Geophys. J. Int. (2008) **172,** 395–404 doi: 10.1111/j.1365-246X.2007.03664.x

On the recurrence time of earthquakes: insight from Vrancea (Romania) intermediate-depth events

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Accepted 2007 October 21. Received 2007 October 21; in original form 2007 July 18

SUMMARY

The statistics of earthquake inter-occurrence times in broad areas have been reported to obey universal scaling laws (e.g. by Bak *et al.* and Corral). We investigate the recurrence times of intermediate-depth Vrancea earthquakes (depth >60km), taking advantage of the scarcity of aftershocks for deeper events. We use a complete earthquake catalogue (M $\geq$ 2.8) spanning from 1974 to 2002. The analysis of the probability density distribution of the recurrence times for the entire catalogue reveals a power-law regime at small scales. In order better to understand this scaling, we also analyse declustered catalogues, from which the distinct aftershock sequences following the 1977, 1986 and 1990 major earthquakes have been removed, and a time period without large events. For these data sets, the recurrence times follow an exponential distribution at all scales. This observation suggests that deviations from the exponential model – characteristic of the scaling laws recently proposed – result primarily from short-term aftershock clustering.

Key words: Time series analysis; Persistence, memory, correlations, clustering, Earthquake interaction, forecasting and prediction; Seismicity and tectonics.

1 INTRODUCTION

Although earthquakes are an extremely complex spatio-temporal phenomenon, certain simple general laws govern the statistics of their occurrence. Thus, the number of earthquakes with a magnitude M larger than a threshold value m is indicated by the Gutenberg–Richter law (Gutenberg & Richter 1944), which is valid for all earthquakes both regionally and globally (Turcotte 1997). If one uses seismic energy E instead of magnitude M ($M \sim \log E$), the Gutenberg–Richter law becomes a power-law size distribution. The temporal decay of aftershock activity, which follows the occurrence of a main event, is well described by another simple power-law, known as Omori law (Omori 1894) or its modified version (Omori-Utsu law: Utsu 1957, 1961; Utsu *et al.* 1995). Power-law scaling, which is the hallmark of self-similarity and fractality, is also observed for the spatial distribution of earthquakes (e.g. Turcotte 1997).

An important quantity characterizing earthquake occurrence is the time interval between successive earthquakes (referred to as inter-occurrence time, recurrence time or waiting time). The traditional approach to studying the temporal distribution of earthquakes, hence their waiting times, is to separate them into two distinct processes: one for mainshocks and another for aftershocks. While the temporal distribution of aftershocks is clearly established by the Omori law, it is still under debate how are mainshocks distributed in time. The intermediate and large earthquakes in a given region occur generally clustered in time (e.g. Kagan & Knopoff 1976; Kagan & Jackson 1991), while small earthquakes after removal of aftershocks have a Poisson distribution (Gardner & Knopoff 1974). However, according to other studies, small earthquakes with no significant aftershock activity show significant temporal clustering (e.g. Smalley *et al.* 1987; Ebel & Kafka 2002).

Bak *et al.* (2002) proposed a different approach: they studied the recurrence time of earthquakes, without taking into consideration if they were mainshock or aftershock activity. Remarkably, they found that the waiting time distribution averaged over multiple regions and threshold magnitudes collapsed into a single *universal* curve if a simple rescaling of axes was performed. Corral (2003, 2004) followed a similar approach for single homogeneous regions and tried to explain in detail the scaling behaviour obtained. One of the main results of these studies is a crossover in the scaling of the waiting times. At small scales, we have essentially a decreasing power-law behaviour, while at larger scales a faster, exponential-like decay is obtained. Davidsen & Goltz (2004) confirmed this pattern, but found yet another power-law regime for the smallest waiting times. For the distribution of aftershock inter-occurrence times, a model has been proposed by Shcherbakov *et al.* (2005) and applied to several major aftershock sequences in California.

Here, by studying the inter-occurrence time distribution of Vrancea (Romania) intermediate-depth earthquakes, using the approach of Corral (2004), we show that: (1) The universal scaling reported in the above-mentioned studies does not describe well the Vrancea events, which are best modelled by a random temporal occurrence process; (2) The scarcity of aftershocks for the Vrancea intermediate-depth seismicity allows one better to understand the double-scaling reported by Corral (2003, 2004) and helps to identify aftershocks as the mechanism responsible (Hainzl *et al.* 2006; Saichev & Sornette 2007).

2 DATA AND METHOD OF ANALYSIS

The Vrancea seismic region (Fig. 1a, b) is situated beneath the Eastern Carpathians in Romania and is characterized by isolated and persistent intermediate depth activity (e.g. Jeffreys 1935; Constantinescu & Enescu 1964; Gutenberg & Richter 1965; Trifu & Radulian 1994; Wenzel at al. 1998; Oncescu *et al.* 1999). The crustal seismic activity is rather low, with maximum magnitudes in the range 5.0–5.5 (Radu 1979). Accurate hypocenter locations (e.g. Trifu and Radulian 1994) clearly show the presence of a relative gap of seismicity between 40 km and 60 km, that separates the crustal events from the deeper ones. They also show that the epicentres of the Vrancea intermediate-depth events define an extremely

