SCALING PROPERTIES OF THE VRANCEA (ROMANIA) SEISMIC SOURCE AT INTERMEDIATE DEPTHS

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For the present study we selected 126 earthquakes of moderate magnitudes ($3.2 \leq M_D \leq 6.2$) occurred in the time interval 1997–2005 in the Vrancea seismic region at intermediate depths ($62 \leq h \leq 166$ km). Two relative deconvolution techniques (spectral ratios and empirical Green's function) are applied to retrieve the source parameters. To this purpose, the data set was divided into pairs of main and empirical Green's function events. We could select 28 main events and 98 empirical Green's functions. Six main events are generated in the upper segment of the subducting lithosphere ($60 \leq h < 110$ km) and twenty two in the lower one ($h \geq 110$ km). In all cases, the signal/noise ratio as recorded by the Romanian seismic stations is acceptable for our purpose. Once the seismic source parameters (seismic moment, source dimension, stress drop) are estimated, we investigate the scaling properties for the Vrancea subcrustal source. A slight deviation from a homogeneous rupture process and significant variations on depth and on magnitude of the stress drop and source size are emphasized. They can be tentatively explained by a more efficient seismic energy release in the deeper segment of the subducting lithosphere and by the role played by fluids at intermediate depth.

Key words: subcrustal earthquakes, source scaling, spectral ratios, empirical Green's function, Vrancea.

1. INTRODUCTION

Seismic source study cannot be achieved in most of the cases other way than using the seismic motion effects recorded at the Earth surface, therefore corrections for the propagation effects on the hypocenter – seismic station path and for the site effects induced by the local structure are fundamental to properly understand physics of the source process.

The corrections are substantially more difficult to introduce at high frequencies, which are strongly influenced by the structural and process heterogeneities at small scale (much more difficult to understand and control than the large-scale heterogeneities). For this reason, most of the source studies are limited to low frequencies and the large-scale processes and detailed source features are simply ignored and any step forward in extending the frequency range considered to higher values represents for seismologists a real challenge.

However, to simulate the strong ground motion, which is of highest interest for seismic hazard assessment and engineering purposes, we need to introduce the high-frequency contribution since this one plays an important role in characterizing the earthquake motion both as waveform in time and spectra.

Looking to the seismic signal at high frequencies is the main objective of this paper. The chance of correctly decoding the source and structure effects in the Vrancea region from the recorded seismograms is greater now because a dense seismic network has recently been installed in Romania: 38 digital stations with high quality recordings of moderate and strong earthquakes (Fig. 1) are operated at present by the National Institute of Research and Development for Earth Physics (www.inp.ro). Starting with 1995 this network has been continuously developed in the framework of Romanian-German program "Strong Earthquakes: A Challenge for Geosciences and Civil Engineering".

We apply relative deconvolution methods (spectral ratios method and empirical Green's function method) to retrieve the source parameters from the acceleration records. Basically, the methods remove the path and instrument effects by using pairs of earthquakes with close hypocenters recorded by common stations. They are very suitable for seismic sequences, characterized by occurrence in space and time clusters.

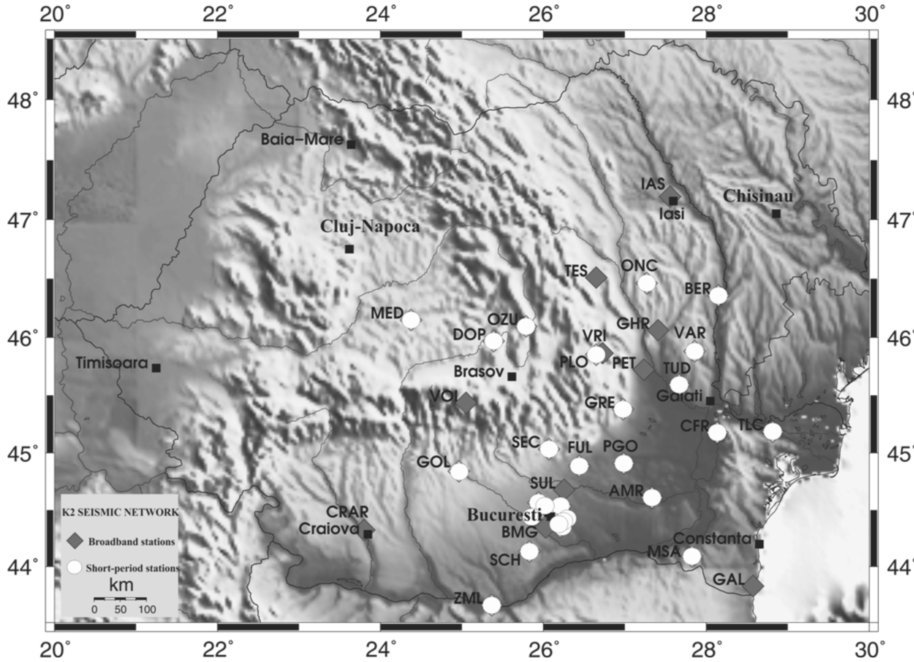

Fig. 1 – The K2 stations distribution.

2. DESCRIPTION OF RELATIVE METHODS

The relative methods of the spectral ratios (SR) and empirical Green's function (EGF) deconvolution are widely used in analyzing ground motion recordings at earthquakes. The methods are applied to pairs of earthquakes located approximately in the same place and recorded by common seismic stations. This class of methods allows the elimination of the propagation, site and instrument effects for the main event through the deconvolution of the waveform of the smaller co-event, considered as EGF. A pair main – EGF events should fulfill the following conditions:

– waveforms should be similar (therefore the focal mechanisms should be similar);

– hypocenters should be close relative to each other;

– the difference between the magnitude of main event and EGF event should be at least one unit;

– the width of the EGF pulse should be sufficiently small relative to the width of main event pulse (to approximate EGF with a delta-type function).

EGF and SR methods have been developed relatively recently in seismology and have been applied in a series of seismic zones of the World (*e.g.*, Mueller, 1985; Frankel *et al.*, 1986; Hough *et al.*, 1989; Mori and Frankel, 1990). In addition to EGF method, the SR method allows the simultaneous determination of the source parameters for both main and EGF event in a selected pair, if broadband and high signal-to-noise ratio recordings are available (Lindley, 1994).

For a source model with uniform rupture and spectral fall-off at higher frequencies of ω^{-2} type, the spectral ratio can be approximated by the theoretical function:

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

where Ω_0^P, Ω_0^G are low-frequency levels of displacement amplitude spectra of the principal event and Green's event, respectively, and f_c^P, f_c^G are the corner frequencies of the two events. They are the spectral free parameters which are determined by a procedure of non-linear regression which find the best fit of the observed spectral ratios with a function of type (1). The ratio of the low-frequency spectral levels is equivalent to the ratio of the seismic moments.

