is to achieve scaling relationships for the Vrancea intermediate-depth earthquakes based on BURAR array recordings and applying relative deconvolution techniques. To this aim, we applied both spectral and time-domain analyses for the dataset of 36 earthquakes considered in this study. First, we determined the source parameters for the main events of Table 1, as average of all available estimations using spectral ratios and EGF techniques (Table 2). The source parameters of the EGF events are estimated from spectral ratios alone and are given in Table 4.

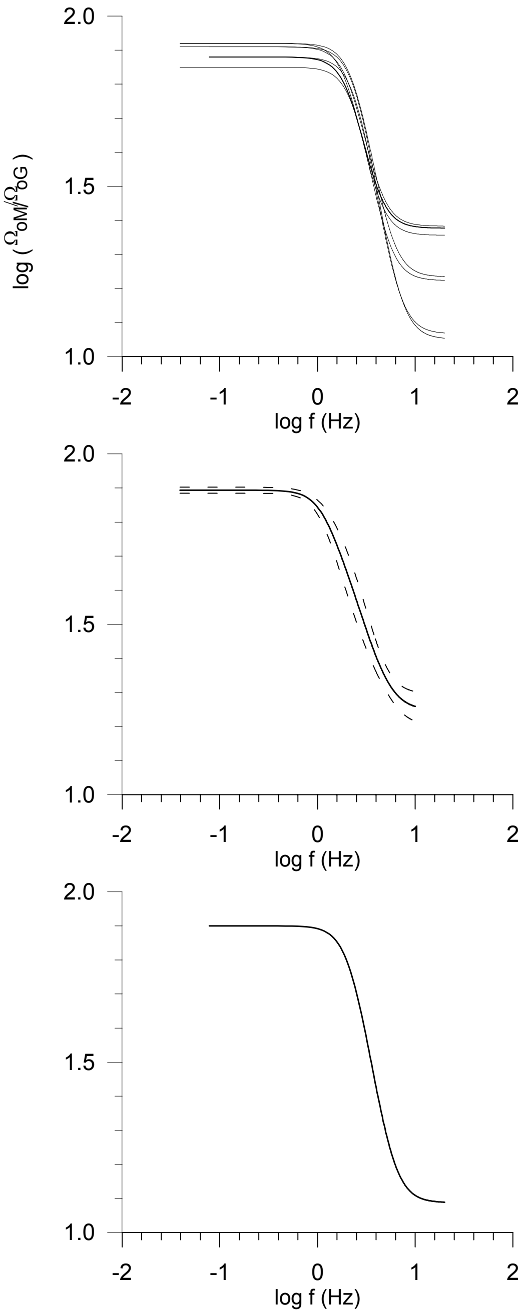

Fig. 7 – Test of variability for the spectral ratios; the case of the 27 September 2004 earthquake and the associated EGF of 6 April 2004. Upper slide: SR obtained from the short-period instruments; middle slide: average SR and standard deviation using the short-period instruments; lower slide: SR obtained from the broadband instrument.

Table 4

Source parameters for the empirical Green's functions of Table 1.
All the values are retrieved by the spectral ratios method.

