Repeated Earthquakes in the Vrancea Subcrustal Source and Source Scaling

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Abstract. The Vrancea seismic nest, located at the South-Eastern Carpathian Arc bend, in Romania, is a well-confined cluster of seismicity at intermediate depth (60 – 180 km). During the last 100 years four major shocks were recorded in the lithosphere body descending almost vertically beneath the Vrancea region: 10 November 1940 (Mw 7.7, depth 150 km), 4 March 1977 (Mw 7.4, depth 94 km), 30 August 1986 (Mw 7.1, depth 131 km) and a double shock on 30 and 31 May 1990 (Mw 6.9, depth 91 km and Mw 6.4, depth 87 km, respectively). The probability of repeated earthquakes in the Vrancea seismogenic volume is relatively large taking into account the high density of foci. The purpose of the present paper is to investigate source parameters and clustering properties for the repetitive earthquakes (located close each other) recorded in the Vrancea seismogenic subcrustal region. To this aim, we selected a set of earthquakes as templates for different co-located groups of events covering the entire depth range of active seismicity. For the identified clusters of repetitive earthquakes, we applied spectral ratios technique and empirical Green’s function deconvolution, in order to constrain as much as possible source parameters. Seismicity patterns of repeated earthquakes in space, time and size are investigated in order to detect potential interconnections with larger events. Specific scaling properties are analyzed as well. The present analysis represents a first attempt to provide a strategy for detecting and monitoring possible interconnections between different nodes of seismic activity and their role in modelling tectonic processes responsible for generating the major earthquakes in the Vrancea subcrustal seismogenic source.

1. Introduction
The Vrancea seismic nest is characterized by a strong clustered seismicity at intermediate depths. The hypocentre locations are restricted close to a narrow vertical plane [6] and the seismicity regime is persistent with fairly invariant occurrence rate for the background seismicity (10 ± 5 events of local magnitude above 3 per month) and 3 ± 1 events of magnitude above 7 per century (rate estimated for six centuries time interval). Source scaling properties are essential elements to understand and model the tectonic processes responsible for generating earthquakes in the confined lithospheric volume beneath Vrancea. The continuously increasing number of waveforms digitally recorded by the National Institute for Earth Physics (NIEP) provides the opportunity to systematically evaluate individual source properties and to investigate collective scaling properties in order to understand the overall seismogenic process in this particular geotectonic area.

The purpose of the present paper is to investigate the scaling laws for Vrancea earthquakes on the basis of well-defined source parameters. To this aim, all the information we found available from
previous investigations and processed new data recorded for 161 Vrancea earthquakes has been taken into account.

One intrinsic challenge for this kind of approach is the separation of different factors which intervene and modify the signal recorded at surface: source, propagation path, site and instrument response. This is once more difficult for the Vrancea region, where strong lateral inhomogeneities in the structure are expected both in the crust and in the mantle [14].

The best methods to remove the undesirable propagation and site effects in retrieving source parameters are relative and apply on set of grouped earthquakes recorded by common stations. For example, in the empirical Green’s function (EGF) method the smaller events in a set of co-located earthquakes act as a transfer-medium function that empirically accounts for the path, site, and instrument-response effects on the waveform [3], [8], [11], [17], [18]. In the spectral ratios (SR) method [1] and [15] the requirements are less restrictive as concerns the relative size among the events in a given set.

The relative deconvolution techniques are applied in the present study for a dataset containing waveform recordings for 161 Vrancea intermediate-depth earthquakes. Additional data were provided from previous studies by [22] and [25] who applied EGF technique to evaluate source parameters and scaling properties for a limited number of Vrancea events (8 and 9 events, respectively). Finally, we compare the results obtained using relative spectral techniques with similar results using absolute spectral technique by [9] and [19]. Estimations of the source parameters for the last Vrancea major earthquakes (1940, 1977, 1986, 1990) were included as well in order to extend the magnitude range for scaling purposes.