According to Brune (1970), the corner frequency is directly related to the size of the rupture area:

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

$\boldsymbol{r}$ representing the equivalent radius of the source and $\boldsymbol{\beta}$, the velocity of shear waves at source depth. Thus, knowing the corner frequencies for the main and EGF events, we can apply (2) to estimate the source dimension (average radius).

Once we know the seismic moment and source radius values, we can evaluate the source stress drop (Brune, 1970):

$$\Delta\sigma_B = \frac{7M_0}{16r^3} \tag{3}$$

Alternatively, applying the EGF technique, we can estimate in time domain the width of the source pulse, which is a measure of the duration of the rupture process. In this case, the radius of the source was determined using the formula of Boatwright (1980):

$$r = (\tau 1/2v)/(1\text{-}v/\alpha\sin\theta) \tag{4}$$

where $\tau_{1/2}$ is the rise time (approximately half of the source duration), $\boldsymbol{v}$ is the rupture velocity (taken as a fraction of the shear wave velocity β at the source depth), α is the P-wave velocity in source, θ is the angle between the normal to the fault and P-wave emergent direction.

3. DESCRIPTION OF DATA SET AND DETERMINATION OF SOURCE PARAMETERS

The data set selected to estimate the source parameters consists of 126 intermediate-depth earthquakes ($62 \le h \le 166$ km) with magnitudes range $3.2 \le M_D \le 6.2$. The magnitudes are calculated from the duration measured on the seismograms recorded by Vrâncioaia (VRI) and Muntele Roşu (MLR) stations, using the calibration technique proposed by Trifu and Radulian (1991). This technique assures a homogeneous scale for magnitude. We consider the earthquakes separated in two segments of the subducted lithosphere, the upper segment ($60 \le h < 110$ km; segment A, 28 events) and the lower segment ($110 \le h < 230$ km; segment B, 98 events).

From the total number of events, 28 are considered as main events. For each of them, we can find at least one co-located event (EGF). Note at the same time that an event may act as EGF for different main events.

An example of a pair main event – EGF is presented in Fig. 2.

To apply the EGF deconvolution procedure, the seismograms are first corrected for instrument response, then P-wave windows are selected and cosine tapering process is applied to the window edges. The Fourier spectra of the main and associated EGF event and their spectral ratio are computed using FFT algorithm. By inverse FFT application we obtain the source time function of the main event. Generally, the source time function is like a simple pulse with the width measuring the source duration and half-width time ($\tau_{1/2}$) measuring the rise time. Subsequently we estimate the source radius on the basis of rise time value (eq. 4). For the present study, only P-wave recordings are considered in the relative deconvolution procedures.

The source radius estimate for a given main event is the average of the radii obtained for each individual pair (in case there are several EGFs for the main event) and for all the considered stations.

In parallel we applied the spectral ratios technique to the same event pairs. The ratio of the low-frequency asymptotes, $\boldsymbol{a}$, the corner frequency of the main earthquake f_c^P as well as the corner frequency of the EGF event, f_c^G, are estimated by approximating the theoretical function of the relationship (1) with the observed ratios. These operations were repeated for each pair of earthquakes and for each seismic station. The values of parameters were estimated as the average of all determinations available. Contrary to EGF procedure, the SR approach allows the estimation of the corner frequency (source radius) for the EGF event in addition to that of the main event.

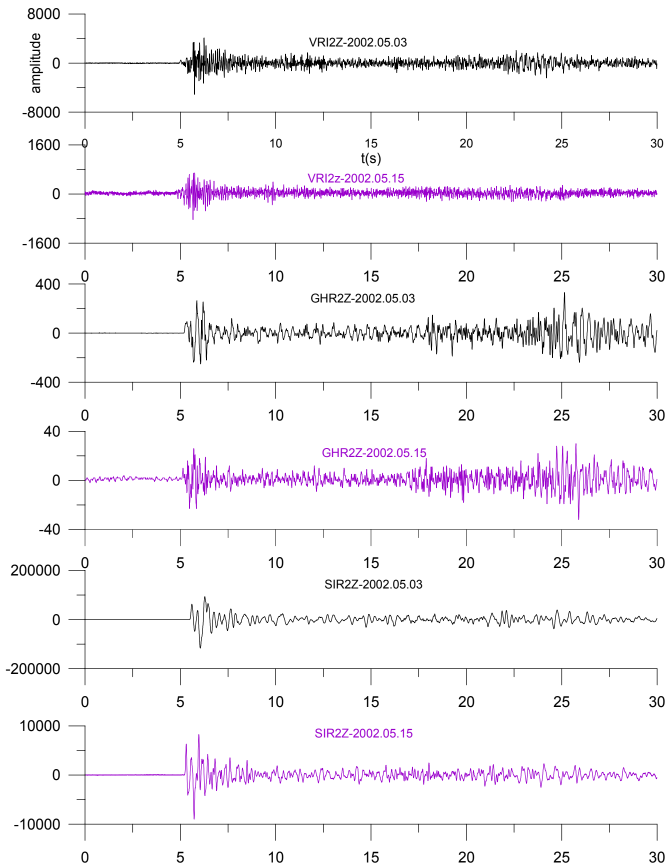

Fig. 2 – Waveforms of the main event of 3 May 2002 and the EGF event of 15 May 2002 recorded at three stations of the K2 network (VRI, GHR, SIR).

The method is relative and does not allow simultaneous estimation of absolute values of seismic moments for both earthquakes. It is necessary to have independently a reference moment value for one of the two earthquakes in a pair. We preferred to use the seismic moment of the main event, which generally is better determined from independent methods. We adopted the seismic moments estimated from the spectral analysis of the moderate earthquakes from Vrancea region (Popescu *et al.*, 2003a, Popescu *et al.*, 2003b, Radulian *et al.*, 2004).

We present in detail the results obtained by the two methods for the pair of events given in Table 1 (3 May 2002, and his co-located aftershock of 15 May 2002). The source parameters estimated separately for each station and as average are presented in Table 2.

The spectral ratios and the source time functions are shown in Fig. 3 and Fig. 4, respectively. Note that when we use as co-located event an aftershock (an event occurred in a small time interval after the main shock occurrence) with similar focal mechanism as the main event, the resulted pulse from deconvolution is well constrained. We can observe also the perfect shape of the average of the source time function in this case, suggesting a simple uniform rupture process for the event of May 3, 2002 (Fig. 5).

The source parameters obtained by the EGF deconvolution and SR technique together with the associated errors are given in Tables 3 (for the main events) and 4 (for the EGF events).

