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Analysis of the Spatial Distribution between Successive Earthquakes Occurred in Various Regions in the World

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Abstract

The earthquake spatial distribution is being studied, using earthquake catalogs from different seismic regions (California, Canada, Central Asia, Greece, and Japan). The quality of the available catalogs, taking into account the completeness of the magnitude, is examined. Based on the analysis of the catalogs, it was determined that the probability densities of the inter-event distance distribution collapse into single distribution when the data is rescaled. The collapse of the data provides a clear illustration of earthquake-occurrence self-similarity in space.

Key words: earthquakes, earthquake catalogs, spatial distribution, scaling.

1. INTRODUCTION

Seismicity is a complex spatiotemporal phenomenon which obeys certain simple general laws which govern the statistics of their occurrence (Turcotte 1997, Kagan 2006, Corral 2006c).

As pointed out in Baiesi (2009), at the recent moment there is no detailed explanation of the mechanisms to reach the complex phenomenology of earthquakes. The magnitude distribution of earthquakes is depicted by the Gutenberg–Richter (GR) law (Gutenberg and Richter 1944), which is a scale-invariant distribution of energy release. Research shows that earthquakes are clustered in space and time (Turcotte 1997, Scholz 2002) and they occur in complex fault patterns (Bonnet *et al*. 2001). A well-known example of temporal clustering of earthquakes is Omori law of aftershocks rate (Utsu *et al.* 1995). Davidsen and Paczuski (2005), also Corral (2006a) noted that the distance between epicenters of subsequent events is characterized by power-law distributions. Bak *et al.* (2002), Corral (2003, 2004a, b; 2005a), Mega *et al.* (2003), and Davidsen *et al.* (2006) give examples showing that the magnitudes, inter-event times and locations of earthquakes are part of a single scaling picture.

Since seismic activity is one of the most prominent examples of phenomena involving a wide range of energy, spatial, and temporal scales, it is assumed that its modeling is very difficult.

Correlations in earthquake occurrence are prominent features of seismic dynamics investigated in many works (Christensen *et al*. 2002, Corral 2003, 2004a, b; 2005a, b, c; 2006a, b, c; Corral and Christensen 2006, Livina *et al*. 2004, 2005, Helmstetter 2003, Helmstetter and Sornette 2004, Saichev and Sornette 2006, Kanamori and Brodsky 2004, Mega *et al.* 2004, Peixoto and Prado 2004, Baiesi and Paczuski 2004, Davidsen and Paczuski 2005, Davidsen *et al*. 2006, Lindman *et al*. 2005, 2006, Shcherbakov *et al*. 2005a, b; Holliday *et al.* 2005, 2006, De Arcangelis *et al.* 2006, Bottiglieri and Godano 2007, Balankin *et al.* 2009, Deluca and Corral 2013). Much research work has been devoted to studying the spatio-temporal correlations of seismic events in the world. Turcotte (1997) has shown that the epicenters within a seismic region follow a fractal distribution. The scaling laws of temporal and spatial variability of the earthquakes have been obtained by Christensen *et al*. (2002) and Corral (2003, 2004a, 2005a, 2006a) investigations, which include various seismic regions with different tectonics.

However, despite the efforts made by geologists and physicists to understand the earthquake phenomena, the dynamics of seismic activity remains poorly understood (Kagan 2006, Corral 2008).

Earthquake statistics provide important knowledge about seismic processes (Stein and Wysession 2003, Kagan 1994). Important laws of seismicity such as Gutenberg–Richter frequency-magnitude relation and Omori law of temporal decay of the seismic activity (Utsu 2002) allows an evaluation of the spatial distribution of the stress in a fault, or estimation of the seismic risk after a strong event (Schorlemmer *et al.* 2005).

The structure of earthquake occurrence in magnitude, space, and time should reflect all complex interactions in the lithosphere.

The first systematic analysis of seismicity, taking into account its multidimensional nature, was performed by Bak *et al.* (2002), who studied the dependence of waiting-time distributions on the magnitude range and the size of the spatial region selected for analysis.

Waiting times (also referred to as return times, inter-event times, *etc*.) are the time intervals between consecutive earthquakes in a region, and they can be studied in two ways:

- by using single-region waiting-time distributions, in which an arbitrary region is characterized by its own distribution (Corral 2004a), or
- by another approach (Corral 2003, 2008), in which a large region is divided into smaller, equally sized areas and waiting times are measured for the smaller areas but are included together into a unique mixed distribution for the whole region. The outcomes of both approaches are clearly different, but in any case scaling turns out to be a fundamental tool of analysis, reducing the multidimensional dependence of the waiting-time distributions to simple univariate functions.