The distribution in space of the events analyzed in this paper is represented in figure 1. The two vertical cross-sections represent the projections of the hypocentres on the two perpendicular planes figured in the first diagram. The locations of the major shocks of 1940, 1977, 1986 and 1990 and of the events investigated by [25] are included in the figure. For all the events, the locations are those of the Romanian catalogue, performed routinely using Hypoplus software [21]. The hypocentres are located in a constraint focal volume situated between 62 and 171 km depth, contracted on NW-SE direction and dipping from NE to SW tangentially to the Carpathians Arc bend. Except the major shocks of 1940, 1977, 1986 and 1990, any event in the input data has at least one associated co-located event. Apparently, the hypocentre of the 1940 major event is outside the event cluster of the dataset selected in this paper, but there are doubts about the real position of the focus (for example, the depth for this event is 133 km in [20] and 124 km in [12].

2. Deconvolution techniques
For the data set investigated in this paper, the source parameters were determined by applying relative techniques: spectral ratios and empirical Green’s function deconvolution. The earthquakes selected as main events are limited to magnitudes below Mw 5.5, except one single event of magnitude 6.0. A circular rupture process is assumed in all cases which is a reasonable assumption for small and moderate earthquakes. Also, a simple rupture process is considered as a general characteristic of the Vrancea small-to-moderate-magnitude earthquakes [23] and [24].

The EGF and SR techniques have the advantage of removing path, site and instrument effects when the events are co-located, have similar focal mechanism and are recorded by the same instruments at the same sites. The station coverage for Vrancea earthquakes is enough to find at least three common stations with acceptable S/N ratio for a given main event – EGF pair. For the earthquakes occurred after 2009, pairs of events with more than 15 common stations are frequently found. At the same time, for many of the main events more than one EGF could be selected.
Figure 1. Distribution of epicentres of the study events and seismic stations of the National Institute for Earth Physics (upper slide) and projection of the hypocenters on the two vertical cross sections drawn on the map (bottom slides). Diamonds – present study events; solid circles – events of \[25\] squares – major events.

The deconvolution techniques are applied in the spectral domain using three-component velocity seismograms for both P and S waves. To compute Fourier spectra time windows of 5-10 and 8-15 s, respectively, are extracted starting 0.1 – 0.2 s before the wave arrival time. A cosine tapering procedure is applied over ten points at window ends. From the complex spectral division, the spectral ratio is obtained as the amplitude spectral ratio:

\[
R(f) = \frac{A_M}{A_S} \left[ 1 + \left( \frac{f}{f_c} \right)^2 \right]^{1/2}
\]

(1)
where $\Omega_0^M, \Omega_0^G$ are the low-frequency plateaus and $f_{cM}, f_{cG}$ are the corner frequencies of the two events in the pair ($M$ – main event, $G$ – EGF event), while the source time function by inverse Fourier transforming the complex spectral ratio back to the time domain. In order to smooth the inherent noise resulting from spectral division at high frequencies, we applied a running window to the spectral ratio and a low-pass filter at 10 Hz, after applying inverse Fourier transform.

A clear source pulse indicates that the EGF earthquake is good in both amplitude and phase. In most cases, rather similar amplitudes and durations are obtained for the source pulses and for the spectral ratios independently of station position. This indicates that source-directivity effects are practically absent and that the EGF earthquake is suitably selected both as location and radiation pattern relative to the main event.

The corner frequencies for the EGF event ($f_{cG}$) and for the main event ($f_{cM}$) are estimated by fitting the observed spectral ratio with a function given by (1) iteratively by a nonlinear regression procedure [15]. The free parameters are the ratio of the seismic moments (proportional to the ratio of the low-frequency plateaus of the displacement spectra recorded for the co-located events of the pair) and the corner frequencies. The source duration is estimated from the source time function resulted from the application of the EGF technique. A typical example of spectral ratio and source time function for a pair of Vrancea earthquakes is given in figure 2.

The corner frequency and source duration are estimated as means of the available estimates for different components, different stations and different EGFs (in the last case only for main events).