Ev.	**$\langle f_c \rangle$** (Hz)	**$\langle r_s \rangle$** (m)	$\langle \Delta\sigma_s \rangle$ (MPa)	**$\langle M_o \rangle$** (Nm)
2002/08/27	2.29±0.59	708±212	15	12.40×10^{15}
2002/12/15	3.14±0.52	505	2	4.39×10^{14}
2002/12/23	7.02±1.49	234±54	2	4.44×10^{13}
2002/12/30	3.28±0.38	489±61	62	16.6×10^{15}
2003/04/05	3.96±1.34	437±125	2	3.25×10^{14}
2003/05/02	2.61±0.65	634±129	13	7.29×10^{15}
2003/05/19	3.33±1.00	493±167	25	6.80×10^{15}
2003/07/18	7.67±1.27	211±35	79	1.7×10^{15}
2003/08/02	2.43±0.62	686±148	16	11.7×10^{15}
2003/08/27	2.60±0.79	672±168	26	18.2×10^{15}
2003/09/16	5.68±1.55	316±116	13	9.16×10^{14}
2003/11/20	6.42±0.00	247±0	10	3.41×10^{14}
2004/03/14	3.93±1.01	423±92	1	1.52×10^{14}
2004/04/06	4.18±0.86	397±99	1	1.76×10^{14}
2004/04/24	4.75±1.35	360±107	2	1.56×10^{14}
2004/06/16	12.15±2.38	137±39	103	6.07×10^{14}
2004/07/02	3.97±0.76	399	2	3.40×10^{14}
2004/08/13	4.64±0.95	353±66	4	3.65×10^{14}
2004/09/12	8.92±2.20	186±42	44	6.50×10^{14}
2004/10/30	4.82±1.81	392±137	3	3.48×10^{14}
2004/11/23	5.73±0.79	282±40	5	2.70×10^{14}
2005/03/06	4.81±0.73	336±51	8	6.90×10^{14}
2005/04/04	6.77±1.18	241±42	2	7.57×10^{13}
2005/05/09	3.54±1.28	563±201	2	9.53×10^{14}
2005/05/14	3.27±0.83	515±140	4	1.20×10^{15}

The scaling of seismic moment and magnitude is given in Fig. 8 and Fig. 9, for moment magnitude and duration magnitude, respectively. The regression approximation gives:

$$\log M_0 = (1.50 \pm 0.22)\, M_W + (9.24 \pm 0.90) \qquad (5)$$
$$R = 0.76,\ \sigma = 0.66$$

$$\log M_0 = (1.29 \pm 0.18)\, M_D + (9.59 \pm 0.79) \qquad (6)$$
$$R = 0.78,\ \sigma = 0.63$$

The scaling of the seismic moment and corner frequency is approximated by the relation:

$$\log M_0 = -(3.54 \pm 0.54) \log f_c + (17.36 \pm 0.35) \qquad (7)$$
$$R = 0.73,\ \sigma = 0.70$$

and is represented in Fig. 10. The slope of -3.54 is slightly different from the typical -3 value which characterizes a simple homogeneous rupture process, but having in mind the data dispersion, we consider that the slope deviation from -3 is not relevant to denote a real deviation of source properties from the typical source scaling.

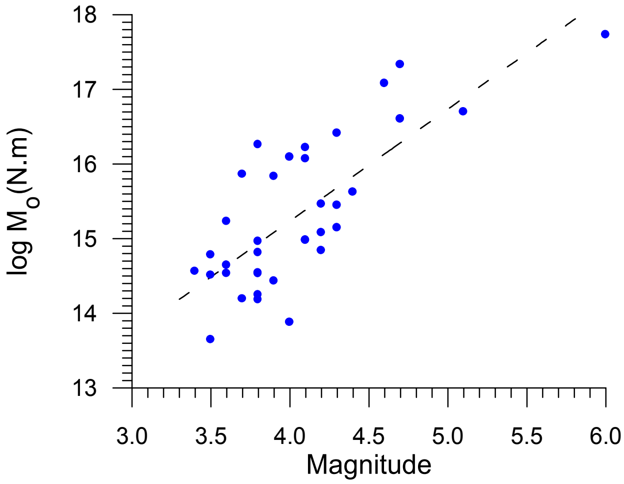

Fig. 8 – Seismic moment – moment magnitude scaling.

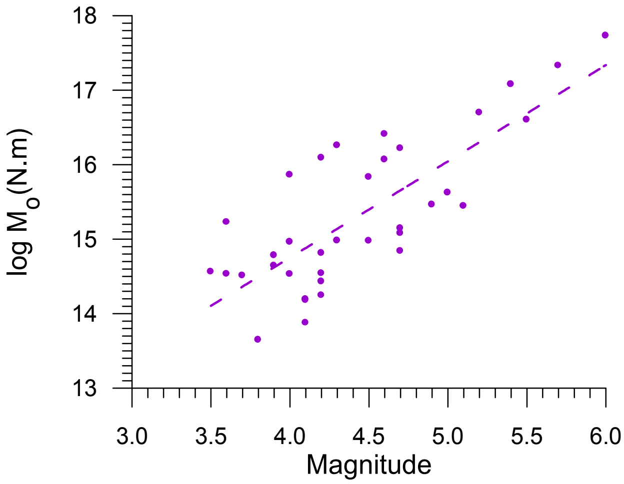

Fig. 9 – Seismic moment – duration magnitude scaling.