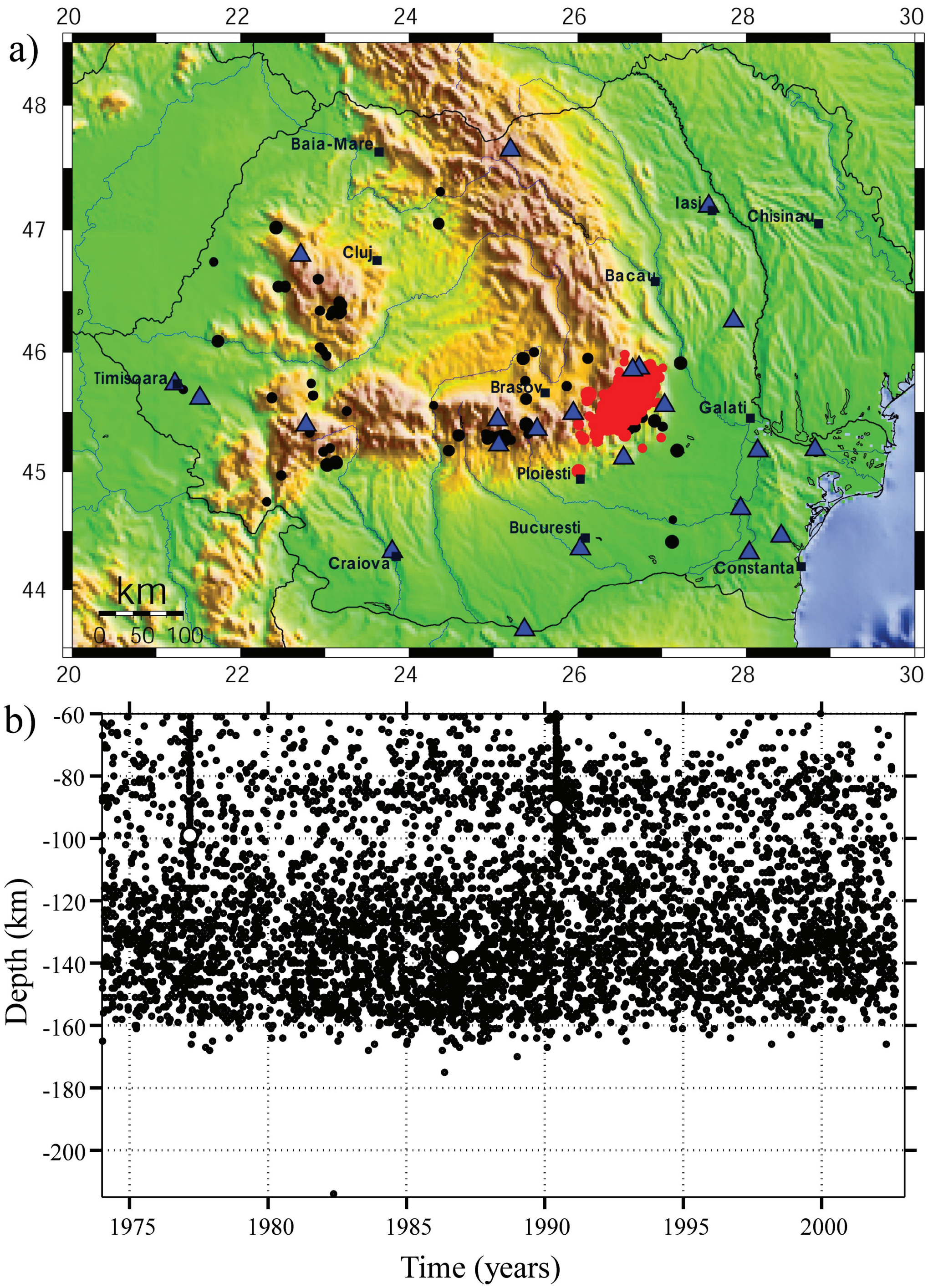

Figure 1. (a) The seismicity of Romania (Romanian Earthquake Catalogue, Oncescu *et al.* 1999; Mw ≥ 4.0, from 984–2006). The crustal and subcrustal Vrancea events are shown as black and red circles, respectively. Blue triangles show seismic stations. (b) Time-depth distribution of Vrancea intermediate-depth seismicity from the catalogue used in this study (M ≥ 1.5; 1974–2002).

confined area of about 50 km by 20 km (e.g. Trifu & Radulian 1994). Most intermediate-depth earthquakes are shallower than 180 km depth (Trifu & Radulian 1994; Oncescu *et al.* 1999), although very few, with depths up to 220 km, are also reported (e.g. Oncescu *et al.* 1999). Previous research (e.g. Enescu *et al.* 1974; Purcaru 1974, 1979) has shown that the occurrence of major Vrancea events ($M \geq 6.5$) is characterized by a complex, quasi-cyclic temporal pattern.

The seismic catalogue used in this study consists of 5630 intermediate-depth Vrancea earthquakes, with $Mw \geq 1.5$ (Fig 1b), occurring between 1974 and 2002. Trifu & Radulian (1991, 1994); Radulian & Trifu (1991); Enescu *et al.* (2005, 2006) present the catalogue in detail, together with the main characteristics of the intermediate-depth seismicity. As shown by Trifu & Radulian (1991), the catalogue was obtained using carefully tested calibration procedures to ensure homogeneity in depth and magnitude.

The correct estimation of the magnitude of completeness of seismic catalogues in general (e.g. Woessner & Wiemer 2005) and during aftershock sequences in particular (e.g. Wiemer & Katsumata 1999; Enescu *et al.* 2007) is a quite challenging problem, mainly because it can vary significantly as a function of time and space. There is reasonable evidence that the frequency–magnitude distribution of Vrancea earthquakes deviates significantly from a simple exponential scaling relation (e.g. Trifu & Radulian 1991, 1994), thus the correct estimation of the magnitude of completeness becomes even more difficult since usual methods based on the Gutenberg–Richter law can not be easily used. In this study, as in previous ones (e.g. Trifu & Radulian 1991), we applied the procedure of Rydelek & Sacks (1989) to our data and, to minimize the risk of a biased result, we tested our findings for several threshold magnitudes above the completeness level. The magnitude of completeness of the catalogue is a function of depth *h*: the 95% completeness magnitude thresholds are 2.2, 2.6 and 2.8 for $h = 60$–115 km, 116–145 km and 146–220 km, respectively. Based on these observations, we have opted for the analysis of earthquakes with $Mw \geq 2.8$, resulting in a catalogue of 3905 events. The examination of the waveform data and the arrival-time picks at seismic stations that recorded the Vrancea subcrustal events shows also that the magnitude of completeness is around 2.8 (Trifu & Radulian 1991).