Table 1

Hypocentral parameters of main shock of May 3, 2002 and the associated empirical Green's function of May 15, 2002 (bold line is the main event)

	Data	hh:mm	Lat (°N)	Lon (°E)	h (km)	M_D
M	**2002/05/03**	**18:31**	**45.57**	**26.33**	**162**	**5.2**
EGF	2002/05/15	04:26	45.55	26.36	153	4.3

Table 2

Main event of 2002/05/03 and associated earthquake of 2002/05/15

Station	**a**	f_c^G (Hz)	f_c^P (Hz)	r_{sp}^G (m)	r_{sp}^P (m)	$\tau_{1/2}^P$ (s)	r_{egf} (m)
CFR	1.48	7.40	3.27	214	484	0.093	604
GHR	1.40	4.50	2.02	352	784	0.098	640
VAR	1.48	6.32	2.62	306	720	0.114	744
VRI	1.36	5.02	2.34	251	605	0.128	832
TUD	1.40	6.32	2.62	352	714	0.091	594
SIR	1.42	5.17	2.20	316	672	0.149	973
Average	1.42± 0.05	5.49± 1.15	2.45± 0.45	299±56	663±106	0.112±0.023	731± 150

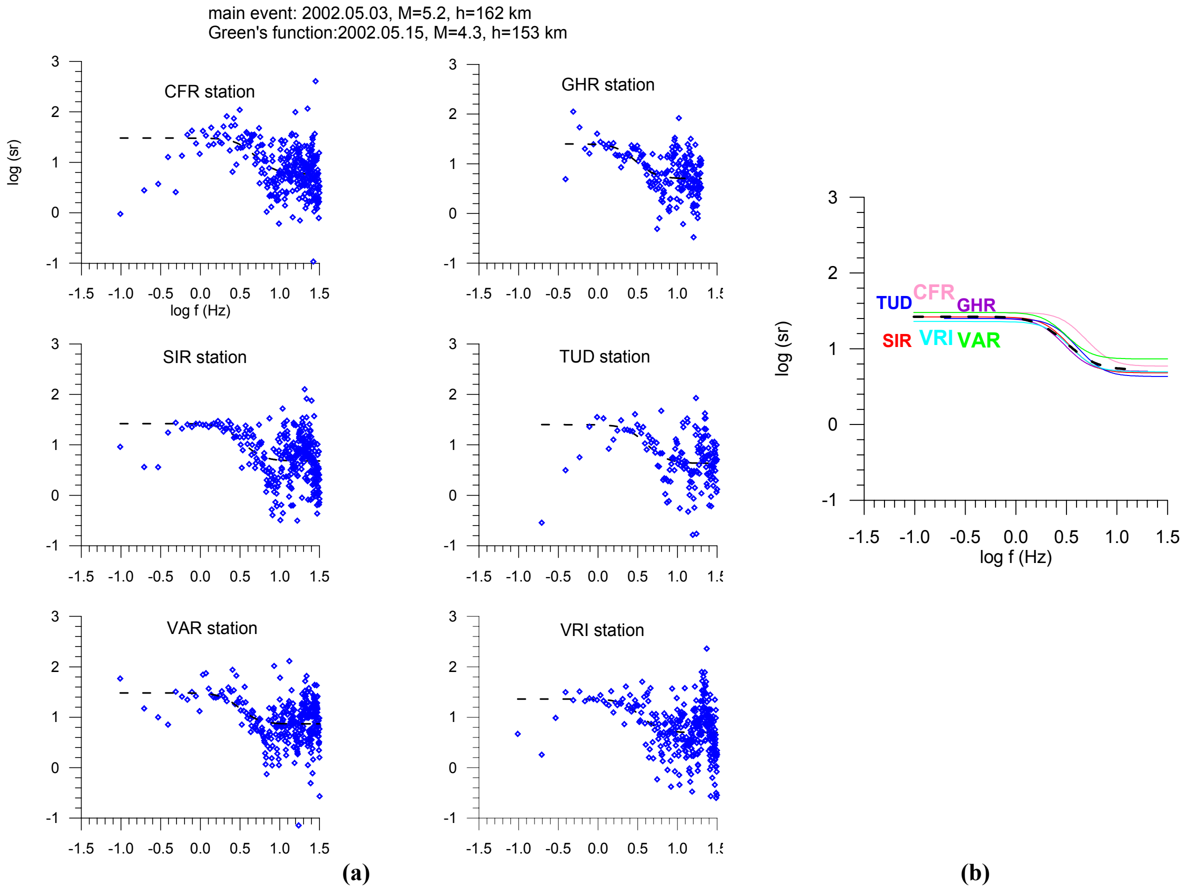

Fig. 3 – (a) The spectral ratios for the main earthquake of May 3, 2002 and the EGF of May 15, 2002 at different stations; (b) spectral ratio (dashed line) obtained by averaging the individual spectral ratios for the 6 available stations.