Finally, we estimate the scaling of seismic moment and stress drop (Fig. 11):

$$\log \Delta\sigma = (0.50 \pm 0.07) \log M_0 - (6.65 \pm 1.06), \quad (8)$$
$$R = 0.78, \sigma = 0.41$$

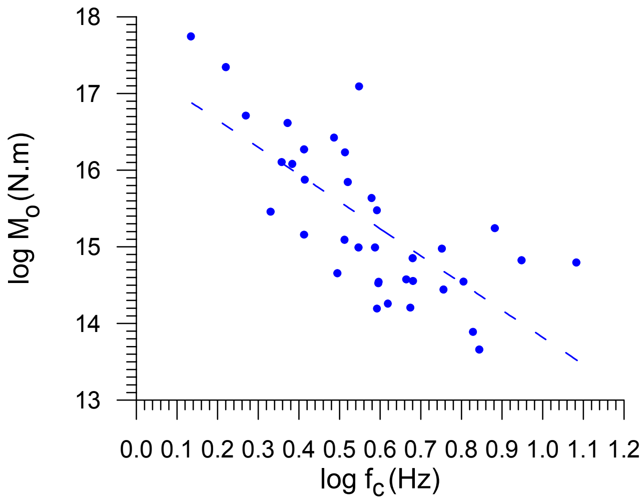

Fig. 10 – Seismic moment – corner frequency scaling.

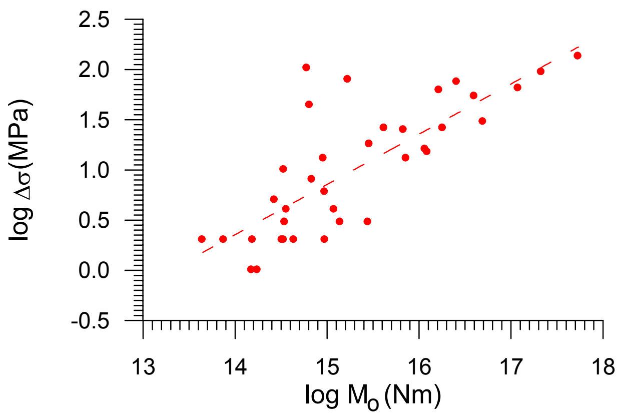

Fig. 11 – Scaling of the stress drop against the seismic moment.

The increase of the stress drop with the increase of the seismic moment is a common result for the source scaling in case of Vrancea earthquakes (Radulian, Popa, 1996; Popa, Radulian, 2001). Despite the intrinsic errors related to stress drop estimations, this result seems quite reliable. It reflects a change in the source process behaviour when the rupture size increases.

CONCLUSIONS

Relative techniques of analysis are applied for a set of 36 earthquakes occurred in the Vrancea intermediate-depth focus, using the recordings of the BURAR array, located about 250 km to the north. To apply relative techniques we have to select a cluster of events located close to each other. For the empirical Green's function deconvolution another condition requires a difference in size between the so-called main event and the EGF event. This difference should be enough to justify a behaviour like Dirac's function of the smaller event relative to the larger event. Such a constraint is not necessary when applying the spectral ratio technique.

The EGF simulates the response of the path between the source and the site, including local and instrument effects, and the relative analysis allows to efficiently remove these effects and retrieve in this way the source directly. The source parameters (seismic moment, corner frequency, source duration, source radius and stress drop) are estimated both in time and spectral domains. Since the procedure we propose in this work provides redundant values, final source parameters are determined averaging all the individual values (for particular main/EGF evens pairs and seismic stations). At the same time, our procedure applied for the small-aperture BURAR array allows stability, accuracy and significance tests of the retrieved source parameters. We compared the source time functions and spectral ratios obtained for the array stations among them and they look basically similar for all the study earthquakes. The similarity is obtained as well when different main event/EGF event pairs are available for a given earthquake. In this way, we validate the application of the relative deconvolution techniques using the BURAR array recordings for reliably retrieving the source parameters of the Vrancea intermediate-depth earthquakes.