The dotted blue line in Fig. 2(a) shows the time variation of the event frequency per ~10 days. One notices a sharp increase in the earthquake frequency associated with the three major earthquakes that occurred in 1977, 1986 and 1990, with moment magnitudes *Mw* of 7.5, 7.3 and 6.9, respectively.

Because of the multiple timescales involved (from seconds to days), the probability density of the recurrence time must be calculated with care. Following Corral (2004), we define bins over which the probability density is calculated, as increasing exponentially c^a, with $c > 1$. We take $c = 2.5$, although this particular value is not relevant. The value a increases monotonically, with a constant increment of 0.5. This ensures an appropriate bin size for each timescale. We then count the number of pairs of consecutive events separated by a time whose value lies in a given bin, and divide it by the total number of pairs of events and by the size of the bin to obtain the probability density $D(\tau)$ over the bin. Corral (2004) showed that the rescaling of the waiting time distributions for different tectonic regions and threshold magnitudes (above the magnitude of completeness) with the mean rate *R* in the region, produces a *data collapse*, that is, a functional invariance:

$$D = Rf(R\tau). \tag{1}$$

The scaling function f can be well fit by a generalized gamma distribution:

$$f(\theta) = C\frac{1}{\theta^{1-\gamma}}\exp(-\theta^{\delta}/B), \tag{2}$$

with parameters $\gamma = 0.67 \pm 0.05$, $\delta = 0.98 \pm 0.05$, $B = 1.58 \pm 0.15$ and $C = 0.50 \pm 0.10$.

In Section 3 we compare our results for Vrancea to the fit (i.e. the function f) obtained by Corral (2003).

3 RESULTS

3.1 Recurrence times of the non-declustered catalogue

The rescaled probability density distribution, *D/R*, for the recurrence times of the Vrancea intermediate-depth events, $M \geq 2.8$, is shown in Fig. 3. The mean occurrence rate, *R*, obtained by dividing the total number of events (3905) by the time interval over which these events span (1974–2002), is $4.32 * 10$–6 events s^{-1}. (0.37 events/day).

In the same Fig. 3 the scaling function f, eq. (2), is shown, as well as a curve which corresponds with the exponential distribution of waiting times. The scaling function f fits the data reasonably well. It is also evident that the rescaled probability density distribution deviates from the exponential model at small scales. We will try to explain this scaling pattern in more detail. As discussed by Corral (2004), the value of parameter δ in eq. (2) can be approximated to 1.0, so f corresponds with the standard gamma distribution. At small scales, a decreasing power-law with an exponent close to 0.3 is dominant, up to values of the argument $\theta = R\tau$ around 1.0, where the exponential factor comes into play. Therefore, at larger scales, the function f more closely resembles the exponential distribution. The power-law type behaviour is found in the data in Fig. 3 up to scales of $0.1 \sim 1.0$, in good agreement with Corral (2004). Taking into account the mean earthquake occurrence rate, *R*, we estimate that the power-law scaling in Fig. 3 holds for recurrence times up to 6.4 hr $\sim$ 2.7 days ($0.1/R \sim 1.0/R$). A close inspection of Fig. 3 also reveals that the exponential model, rather than the scaling function f, is more adequate to describe the data at large scales. This observation becomes more evident when the graph in Fig. 3 is plotted in lin-log coordinates. We performed the same analysis using higher magnitude thresholds (from 2.9 to 3.4) and obtain a similar scaling behaviour as that shown in Fig. 3.

In order to uncover the nature of the two regime scaling of the Vrancea intermediate-depth earthquakes, we analyse in section 3.3 the declustered catalogue obtained by eliminating the aftershock sequences following the three major earthquakes that occurred in 1977, 1986 and 1990 (Fig. 2a). Before doing this analysis we discuss in the next section some important characteristics of the aftershock activity for the intermediate-depth Vrancea earthquakes.

3.2 Aftershock activity following the 1977, 1986 and 1990 major events. Declustering

The aftershock activity occurs in time windows of a few months, however it is especially concentrated in the first days following the occurrence of a major event (Fig. 2a). Figure 1b shows that the aftershocks of the three major Vrancea events cluster as a function of depth. Their epicentral distribution is about the same as that of the whole intermediate-depth seismicity, so it can not be separated well from the background activity. The declustering approach used (Trifu & Radulian 1991, 1994; Radulian & Trifu 1991; Enescu *et al.* 2005) takes advantage of the distinct spatio-temporal distribution of the