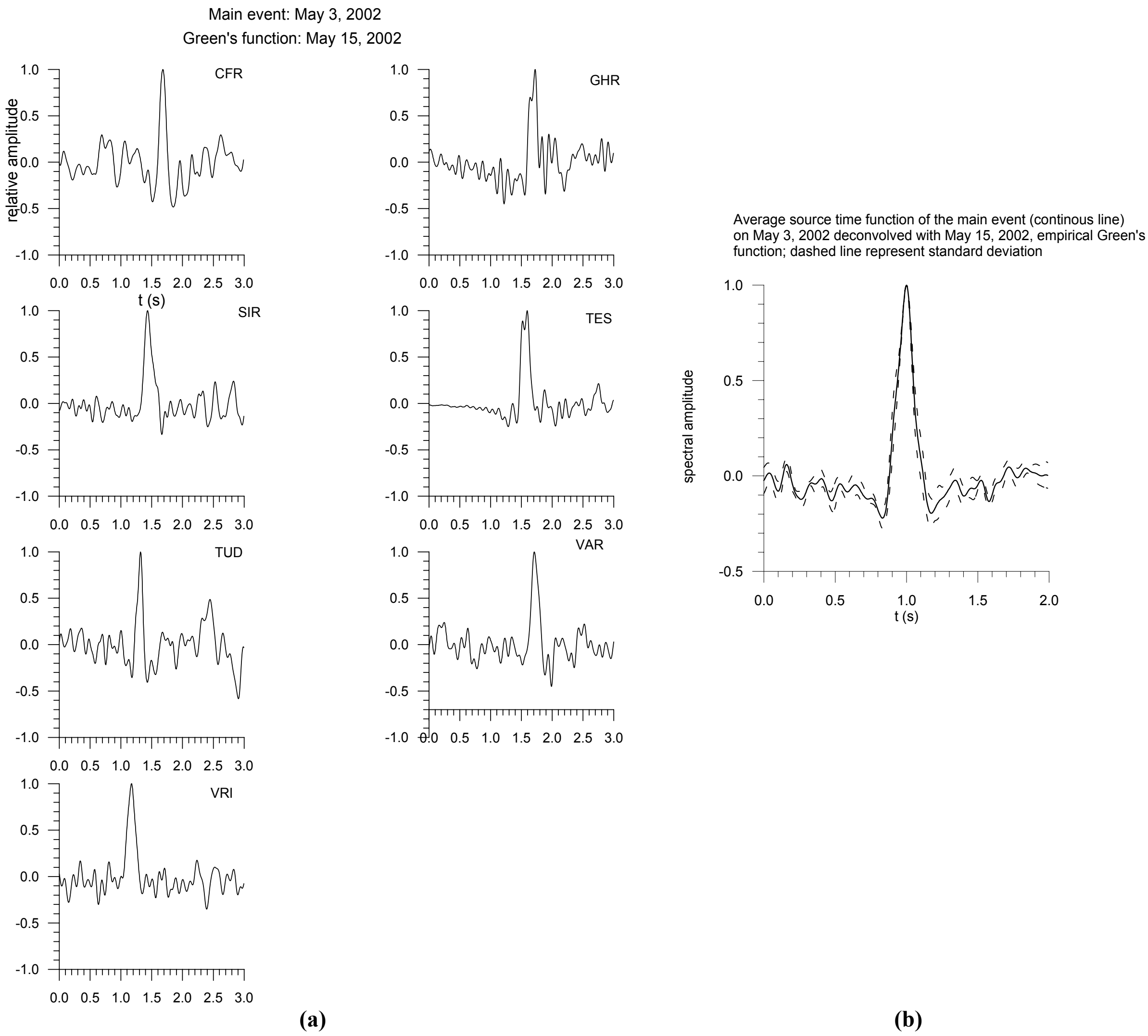

Fig. 4 – (a) Apparent source time functions of the main earthquake of May 3, 2002 resulted from the deconvolution with event Green function of May 15, 2002 for the common stations available; (b) Average source time function in the case of the same earthquake (continuous line) and the standard error (dashed line).

Table 3

Source parameters and associated errors for the considered main events; N_{sr} – number of values used to obtain the average estimation by SR technique; N_{egf} – number of values used to obtain the average estimation by EGF technique.

No.	Data	f_c (Hz)	r_{sr} (m)	N_{sr}	$\tau_{1/2}$ (s)	r_{egf} (m)	N_{egf}
1	1997/10/11	3.35±0.82	571±136	23	0.110±0.027	729±177	12
2	1997/11/18	2.53±0.27	742±82	10	0.150±0.02	952±148	8
3	1997/12/30	3.56±0.59	536±99	8	0.090±0.020	595±129	6
4	1998/01/19	4.25±0.81	440±84	8	0.086±0.005	564±34	4
5	1998/03/13	2.40±0.40	795±158	11	0.120±0.030	793±201	10
6	1998/07/27	2.83±0.69	712±270	11	0.130±0.020	846±117	6
7	1999/03/22	2.79±0.51	687±130	12	0.121±0.015	787±95	4
8	1999/04/28	1.84±0.49	1051±344	57	0.156±0.036	1015±233	26
9	1999/04/29	4.30±0.83	443±78	5	0.100±0.041	653±270	6

Table 3 (continued)

10	1999/06/29	3.08±0.76	635±149	11	0.101±0.025	659±160	10
11	1999/11/08	2.91±0.15	639±33	11	0.117±0.020	766±129	12
12	1999/11/14	3.03±0.71	658±216	14	0.114±0.021	745±140	4
13	2000/03/08	2.55±0.68	756±185	17	0.115±0.004	755 ±36	4
14	2000/04/06	1.88±0.46	1044±245	58	0.160±0.028	1047±189	36
15	2000/05/10	3.32±0.69	581±121	13	0.077±0.015	504±99	16
16	2001/03/04	1.79±0.39	1196±292	18	0.160±0.020	1065±154	13
17	2001/05/24	1.73±0.41	1131±270	37	0.150±0.040	967±237	26
18	2001/07/20	1.87±0.47	1063±302	46	0.140±0.030	918±210	34
19	2001/10/17	2.90±0.63	649±130	7	0.124±0.005	808±31	4
20	2002/05/03	2.45± 0.45	663±106	6	0.112±0.023	731±150	6
21	2002/09/06	3.76±1.03	501±137	2	0.076±0.019	498±121	3
22	2002/11/30	1.92±0.72	933±340	39	0.166±0.047	1087±308	14
23	2003/10/05	3.27±0.56	586±114	14	0.122±0.036	795 ±238	13
24	2004/02/07	3.17±0.40	590±73	8	0.140±0.060	848±342	7
25	2004/07/10	2.92±0.58	661±138	19	0.131±0.038	878±241	14
26	2004/09/27	2.16±0.36	882±153	39	0.120±0.020	782±142/	38
27	2004/10/27	1.60±0.46	1222±360	74	0.170±0.040	1140±242	47
28	2005/05/14	1.72±0.57	1190±358	59	0.161±0.045	1052±292	41