These studies revealed, by means of a scaling law, the complexity of a self-similar dynamical process with a hierarchy of structures over a wide range of scales (Corral 2003, 2004a, b; 2008, Corral and Christensen 2006).

In recent times, earthquake researchers have deduced several underlying mechanisms of seismicity through the statistics of inter-event properties, *i.e*., separation of successive earthquake events in space and time. Many works have attempted to describe the form and implications of the distributions of these inter-event properties, using global and regional earthquake catalogs (Davidsen and Paczuski 2005, Corral 2004a, b; 2006a, b, c; Bak *et al.* 2002, Davidsen and Goltz 2004, Touati *et al.* 2009). For example, in the seismic region of Southern California, where extensive records exist of several decades of observation, earlier works report that both inter-event distances or “jumps’’ between earthquake epicenters (Corral 2008, Davidsen and Paczuski 2005) and the inter-event times, or return times (Bak *et al*. 2002, Corral 2004a, b) exhibit statistical distributions involving power-law regimes, revealing the complex spatiotemporal (self-) organization of seismicity (Saichev and Sornette 2006).

While some authors observe universal return time distributions obtained upon rescaling the data (Corral 2004a, b), others argue that the spatial extent of observation plays role in the distribution of return times (Davidsen and Goltz 2004, Touati *et al.* 2009). In particular, Touati *et al.* (2009) reports observable differences between the return time distributions of regional and global earthquake catalogs: the distributions of inter-event times of Southern California earthquakes show two distinct peaks, signifying the difference in characteristic waiting times between correlated (same aftershock sequence) and independent (different sequences) events, while global statistics reveal a single characteristic peak due to overlapping sequences from various locations.

Białecki (2012a) presents an explanation of a possible mechanism underlying the shape of the universal curve of scaling law for earthquake recurrence time distributions. The presented simple stochastic cellular automaton model (Białecki 2012a, b; Białecki and Czechowski 2013) reproduces the gamma distribution fit with the proper value of the parameter γ characterizing Earth's seismicity and also imitates a deviation from the fit at the short inter-event times, as observed in real data.

It is noted that most authors focus on only one of these properties, *i.e.* either the inter-event times or distances. Batac and Kantz (2013) suggest a direct relation between these inter-event properties. Here they aim to complement the analysis of Touati *et al.* (2009) by using an actual measure of epicenter separation distance in classifying the corresponding return time data. The analyses are guided by the fact that spatiotemporal clustering is a well-established phenomenon in seismicity (Kagan and Knopoff 1980) and must therefore manifest in any substantially large earthquake catalog regardless of the region of origin and threshold magnitude. Therefore, instead of trying to find an approximate fitting function for the statistics of inter-event distances and times, researchers highlight the relation between them using a procedure whose parameters are all derived from the data. Conditional distributions of earthquake return times subject to the corresponding spatial separation reveal that events separated by short (long) distances are also more likely to be separated by short (long) waiting times, clearly demonstrating clustering (separation) of correlated (independent) events. Interestingly, the different catalogs they used show a range of behaviors earlier observed in the ETAS model (Touati *et al.* 2009), and suggest a non-universal distribution.

Equally important for risk estimations and forecasting, though much less studied (Ito 1995, Abe and Suzuki 2003), should be the statistics of the distances between consecutive earthquakes, which we can identify with "jumps" of earthquake occurrence. Davidsen and Paczuski provided a coherent picture using Bak *et al.*'s mixed-distribution procedure (Davidsen and Paczuski 2005); in contrast, Corral (2008) made the study of the earthquake-distance problem considering the single-region distribution and stationary seismicity.

The results make the authors examine the distribution of waiting times conditioned to different values of the jumps. Ultimately, they measure the profile of seismic occurrence, giving the justification that the profiles are determined to a great extent by the distribution of jumps. Spatial properties of seismicity are investigated for a worldwide (WW) catalog and for Southern California (SC) showing a nearly universal scaling behavior. Distribution of distances between consecutive earthquakes (jumps) are magnitude-independent and show two power-law regimes, separated by jump values about 200 km (WW) and 15 km (SC) (Corral 2008).

2. DATA AND DECLUSTERIZING PROCEDURE

The present paper undertakes a study of the earthquake-distance statistics considering the approach of single-region distribution. For this purpose "accidental" spatial regions have been selected for analysis and cases of stationary seismicity are not necessarily available for all of them, as in Corral (2006a).