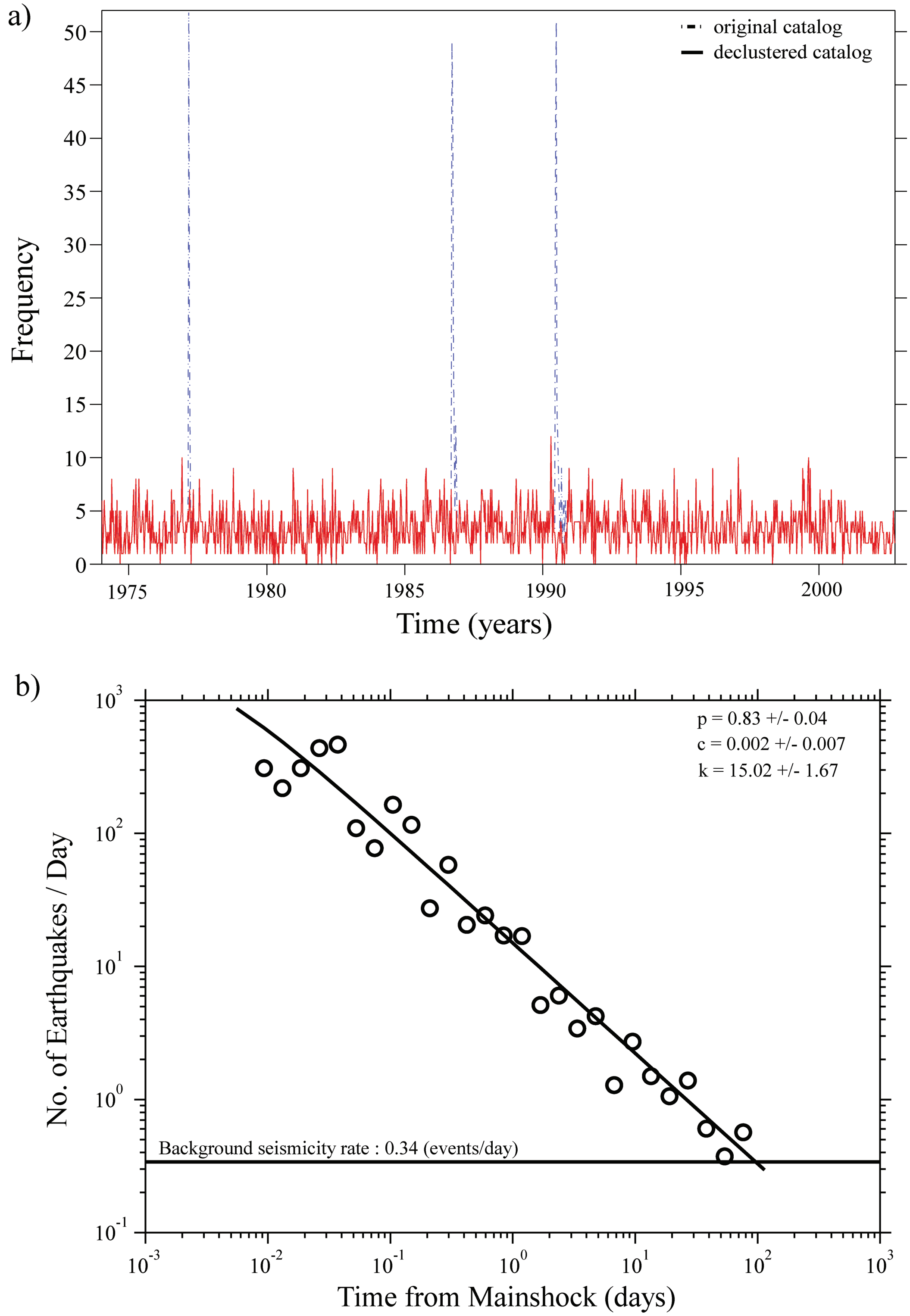

Figure 2. Frequency of events (per 10 days) versus time for the original (dotted blue line) and declustered (continuous red line) intermediate-depth Vrancea earthquakes. b) Decay of aftershock rate, following the occurrence of 1990 *Mw*6.9 Vrancea earthquake. The continuous curve represents the fit of the Modified Omori law (eq. 3) to the data. The parameters of the fit are: $p = 0.83 \pm 0.04$; $c = 0.002 \pm 0.007$ and $k = 15.02 \pm 1.67$. The horizontal line represents the background seismicity rate (0.34 events/day).

three aftershock sequences and results in a declustered catalogue of 3560 events, at a mean occurrence rate of $3.94 * 10\text{–}6$ events s^{-1}. (0.34 events/day). Explicitly, taking into account the rupture area of three major Vrancea events (Oncescu *et al.* 1997; Enescu & Enescu 1998) and the clustering of their aftershocks with depth, we defined depth-windows for the aftershocks. The time window is chosen as the return-time of the earthquake rates, after a major event, to the background level. The depth-time windows that correspond

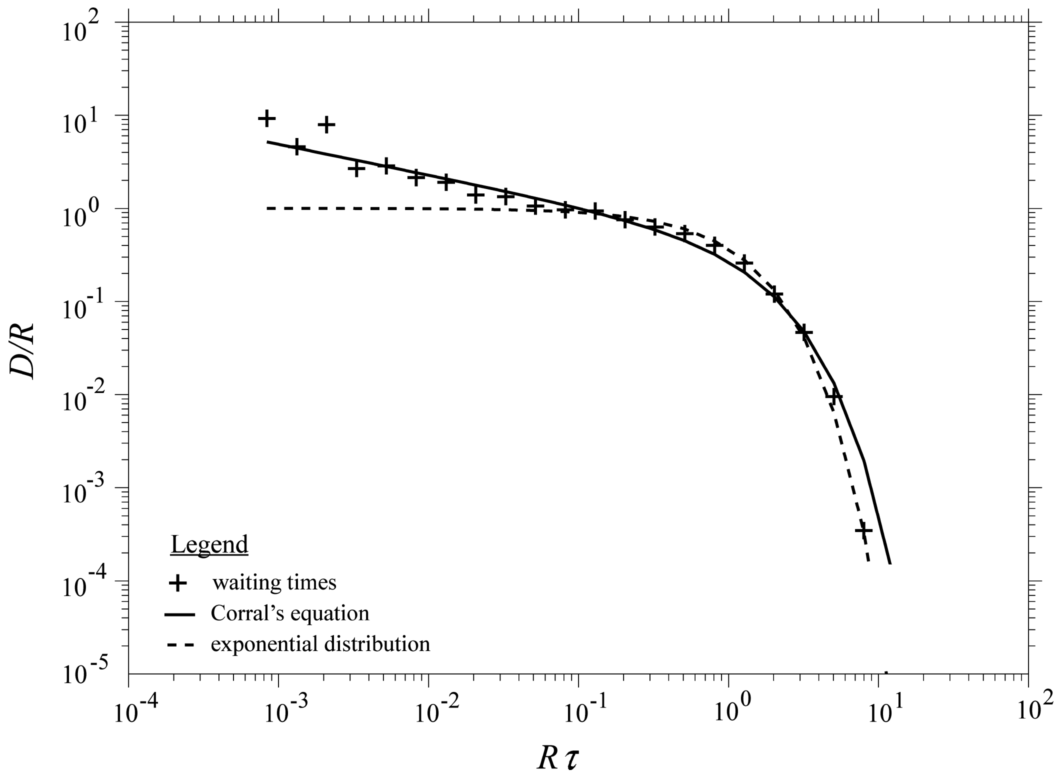

Figure 3. Rescaled probability density distribution, *D/R*, for the waiting times of the original Vrancea intermediate-depth earthquake catalogue ($M \geq 2.8$), spanning from 1974 to 2002. The continuous and dotted lines represent the scaling function f (eq. 2) and the exponential distribution, respectively.