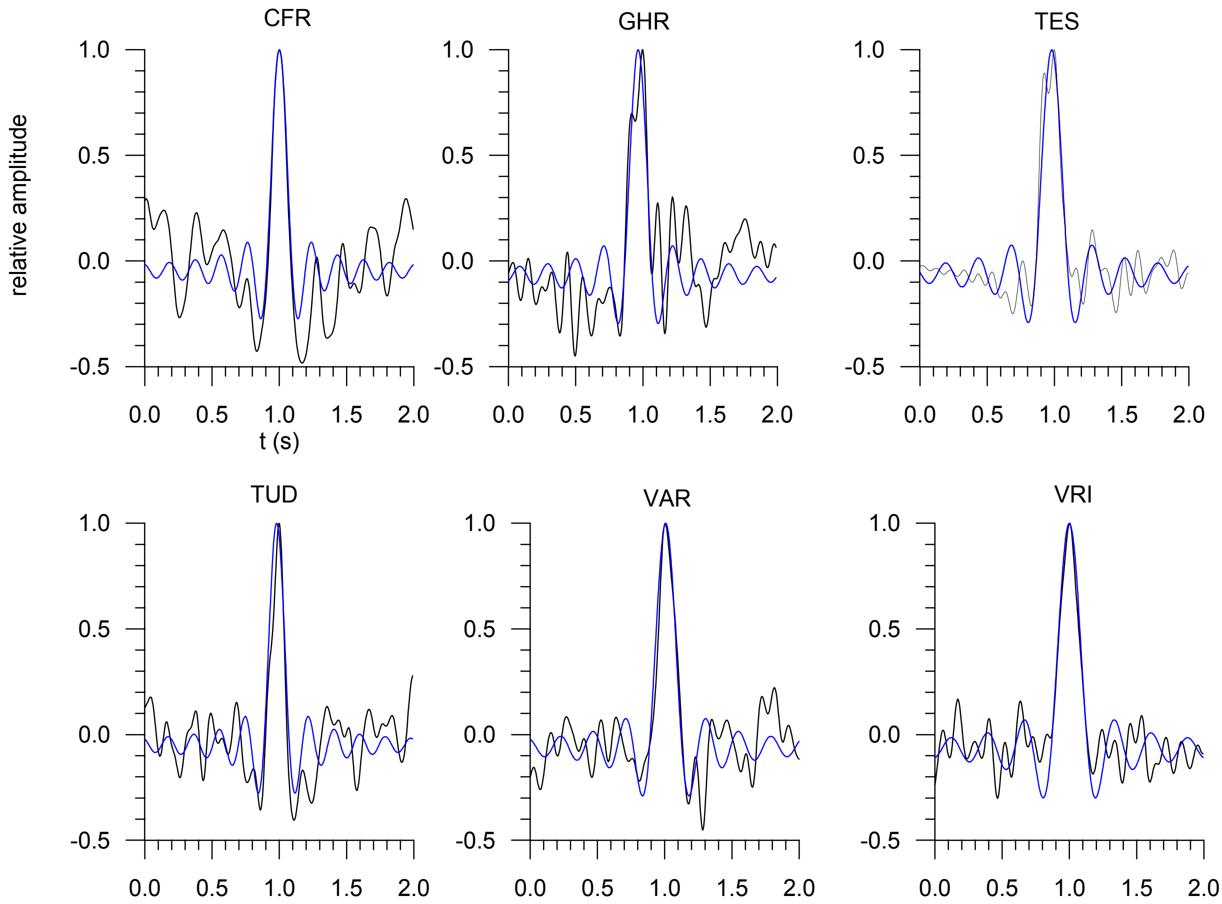

Fig. 5 – Approximation of source time function for the main earthquake of May 3, 2002 with a theoretical function of the type sin x/x.

Table 4

The source parameters and associated errors for the EGF events estimated through spectral ratios method

N	**Data**	**f_c** (Hz)	**r** (m)
1	1997/03/19	6.82±2.16	290±72
2	1997/07/14	4.19	443
3	1997/11/11	8.24±1.34	224±38
4	1997/12/18	5.30	350
5	1998/01/14	9.01±2.69	234±52
6	1998/01/31	7.61±1.93	258±66
7	1998/02/19	4.71±0.40	397±42
8	1998/03/06	6.02±0.03	308±1.41
9	1998/06/06	6.90	269
10	1998/08/24	11.60	160
11	1998/09/21	7.47±2.05	264±68
12	1998/11/14	7.53±1.29	252±41
13	1998/12/12	5.65±1.93	361±118
14	1998/12/17	10.47±2.53	189±57
15	1998/12/28	9.65±1.69	197±38
16	1999/01/06	11.52±0.94	162±13
17	1999/01/09	9.16±2.29	215±56
18	1999/01/23	7.40±1.83	259±64
19	1999/03/09	7.14±0.40	261±15
20	1999/03/17	6.49±1.29	286±54
21	1999/03/23	3.88±0.71	491±89
22	1999/04/04	8.13±1.25	233±39
23	1999/04/15	9.11±0.96	200±20
24	1999/04/30	5.57±1.67	277±116
25	1999/05/05	6.72±0.01	277±0.71
26	1999/06/06	11.23	165
27	1999/06/22	6.57±2.22	310±113
28	1999/07/15	5.26	353
29	1999/10/12	7.34±2.79	374±228
30	1999/11/24	10.94±3.84	186±67
31	1999/12/17	8.12±2.27	242±78
32	2000/05/13	7.70±2.34	259±97
33	2000/05/28	10.62±0.95	166±17
34	2000/07/01	6.88±1.96	283±90
35	2000/07/27	7.70±3.15	302±199
36	2000/08/06	6.33±2.00	299±80
37	2000/10/12	7.06±2.56	217±50
38	2000/12/19	3.91±0.83	489±99
39	2000/12/28	3.94±0.40	466±33
40	2001/01/17	4.74±1.02	407±83
41	2001/02/03	10.22±2.96	204±79
42	2001/02/27	8.14±3.85	237±116
43	2001/03/18	4.64±2.12	452±224
44	2001/03/28	5.91±1.51	315±76
45	2001/05/20	5.10±1.21	390±126
46	2001/07/06	5.91±2.52	320±93
47	2001/07/23	4.74±1.41	422±128
48	2001/07/29	8.34±2.85	240±61

Table 4 (continued)

49	2001/09/25	3.56±1.26	562±134
50	2001/09/28	10.40±1.84	178±34
51	2001/10/17	5.90±4.5	400±273
52	2001/12/14	11.27±1.58	162±22
53	2002/01/25	4.81±1.25	406±97
54	2002/03/16	3.5±1.55	615±242
55	2002/05/15	5.83±1.52	299±47
56	2002/05/26	10.31±0.46	176±8
57	2002/06/14	7.10±2.97	301±112
58	2002/07/14	8.21±2.10	235±48
59	2002/08/04	4.61±0.56	406±49
60	2002/08/05	6.42±1.11	262±44
61	2002/08/16	8.61±0.51	216±13
62	2002/08/27	9.04±3.43	225±79
63	2002/09/10	4.27±1.72	474±190
64	2002/11/03	7.77±1.41	244±41
65	2002/11/27	7.33±1.13	258±41
66	2002/12/15	10.33±1.62	178±26
67	2002/12/23	14.72±0.23	123±1
68	2002/12/30	6.31±2.25	292±136
69	2003/01/03	7.08±1.24	269±48
70	2003/01/05	9.30±1.76	200±37
71	2003/04/06	9.50±3.01	207±56
72	2003/05/02	7.27±2.26	288±105
73	2003/05/19	4.62±1.14	423±104
74	2003/05/26	9.76±0.61	191±12
75	2003/08/02	4.15±0.62	455±66
76	2003/08/27	4.94±1.44	410±145
77	2004/01/21	7.21±087	254±30
78	2004/02/13	8.24±2.37	246±82
79	2004/03/17	3.80±1.38	509±249
80	2004/04/02	7.77±1.79	239±48
81	2004/04/04	4.39±0.87	435±81
82	2004/04/06	8.93±2.63	211±55
83	2004/04/15	10.66±2.34	179±57
84	2004/04/22	8.73±1.06	215±27
85	2004/06/03	14.50	125
86	2004/07/02	9.48±3.82	219±87
87	2004/09/12	6.45±1.31	409±194
88	2004/10/24	2.85	651
89	2004/11/17	7.04±1.20	270±49
90	2005/01/10	10.41±2.91	189±67
91	2005/01/10	8.93±0.61	202±17
92	2005/01/29	14.35±1.59	128±15
93	2005/02/17	8.30±1.94	229±56
94	2005/03/06	3.94±0.75	493±108
95	2005/03/07	12.91	144
96	2005/04/15	5.83±0.75	337±96
97	2005/05/09	6.93±1.85	286±77
98	2005/05/14	4.86±1.15	405±108

4. SCALING OF SOURCE PARAMETERS

On the basis of the source parameters obtained as presented in the previous section (corner frequency or source radius and seismic moment) we estimate all the other parameters of interest (seismic moment, source radius, rupture duration, rise time, stress drop) using the conversion formula (2) – (4) and the independent estimations of the magnitude and seismic moments for the main events.