The corner frequency and the source duration both provide equivalent measure of the source size. For a circular source model, in the approximation of a circular simple omega-squared source model, the radius of the rupture area is directly correlated with the corner frequency [16]:

$$r = k v_S f_c$$  \hspace{1cm} (2)

where $r$ is the source equivalent radius, $k$ is a constant ($k = 0.32$ for P waves and $k = 0.21$ for S waves), $f_c$ is the corner frequency and $v_S$ is the velocity of S waves in the focus.
Figure 2. An example of pair main event – EGF event: a) Waveforms recorded at VRI station for event of 27 December 2016, 23:20, Mw = 5.3 (main) and of 20 September 2013, 18:08, Mw = 3.3 (EGF), b) the resulted STFs for main event of 23 September 2016, Mw = 5.6 23:11 and EGF of September 15, 21:56, c) and d) spectral ratios with EGF of 8 May 2010, 00:22 for P and S waves, respectively. Dashed line - the theoretical spectral ratio which is best fitting the curves observed for nine stations.

Equivalently, the source radius can be estimated using source time duration [4]:

$$ r = \frac{\tau_{1/2}}{v/(1 - \beta\sin\theta)} $$  \hspace{1cm} (3)

where $\tau_{1/2}$ is the rise time in the source (for moderate size earthquakes is roughly half of total source duration), $v$ is the rupture velocity in the source (we adopted in the following $v = 0.9\beta$, $\beta$ - shear wave velocity at focal depth), $\alpha$ – longitudinal wave velocity at source and $\theta$ - angle between normal to fault and the emergent angle of the P-wave radiated in the focus.

The relative deconvolution techniques provide only relative measure of the earthquake seismic moment. Thus, the long-period level of the spectral ratio is an estimate of the ratio $M_0^M/M_0^G$. For evaluation of the absolute value of seismic moment we use [5]:

$$ M_0 = \frac{4\pi\rho\alpha^2\Omega_0R}{FR_{df}} $$  \hspace{1cm} (4)

where $\rho$ is the density at source, $\alpha$ is the P-wave velocity at source, $\Omega_0$ is low-frequency plateau of the displacement spectrum, $R$ is the hypocentral distance, $F$ is the free-surface parameter ($F = 2$), $R_{df}$ is the source radiation factor (we adopted average values, 0.52 for P waves and 0.63 value for S waves, according to [2]. The structural parameters in equation (4) correspond with a velocity model adopted by NIEP in routine locations which includes information from refraction and reflection profiles ([29] and herein references).

The stress drop value for a static crack solution is estimated as a function of seismic moment and source radius [7]:

$$ \Delta\sigma = \frac{7M_0}{16r^3} $$  \hspace{1cm} (5)
3. Scaling relationships

Dependence of source duration on corner frequency (figure 3) shows a linear correlation with slope close to 1 ($f_c \sim 1/\tau$) in agreement with the scaling determined by [9] from spectral and time-domain analyses on wide-band digital records for 16 Vrancea intermediate-depth earthquakes.

![Figure 3](image)

**Figure 3.** Dependence of source duration on corner frequency for the main events in table 1. A line of slope 1 is drawn through the points.

The scaling of the source radius (estimated from spectral ratios because only spectral ratios can provide corner frequencies both for EFGs and main events) with the seismic moment (Figure 4) is following the characteristic constant-stress-drop average behaviour with the slope close to -3 [5]. The equation of the regression line in the figure is

$$\log M_0 = (2.87 \pm 0.13) \log r + (7.41 \pm 0.33)$$

with correlation coefficient of 0.80 and standard deviation of 0.67. We integrated in our analysis previous results from [19] and [25] and the parameters for the four major events. We compared also the corner frequency values obtained in our work with the estimations [22] for the events of 1999/11/08 19:22 (Mw 4.6), 1999/11/14 09:05 (Mw 4.6), 2000/04/06 00:10 (Mw 5.0), 2002/09/06 05:04 (Mw 4.1), 2002/11/03 20:30 (Mw 4.0) and 2004/10/27 20:34 (Mw 6.0). While for the 2004 event the corner frequencies are identical, for the other events the estimates [22] are roughly by a factor of 1.5 larger than our estimations.