to the three aftershock sequences are, respectively: (1) 60–120 km, March 4, 1977 to March 28, 1977; (2) 120–160 km, August 30, 1986 to November 16, 1986 and (3) 60–110 km, May 30, 1990 to September 6, 1990. All earthquakes that occurred within the three depth-time windows were considered aftershocks and were therefore removed. The inter-event time distribution for the obtained data set is discussed in Section 3.3.

The simplified declustering procedure described above is straightforward and appropriate for the special case of Vrancea's seismicity (e.g. Trifu & Radulian 1991). However, as pointed out by Zhuang *et al.* (2002) among others, all windows-based declustering methods contain some arbitrary choice of parameters and the concept of what constitutes an aftershock is also non-uniquely defined. The removal of aftershocks could create space–time 'holes' in the data and influence the inter-event time analysis, which is particularly sensitive to the temporal distribution of earthquakes. Therefore, we adopted an additional procedure for the analysis of inter-event times. The steps are: (1) remove from the original catalogue *all the earthquakes* occurred in the three time windows defined above; (2) compute the inter-event time statistics for the declustered data set, without counting the three large inter-event time 'gaps' that were the result of aftershock removal (at step 1). In this way, we make sure that the inter-event distributions are based on the analysis of continuous data that do not contain artificial 'holes'. Both approaches were applied for a range of time and space windows to check the robustness of the results.

Because of the rarity of well-developed aftershock sequences for intermediate-depth and deep earthquakes, the decay of activity has been investigated in only a few cases; as discussed by Frohlich (2006), below 45–50 km depth, the aftershocks become significantly less common and those that occur are most often doublets, rather then sequences of numerous events.

A rough estimation of the number of aftershocks that follow a shallow earthquake of a given magnitude can be obtained using the frequency–magnitude scaling (Gutenberg & Richter 1944) and the Båth's law for the difference between the magnitude of a mainshock and its largest aftershock (Båth 1965). Suppose the magnitude of the mainshock is $Mw = 6.9$. Using Båth's empirical law one can estimate the magnitude of the largest aftershock around $Ma = 5.7$. Then, from the frequency–magnitude relation it follows that the expected number of aftershocks above a magnitude $Mc = 2.8$ is: $N_{aft} = 10^{b(Ma-Mc)} = 794$ events, considering that the *b*-value of the frequency–magnitude distribution equals 1.0. Thus, after three crustal earthquakes with similar magnitudes as those occurred in the Vrancea region in 1977, 1986 and 1990, respectively, one would expect a total number of aftershocks, above $Mc = 2.8$, larger than about 5000. The total number of aftershocks ($M \geq 2.8$) of the three major intermediate-depth Vrancea events is 345, about 10 times less than for the 'normal' crustal seismicity case. In fact, the magnitude of the largest aftershock following a major Vrancea earthquake is significantly smaller than estimated using Båth's law (e.g. the largest aftershock of the 1977, Mw7.5, earthquake had a magnitude M = 4.8) and the frequency-size distribution of earthquakes in Vrancea region deviates significantly from a simple power-law distribution (Trifu & Radulian 1991).

We show in Fig. 2b an example of the aftershock decay rate after a major Vrancea event (1990, *Mw*6.9). The statistics are adequate and the data is fit well by the Omori–Utsu law (Utsu 1957, 1961; Utsu *et al.* 1995):

$$n(t) = \frac{k}{(t+c)^p} \tag{3}$$

where *n(t)* is the frequency of aftershocks function of time, *t*, and *k, c* and *p* are constants. The fit is obtained using a maximum likelihood procedure (Ogata 1983). The p-value of the Omori–Utsu fit is 0.83 ± 0.04. A similar analysis of the aftershocks following the 1970 and 1986 major earthquakes shows a good Modified Omori law fit with exponents p of 0.91 ± 0.09 and 0.92 ± 0.06, respectively. These p-values are comparable to those reported for intermediate-depth and deep earthquakes worldwide (Frohlich 2006).

The seismicity rate returns to the quasi-stationary background rate in about 3 months, Fig. 2b (please note that this time period is used for the removal of aftershocks of this large event – see discussion above). For a similar magnitude crustal event (*Mw* 6.9, 1995 Kobe earthquake), the return-period to the background rate is estimated to be about 23 ± 7 yr (Toda *et al.,* 1998). This difference is caused by the large aftershock productivity of shallow earthquakes as compared to that for the deep ones.

3.3 Recurrence times for the declustered catalogue

Fig. 4(a) shows the rescaled probability density distribution, *D/R*, for the recurrence time of the declustered catalogue. The graph clearly indicates that the power-law type scaling, observed in the original data at small scales, is no longer present. The deviation of the data from the scaling function f is also apparent – conversely, the exponential distribution well approximates the data, from small to large scales. We used equal-probability class intervals to perform a chi-square test for assessing the goodness of fit of the waiting times by the exponential distribution. At a 95% confidence level, we were not able to reject the null hypothesis of inter-event time data being exponentially distributed. (The chi-square test applied to the original catalogue rejected the same null hypothesis at 99% confidence levels.) We also chi-square tested the data to verify whether it is consistent with a gamma distribution given by function f. The null hypothesis was rejected at a 99% confidence level.