The analysis of the source parameters scaling is carried out over the entire depth domain and separately on two segments on depth, characteristic for the Vrancea subcrustal seismogenic zone (Trifu, Radulian, 1994; Enescu, Enescu, 1998; Popescu *et al.*, 2000): zone A, $60 \leq h \leq 110$ km and zone B, $110 < h \leq 180$ km. Notably, the seismic rate is approximately five times higher in the lower segment (B) than in the upper segment (A). Specifically for our data set, 28 earthquakes (6 main events) occurred in zone A, while 98 earthquakes (22 main events) occurred in zone B. According to the previous investigations, the two segments on depth are assumed to be characterized by different seismicity patterns and triggering mechanisms.

First we considered the scaling between the seismic moment and duration magnitude (M_D), plotted in Fig. 6 (a). The duration magnitude was estimated using the total duration of the seismogram and the difference between S-wave arrival time and P-wave arrival time. The equations of the regression lines are as follows:

$$\text{Zone A: } \lg M_0 = (1.39 \pm 0.14)M_D + (8.73 \pm 0.61) \quad R = 0.88,\ \sigma = 0.47 \tag{5}$$

$$\text{Zone B: } \lg M_0 = (1.57 \pm 0.07)M_D + (7.56 \pm 0.32) \quad R = 0.92,\ \sigma = 0.38 \tag{6}$$

$$\text{Zone A+B: } \lg M_0 = (1.43 \pm 0.07)M_D + (8.26 \pm 0.30) \quad R = 0.89,\ \sigma = 0.43 \tag{7}$$

The slope has values between 1.40 and 1.58, which is close to the theoretical value (1.5), obtained for shallow earthquakes. The tendency of the slope of the regression line to increase with increasing depth is probably due to the increase of the stress drop and the more efficient release of the seismic energy at depth.

Similarly, we determined the relationship between the seismic moment and the moment magnitude (M_w), plotted in Fig. 6 (b). The equations of the regression lines are given by:

$$\text{Zone A: } \lg M_o = (1.51 \pm 0.15)M_w + (8.83 \pm 0.58) \quad R = 0.89,\ \sigma = 0.46 \tag{8}$$

$$\text{Zone B: } \lg M_o = (2.05 \pm 0.07)M_w + (6.45 \pm 0.40) \quad R = 0.90,\ \sigma = 0.40 \tag{9}$$

$$\text{Zone A+B: } \lg M_o = (1.80 \pm 0.09)M_w + (7.53 \pm 0.34) \quad R = 0.88,\ \sigma = 0.44 \tag{10}$$

Again the slope of the regression line tends to increase with increasing depth (from 1.5 – which is standard value, see Hanks and Kanamori, 1979 – to 2.0).

We determined subsequently the scaling of the seismic moment with the corner frequency (respectively, source radius), represented in Fig. **7**. The regression lines approximating the observation data are given by:

$$\text{Zone A: } \lg M_o = -(3.51 \pm 0.39) \lg f_c + (17.59 \pm 0.36) \quad R = 0.87,\ \sigma = 0.49 \tag{11}$$

$$\text{Zone B: } \lg M_o = -(3.50 \pm 0.28) \lg f_c + (17.24 \pm 0.21) \quad R = 0.79,\ \sigma = 0.58 \tag{12}$$

$$\text{Zone A+B: } \lg M_o = -(3.32 \pm 0.23) \lg f_c + (17.18 \pm 0.18) \quad R = 0.80,\ \sigma = 0.57 \tag{13}$$

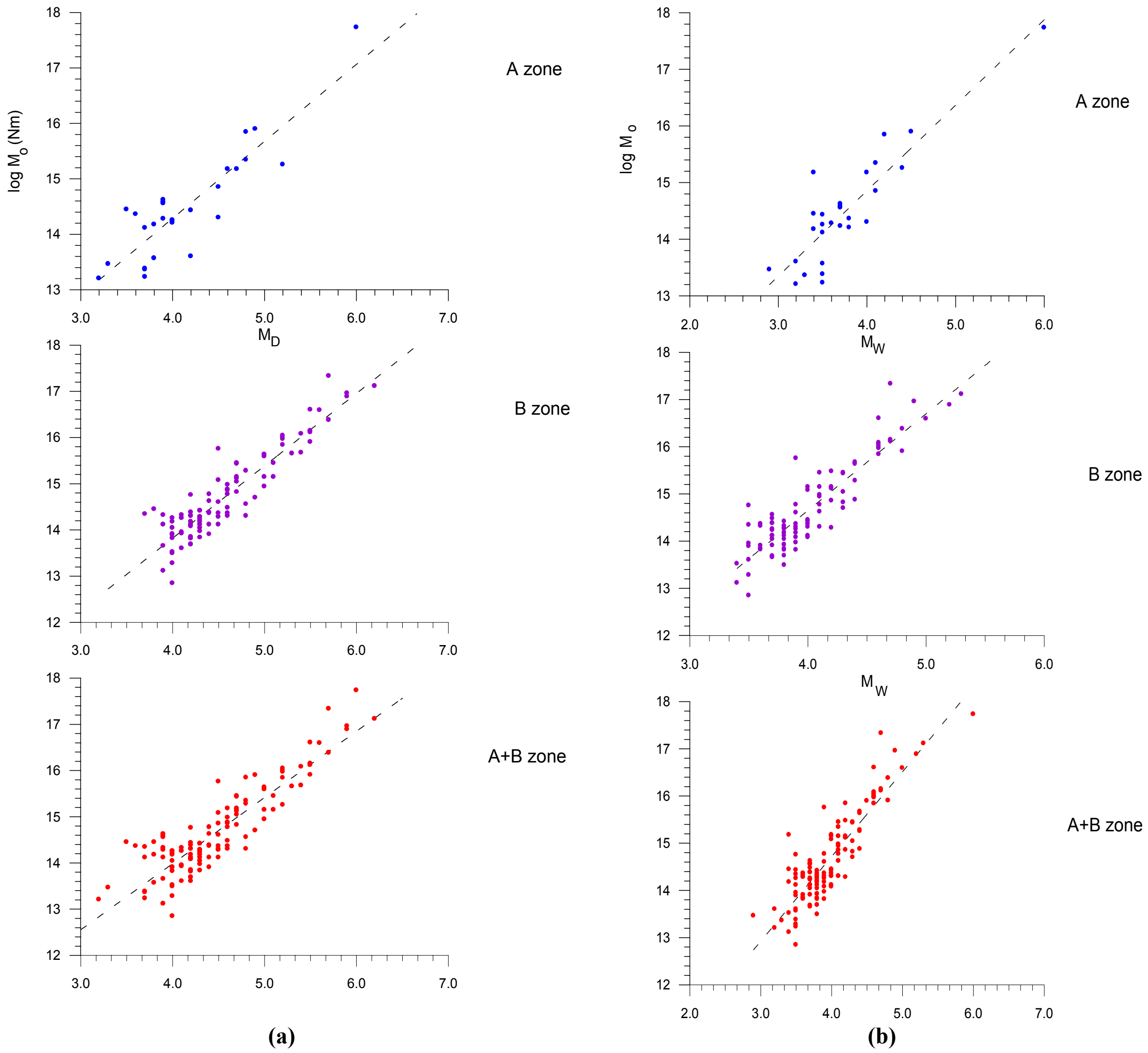

Fig. 6 – Seismic moment – magnitude dependence: (a) magnitude from duration; (b) magnitude from seismic moment.