The success of the relative deconvolution application depends first of all on the proximity of the main and Green's events. From this point of view, the potential of applicability and accuracy level of the resulted source parameters varies in the Vrancea seismic active volume. For example, the clustering of earthquakes is higher in the lower part of the Vrancea subcrustal lithosphere, and consequently the probability to find pair of collocated events is higher here than in the upper lithosphere volume. For this reason, the deconvolution provides in general more reliable and accurate source parameters for the lower side of the seismic active volume than for the upper side.

Unfortunately, for the largest event of our dataset (27 October 2004) generated in the upper part of the lithospheric slab (h ~ 100 km), we could not find appropriate empirical Green's functions in our dataset to constrain the source time function. For this event we could apply only the spectral ratios technique which is more robust than the EGF technique (it is not too sensitive to the discrepancy in the foci locations).

A notable feature common in all the data considered in our study is a significant deficiency in radiating shear waves in the higher frequencies domain. This should be caused by strong path effects that have to be considered separately in future works. Therefore, the contribution of the S waves to the recorded seismograms is always smaller for the smaller events as compared with the larger events and consequently the BURAR data precludes the possibility to apply relative deconvolution techniques for S waves.

The scaling relationships assessed on the basis of the resulted source parameters reveal a behaviour generally close to the typical behaviours for other source areas with a significant dependence of the stress drop on the seismic moment (non-constant stress drop source model).

Although the BURAR array is located relatively far away from the Vrancea epicentral area (about 250 km to the north) and the particular path from the intermediate-depth focus to this site seems to show strong lateral inhomogeneities (*e.g.*, Popa *et al*., 2003), our analysis proves that the recordings of this array alone provides reliable and useful tools to efficiently constrain the source parameters and consequently source scaling properties.

REFERENCES

GHICA, D., RADULIAN M., POPA M. (2004), *BURAR: detection and signal processing capabilities.* Romanian Reports in Physics, **56**, 777–799.

KISSLING, E., KRADOLFER, U., MAURER, H. (1995), *VELEST user's guide-short introduction*. Techn. Rep., Institute of Geophysics, ETH, Zurich.

POPA, M., RADULIAN, M. (2000), *Test of the empirical Green's function deconvolution on Vrancea (Romania) subcrustal earthquakes*. Studia geophys. geod., **44**, 403–429.

POPA, M., RADULIAN, M. (2001), *Depth-dependent scaling relations of the source parameters for the Vrancea subcrustal earthquakes*. Rom. Journ. Phys., **46**, 499–513.

POPA, M., GRECU, B., POPESCU, E., PLĂCINTĂ, A., RADULIAN, M. (2003), *Asymmetric distribution of seismic motion across South-Eastern Carpathians (Romania) and its implications*. Romanian Reports in Physics, **55**, 521–534.

POPESCU, E., POPA, M., RADULIAN, M. (2003), *Efficiency of the spectral ratio method to constrain the source scaling properties of the Vrancea (Romania) subcrustal earthquakes*. Rom. Journ. Phys., **55**, 1, 163–181.

RADULIAN, M., POPA, M. (1993), *Relative methods to set out the seismic source parameters.* Rev. Roum. Géophysique, **37**, 29–40.

RADULIAN, M., POPA, M. (1996), *Scaling of the source parameters for the Vrancea intermediate depth earthquakes.* Tectonophysics, **261**, 67–81.

RADULIAN, M., BONJER, K.-P., POPESCU, E., POPA, M., IONESCU, C., GRECU, B. (2005), *The October 27, 2004 Vrancea (Romania) earthquake*. CSEM/EMSC Newsletter, (in print).

Received: February 28, 2007
Accepted: March 15, 2007