We also performed an additional statistical test which is commonly used (e.g. Main *et al.* 1999) to select the most suitable model to fit the data: the Akaike Information Criterion (AIC; Akaike 1974). Thus, we first computed the log-likelihoods for the two fits, the gamma-distribution given by function f and the exponential model. The function f was approximated with the standard gamma distribution ($\delta = 1$). Then we computed the statistic $AIC = -2LL + 2n_p$, where LL is the log-likelihood value and n_p is the total number of fitted parameters, for the two cases. We obtained a significantly smaller AIC for the exponential fit. The $|\Delta \mathrm{AIC}|$ is 76.58, which is much larger than two, the threshold value for a rough estimate of significance at 5% level (Hainzl and Ogata 2005).

In Fig. 4(b), we show the empirical cumulative distribution plot of the waiting times with superimposed exponential distribution. The exponential distribution generally fits the data well, however small deviations can be seen for recurrence times up to about 1.5 hours. (Such deviations do not show up if one uses linear coordinates, and they are also difficult to identify in Fig. 4(a)). The removal of the aftershocks of the three largest events produces an "almost" random catalogue, with some residual clustering remaining at very small timescales. This may be caused by the very few aftershocks which likely follow the occurrence of smaller size mainshocks (M < 6.5). It may also be due to an incomplete removal of aftershocks of the three major earthquakes. Please note that recurrence times smaller than a few minutes might be influenced by incompleteness in the very short timescale.

The results obtained for a threshold magnitude of 2.8 do not change significantly if one considers larger cut-off magnitudes. We show in Fig. 5(a) the probability density function (PDF) of the interoccurrence times for magnitude thresholds of 2.8, 3.0, 3.2 and 3.4. The deviation of the data from the scaling function f and the better approximation provided by the exponential distribution is apparent. We confirmed this observation using chi-square testing for each threshold value. It is also noticeable that the scatter of the interevent times at small scales is larger for increasing cut-off magnitudes. This may be related to the estimation uncertainty, which is larger for smaller data sets. It may also be a consequence of the slight tendency towards clustering at small scales, which becomes clearer for larger magnitude thresholds.

As it was mentioned in Section 3.2, we also analysed a catalogue from which *all earthquakes* occurred during the time periods: March 4, 1977 to March 28, 1977, August 30, 1986 to Nov 16, 1986 and May 30, 1990 to Sept. 6, 1990 were removed. These time intervals correspond to significant aftershock activity following the three major Vrancea events in 1977, 1986 and 1990, respectively. The three time gaps were not considered when computing the interevent time statistics. The results (Fig. 5b) are very similar with those obtained using the declustered catalogue (Fig. 4a).

We also present the analysis of event time data for a time period without major earthquakes (M $\geq$ 6.5). Selecting from the original catalogue all the events with M $\geq$ 2.8 which occurred between September 1977 and May 1986 results in 1053 events during this time interval, with the largest one of $M = 5.9$. Figure 6 evidences that the rescaled PDF of the recurrence times clearly deviates from the scaling function f for this data set. The exponential distribution, on the other hand, well approximates the data from small to large scales. The null hypothesis of interevent time data being exponentially distributed cannot be rejected at a 95% confidence level, by chi-square test. The cumulative distribution plot of the waiting times follows closely the theoretical exponential distribution, Fig. 6 (inset). We performed such an analysis for other time periods that do not include the aftershocks of the three major Vrancea earthquakes. In all cases we found that the exponential scaling explains better the interevent time statistics. For relatively short periods of time, the statistics becomes inconclusive due to an insufficient number of events. Although the analysis we present here refers to earthquakes between 60 and 220 km depth, we also tested different depth subintervals with analogical conclusions.

4 DISCUSSION AND CONCLUSIONS

The results of our study indicate that the exponential model explains well the interoccurrence time of Vrancea intermediate-depth earthquakes, after the removal of the obvious aftershock sequences of the three largest events occurred during the observation period. The conclusion is supported by the visual inspection of rescaled PDF and cumulative distribution plots and chi-square statistical testing. Random temporal occurrence of mainshocks is a scenario which would lead to these observations.

Indeed, Wyss & Toya (2000) studied intermediate-depth and deep earthquakes in seismic regions worldwide and concluded that background seismicity is randomly distributed in time. Enescu *et al.* (2005, 2006) used a multifractal approach to show that the clustering of Vrancea earthquakes is mainly observed for the short aftershock sequences of the 1977, 1986 and 1990 major events and is extremely weak otherwise. These results are in agreement with those reported here, and the random temporal occurrence of a mainshocks sequence is a sufficient condition for the exponential PDF model observed here.

If one includes in the analysis the aftershocks of the three major Vrancea earthquakes, Corral's gamma distribution fits better the data