In all cases the slope is larger than 3 (absolute value), which is the characteristic slope for a uniform rupture process in the source. This deviation suggests a slightly complex process of breaking for the earthquakes in the Vrancea subcrustal domain.

The scaling of the seismic moment and stress drop is represented in Fig. 8. The regression lines are given by:

$$\text{Zone A: } \lg \Delta\sigma = (0.33 \pm 0.07) \lg M_o - (3.83 \pm 1.07) \quad R = 0.66,\ \sigma = 0.49 \tag{14}$$

$$\text{Zone B: } \lg \Delta\sigma = (0.41 \pm 0.04) \lg M_o - (5.49 \pm 0.59) \quad R = 0.73,\ \sigma = 0.37 \tag{15}$$

$$\text{Zone A+B: } \lg \Delta\sigma = (0.38 \pm 0.04) \lg M_o - (4.84 \pm 0.57) \quad R = 0.66,\ \sigma = 0.41 \tag{16}$$

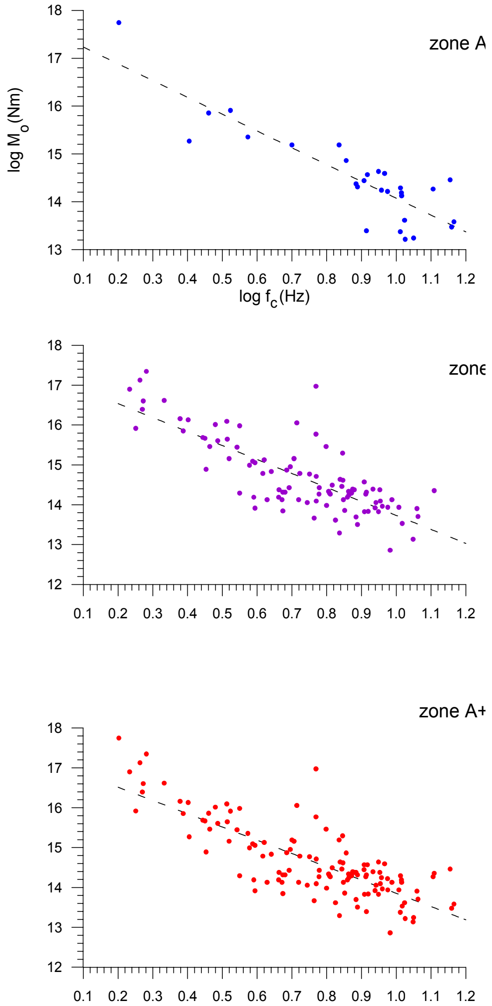

Fig. 7 – Seismic moment-corner frequency dependence for the two segments of subducted lithosphere and for the whole area.

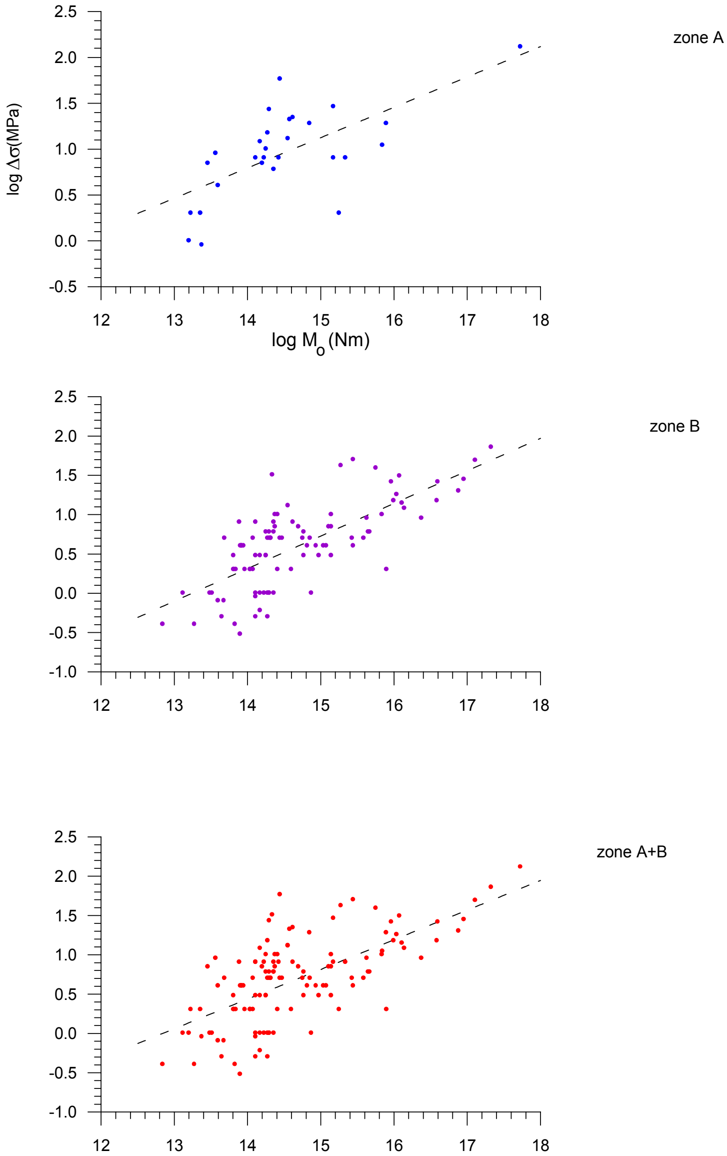

Fig. 8 – Stress drop – seismic moment dependence.

The standard scaling implies a constant stress-drop, independently of source size (slope zero). For our data set and for the magnitude range involved, $3.2 \leq M_D \leq 6.2$ ($2.9 \leq M_W \leq 6.0$), the scaling indicates an increasing stress drop with increasing earthquake size. A similar result was obtained by Popescu *et al.* (2003a) for a data set of 28 Vrancea events occurred in the time interval 1997–2000.

The increase of stress drop with increasing source size shows a more efficient and rapid release of strain for the larger earthquakes than the smaller ones. Perhaps, this result indicates the role of fluids in triggering the larger events, like in a percolation process (Trifu, Radulian, 1991).