![Figure 4](image)

**Figure 4.** Scaling of seismic moment with source radius. Diamonds – present study events; solid circles – events from [25] squares – major events; open circles – events from [19]
The scaling of the static stress drop versus seismic moment is represented in figure 5.

![Figure 5. Scaling of stress drop with seismic moment. Diamonds – present study events; solid circles – events from [25]; squares – major events; open circles – events from [19].](image)

For the data set investigated in this paper, the radius was estimated from spectral ratios by fitting the observations with a function like that in equation (1). Average values for all the available estimates (different components, stations and EGFs) are adopted. The radius in [19] was obtained by simple analysis of the displacement spectra, while for the major shocks we use the estimations inferred from the aftershock distribution in space [25].

The large variability of the stress drop values follows naturally from the relation (5) having in mind the inherent errors in radius and the variability due to hidden parameters, like rupture velocity or source geometry. In addition, it is important how we define the stress drop: average stress release over the entire source area (static value) or stress release when rupturing a resistant patch inside the source area (dynamic value). The apparent stress drop increasing trend with increasing seismic moment for smaller events (up to magnitude 6) can be due to the limited frequency bandwidth of the instrument [1], [10], [13] and low signal/noise ratio at high frequencies leading to an underestimation of the corner frequency for the smaller earthquakes.

4. Discussions and conclusions

The main goal of the present paper is to set the scaling properties characterizing the Vrancea subcrustal source by integrating an extended data set, practically all the data that authors acknowledged from previous studies and new data processed within this study.

Most of the events in the data set considered in our analysis are of small-to-moderate magnitude. For such events, the circular fault approximation is usually considered to be acceptable.

One crucial issue in investigating source scaling properties in a specified seismogenic zone is the magnitude range for which the scaling laws are properly defined. For example, there were discussions and controversies regarding the change of the seismic scaling laws for small-to-moderate earthquakes and large earthquakes in the crust [26], [27] [30]. One of the significant results of our analysis is extension of the scaling laws over the entire magnitude range, from small-to-moderate earthquakes to the major earthquakes. This is not a trivial outcome if we take into account the class of models for the seismogenic process in the Vrancea source which assume a critical jump between the crack-like and
asperity-like rupture processes at small-to-moderate scale to percolation-type processes at large scale [28]. Thus, seismic moment – magnitude, seismic moment – source radius and seismic moment – stress drop scaling appears to be self-similar over the entire magnitude range of the considered data set (3.0 ≤ Mw ≤ 7.7).

Stress drop values as estimated from source radius using spectral ratios or source displacement spectra show a very large dispersion from 0.1 to 1000 MPa. However, if the inherent and systematic errors are taken into account, especially at small earthquakes (underestimation of the corner frequency implying decreasing stress drops) and errors caused by variations in source parameters that were considered similar in our work (rupture velocity or source geometry), it can be assumed that roughly speaking a constant stress drop model is valid with a mean stress drop value around 10 MPa. This is most probably a value characteristic for a static stress drop. Nevertheless, we cannot exclude that some of the stress drop values are rather dynamic than static for moderate events if we assume that the stress release was caused mainly by rupturing single asperities. Indeed, the parameters obtained by [9] using long-range (several hundred to thousands km) and teleseismic data for 12 moderate and large Vrancea earthquakes are systematically lower (corner frequency), respectively greater (source duration) than our determinations. The estimations of source parameters based on source spectral analysis for far-field waveforms are mainly controlled by the entire source area while EGF procedure is more sensitive to local major asperities acting in the rupture process. This way we can explain also the unusual large stress drop values for the moderate size events in our investigation (reaching hundreds of MPa as can be seen in the figure 5).

[22] estimated the dynamic values of the stress drop for the major Vrancea earthquakes which are about ten times larger than the static values that were used in our paper (figure 8). Summing up all these issues, an important conclusion comes out, with special significance in assessing seismic hazard and strong ground motion characteristics: the rupture process for Vrancea earthquakes is rapid and efficient both for moderate and large shocks leading to high values of the dynamic stress drop and low values of the source dimensions, respectively.

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