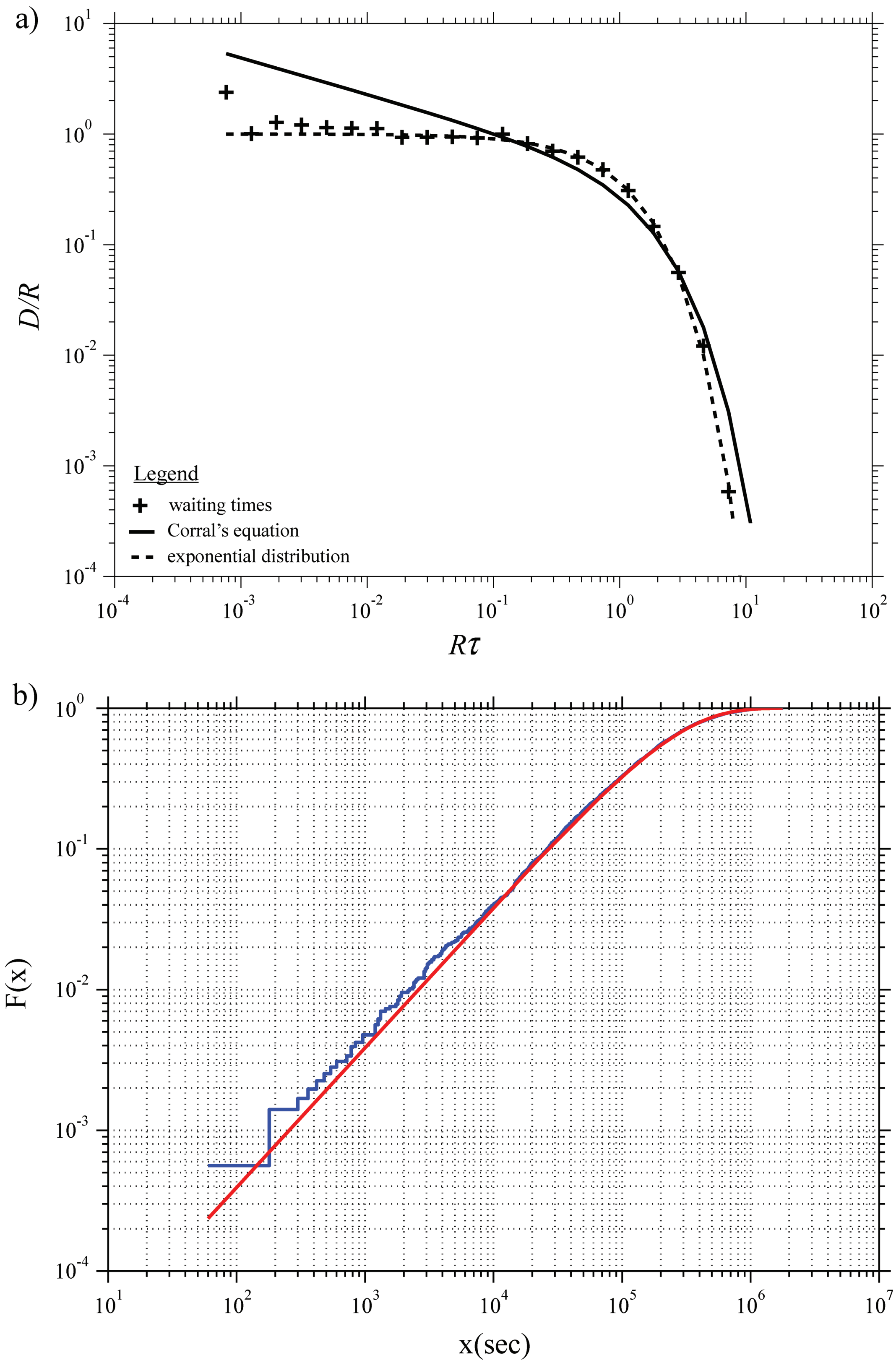

Figure 4. (a) Same as in Fig. 3, but for the declustered catalogue. (b) Cumulative distribution plot for the interevent times of the declustered catalogue (blue line) with superimposed theoretical exponential distribution (red line).