Finally, we analyzed the scaling of source duration (more precisely, half of the source duration which approximates the rise time) with source size (Fig. 9). The linear dependencies are given by:

$$\text{Zone A: } \tau_{1/2} = (0.030 \pm 0.08)\ \lg M_o - (3.38 \pm 0.12) \qquad (17)$$
$$R = 0.91,\ \sigma = 0.02$$

$$\text{Zone B: } \tau_{1/2} = (0.029 \pm 0.06)\ \lg M_o - (0.33 \pm 0.10) \qquad (18)$$
$$R = 0.71,\ \sigma = 0.018$$

$$\text{Zone A+B: } \tau_{1/2} = (0.030 \pm 0.05)\ \lg M_o - (0.36 \pm 0.08) \qquad (19)$$
$$R = 0.77,\ \sigma = 0.017$$

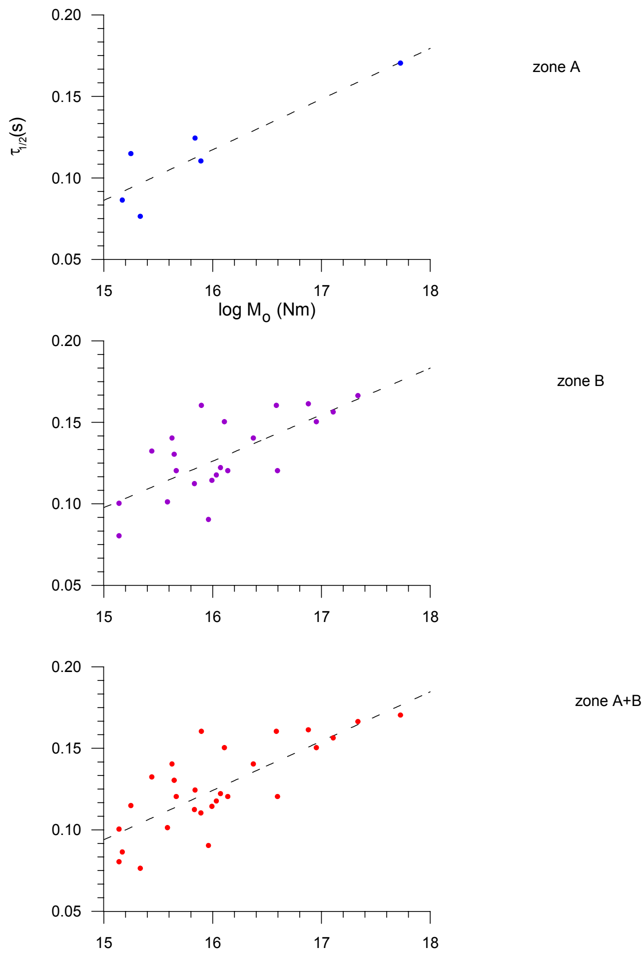

Fig. 9 – Scaling of rise time vs. seismic moment.

The increase of $\tau_{1/2}$ with source size is practically the same all along the Vrancea subducting lithosphere, as shown by relations (17) – (19).

In support of this hypothesis comes and form a complex function of time the source obtained in the case of empirical Green function deconvolution.

The RS method and the EGF deconvolution provide two independent ways to estimate the source radius – formulae (2) and (4). Fig. 10 shows dependence between the two radius estimates for the 28 main events considered. Note that the radius obtained from the rise time tends to be higher than that obtained from spectral ratios at smaller magnitudes and becomes smaller at higher magnitudes.

$$\lg r_{egf} = (0.63 \pm 0.08) \lg r_{sr} + (1.11 \pm 0.22), \quad (20)$$
$$R = 0.84, \sigma = 0.05$$

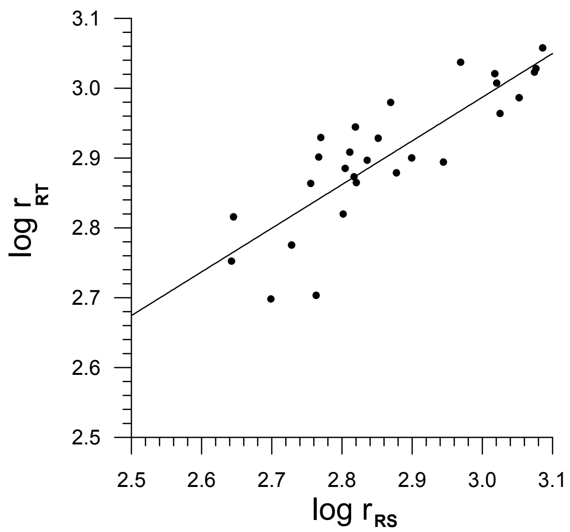

Fig. 10 – The relationship between the source radius of the main earthquakes as obtained from deconvolution with empirical Green's function and from spectral ratios.

The errors of determination were also estimated and in the case of corner frequency and source radius of 98 earthquakes used as empirical Green's functions using spectral ratios method. In this case the errors are larger and are presented in Table 4. The errors in the case of corner frequencies and the source radius of empirical Green functions are contained in the range of [0.2, 76%].

5. CONCLUSIONS

The main objective of the present work is to analyze the Vrancea seismic source characteristics from high-frequency recordings of moderate size earthquakes using the improvements of the digital stations operated by the National Institute of Research and Development for Earth Physics (Bucharest) recently installed on the Romania territory (Fig. 1). The seismic source parameters are retrieved applying to alternate deconvolution methods: spectral ratios and empirical Green's function. These are relative techniques which very efficient in removing the path and instrument effects if adequate pairs of earthquakes with close hypocenters recorded by common stations are available.

The analysis is made on a set of 126 intermediate-depth earthquakes recorded between 1997 and 2005 ($62 \le h \le 166$ km; $3.2 \le M_D \le 6.2$). The source corner frequency, half duration (rise time) and seismic moment are first estimated for the 28 earthquakes selected as main events. Then the source radius and stress drop are computed using standard relationships (Brune, 1970; Boatwright, 1980). Finally, different scaling relationships are determined on the basis of the source parameter values.

The variation of scaling properties on depth (in this study we simply considered two active segments on depth, associated to the triggering of Vrancea major events) indicate a tendency of increasing stress drop with depth and respectively of a more efficient seismic energy release in the deeper part of the Vrancea subducting slab. This behavior correlates also with the decrease noticed in the slope of the frequency-magnitude distribution (Popa, Radulian, 2001). The scaling of the seismic source with corner frequency (or source duration) suggests the presence of a certain complexity in the rupture process. The increase of stress drop with increasing source size shows a more efficient and rapid release of strain for the larger earthquakes than the smaller ones. Perhaps, this result indicates the role of fluids in triggering the larger events, like in a percolation process (Trifu, Radulian, 1991).

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