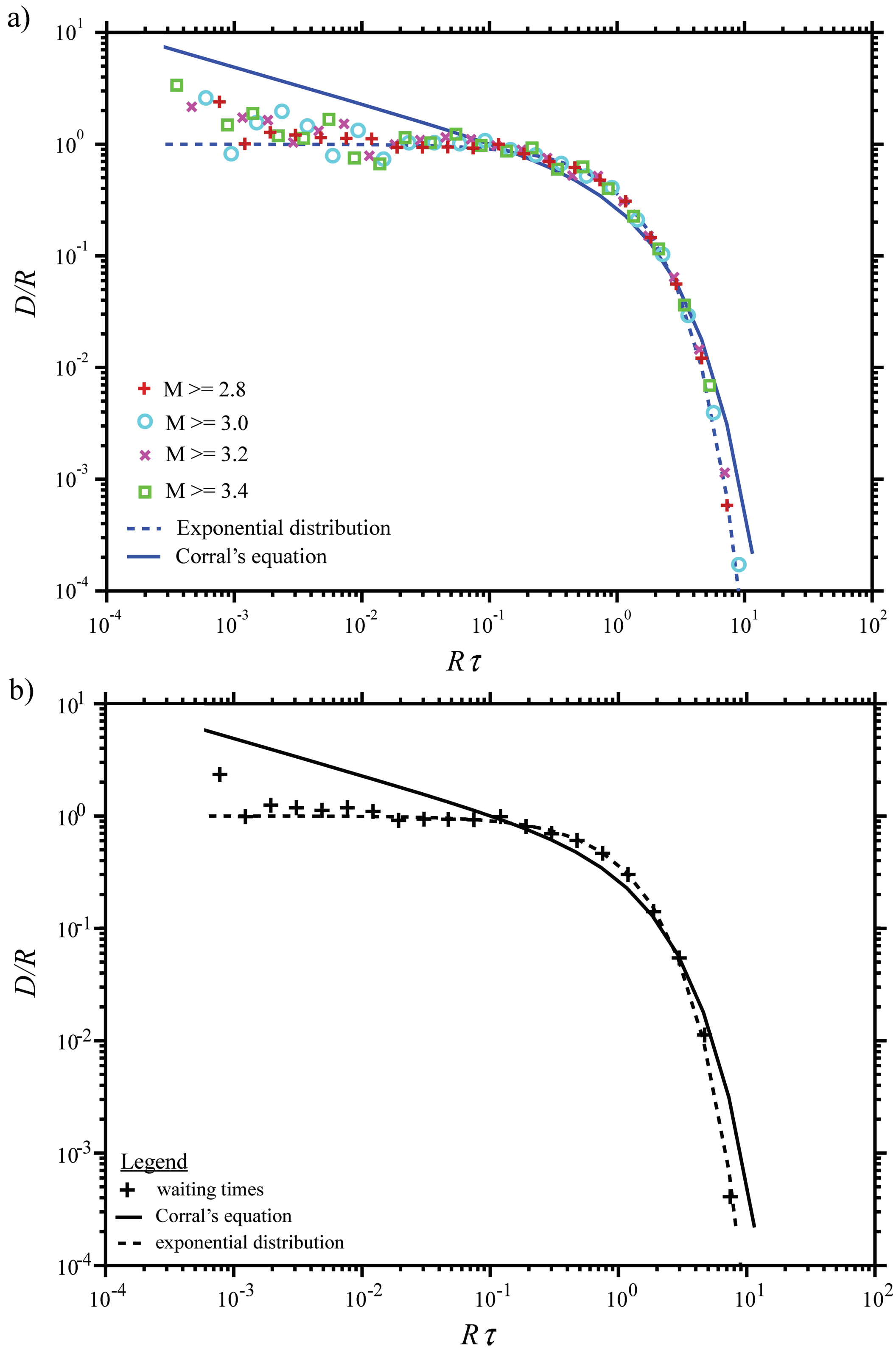

Figure 5. (a) Same as in Fig. 4a, but for a range of threshold magnitudes: 2.8, 3.0, 3.2 and 3.4. (b) Same as in Fig. 3, but for a declustered data-set obtained as explained in the text.

at small scales. The temporal clustering of aftershocks is therefore responsible for the power-law type scaling observed in the rescaled PDF, when *all events* above the completeness magnitude are analysed. Our findings agree with the results of stochastic seismicity simulations (e.g. Hainzl *et al.* 2006) which show that the scaling behaviour reported by Corral (2003, 2004) can be explained by the two fundamental laws of seismicity: the Gutenberg–Richter law (Gutenberg & Richter 1944) and the Omori law (Omori 1894). As

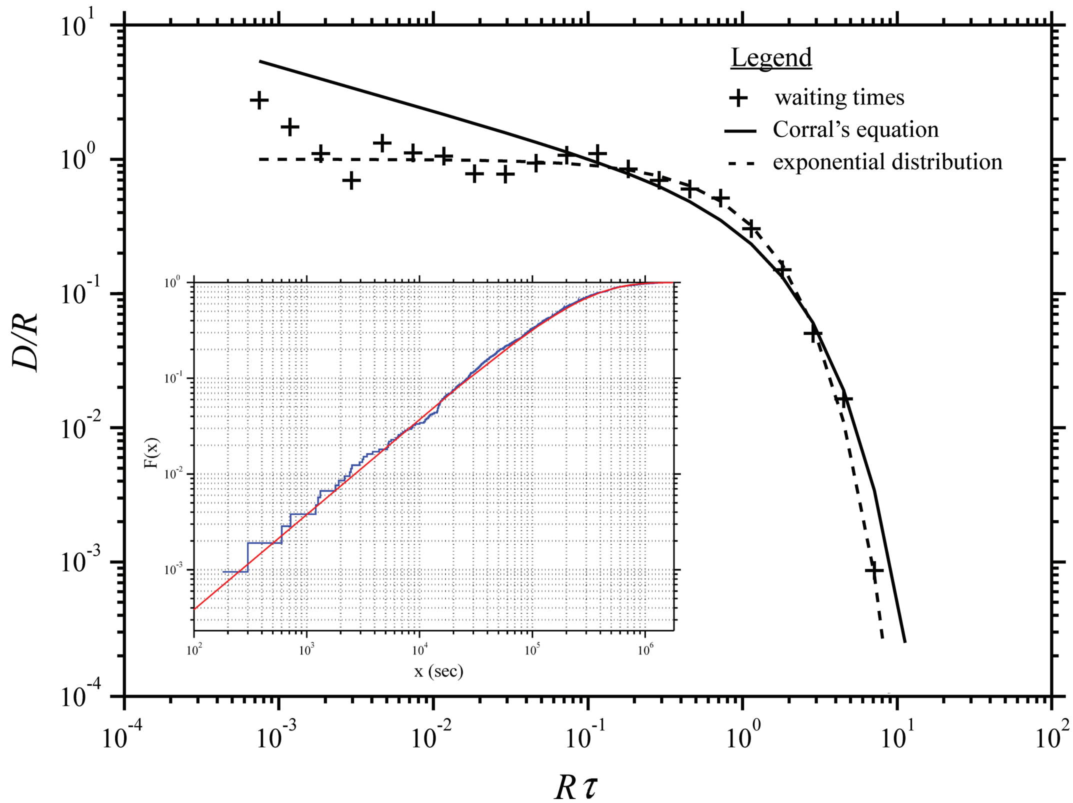

Figure 6. Same as in Fig. 3, but for a shorter period of time (September 1977 to May 1986), when no large earthquakes (M > 6.5) occurred. Inset: Cumulative distribution plot for the interevent times of the 1977–1986, $M \geq 2.8$ catalogue, (blue line) with superimposed theoretical exponential distribution (red line).

these studies conclude, the empirical distribution of Corral (2004) can be explained without any additional long-term clustering.

Reduced heterogeneity at depth compared to the shallow crust may be responsible for the lack of clusters at depth (Frohlich 1987; Wyss & Toya 2000). According to Ben-Zion & Lyakhovsky (2006), who studied a lithospheric model with seismogenic zone governed by damage rheology, the productivity of aftershocks is low for a more ductile material behaviour. Higher temperatures at depth could cause such an increased ductility. We hypothesize that these are the main reasons why Corral's model does not apply in general to the Vrancea intermediate-depth events and may be inadequate to describe intermediate-depth and deep seismic activity worldwide.

ACKNOWLEDGMENTS

The authors are grateful to M. Radulian, C-I. Trifu, E. Popescu and O. Bazacliu for kindly providing the seismic catalogue used in this study and to R. Shcherbakov and S. Hainzl for reading the manuscript and providing many valuable comments. Suggestions and constructive criticism from Y. Ben-Zion, S. Wiemer, and an anonymous reviewer improved considerably the quality and clarity of this study. M.Popa, B. Grecu and G. Marmureanu provided assistance with the Romanian Earthquake Catalogue and the distribution of seismic stations in Romania. B.E. acknowledges financial support from EC-FP6-Project Safer, contract 036936. The GMT software (Wessel & Smith 1995) was used to prepare Fig. 1(a).

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