The seismic zones selected for the present study are described in Table 1. The catalogs are available on the Internet:

- http://seismo.nrcan.gc.ca/stnsdata/nedb/bull_e.php – Cascadia, Offshore region, Charlevoix and Lower St. Lawrence;
- http://neic.usgs.gov/neis/epic/epic.html – Morgan Hill, Imperial Valley, Calaveras fault, West Quebec;
- http://www.wdcb.rssi.ru – Garm, Russia;
- http://zeus.wdcb.ru/wdcb/sep/toktogul/resru.html – Toktogul Region, Russia;
- http://www.gein.noa.gr/services/cat.html – Greece catalog from NOA (National Observatory of Athens);
- ftp://ftp.eri.u-tokyo.ac.jp/pub/data/junec/hypo – Japan University Network Earthquake Catalog;
- http://www.aeic.alaska.edu/html_docs/db2catalog.html – Selection of events from the Alaska Earthquake Information Center (AEIC) database;
- http://www.data.scec.org/ftp/catalogs/SHLK – the Southern California catalog of Shearer (Corral 2009, Shearer *et al.* 2005);
- http://www.ncedc.org/anss – the Advanced National Seismic System (ANSS) catalog (Hainzl *et al*. 2006).

The modern seismic databases, *e.g.*, from California, used in multiple seismic surveys, contain hundreds or thousands of well-defined events. Though of diverse quality, seismic data can be obtained for many other active areas. The study of the different areas allows to improve and expand the model and statistical investigations, as well as to check the repeatability of the obtained results.

The selection was done according to the zones' recognition made by the seismologists from North America, Canada, and Russia (Adams and Basham 1991, Rogers and Horner 1991, Sanford *et al.* 1991, Dewey *et al.* 1989, Wesnousky 1986, Eneva and Hamburger 1989, Eneva *et al.* 1992). Areas are characterized with predominantly shallow seismicity and in which relatively different types of tectonic movement prevail.

Spatial windows were used and their coordinates are indicated in Table 1. The same table shows the periods studied for each catalog, as well as the number of events included in the present study. The catalogs chosen for investigation cover the time after 1900. This selection aims to make the data more complete and homogeneous.

Table 1

Parameters of the zones used in this study

No.	Region	Time period	Space window	M_C	N
1	Charlevoix, Canada	1977-1993	47.2-48 °N, 69.6-70.5 °W	1.7	374
2	Imperial Valley, California	1932-1974	32.5-33.25 °N, 115-115.75 °W	3.5	336
3	Calaveras fault, California	1947-1974	36.92-37.4 °N, 121.42-121.75 °W	2.5	417
4	West Quebec, Canada	1927-1992	44-47.5 °N, 72.0-77.5 °W	2.4	520
5	Morgan Hill, California	1944-1974	37.1-37.4 °N, 121.5-121.8 °W	2.0	356
6	Lower St. Lawrence, Canada	1982-1992	46-50.2 °N, 65-69 °W	2.0	851
7	Garm, Asia	1962-1979	38.5-39.5 °N, 70-71.6 °E	2.8	1740
8	Cascadia, Canada	1964-1999	47.8-52 °N, 121-131 °W	3.9	220
9	Offshore region, Canada	1960-1991	48-52 °N, 127.5-133 °W	3.0	1282
10	Toktogul, Asia	1929-1991	39.23-43.47 °N, 69.23-76.98 °E	1.7	6960
11	Greece catalog (NOA)	1964-2008	33.5-42.1ºN 21-30ºE	3.1	51539
12	Japan catalog (JUNEC)	1985-1998	25-48 ºN 125-148 ºE	3.0	43777
13	Alaska catalog (AIEC)	1970-2008	48-72.6 °N, 130-180 °W	3.0	20553
14	SHLK catalog	1983-2002	31-34 °N, 114-122 °W	2.5	23578
15	NCDEC catalog	1983-2008	32.5-43 °N, 113-123 °W	3.0	13712

Explanations: N is the number of events, M_C is the completeness magnitude.

Following Bak *et al*. (2002), the present study omits any classification of earthquakes; it does not separate major events, nor does it isolate specific sequences. Once more, seismicity is considered as a physical phenomenon itself. This study concentrates on the spatial properties of seismicity and will divide the crust into zones with different tectonic properties, but will place all events and regions on the same footing.

Moreover, Reasenberg's method (Reasenberg 1985) for declusterization will be applied and its effect on the spatial distribution will be investigated.

Before dealing with the frequency distribution of the inter-event distances, the catalog data was checked for magnitude of completeness, M_C. For each one, only events with magnitude above M_C were considered. The freely available software ZMAP (Wiemer 2001) was used for this purpose.

3. RESULTS AND DISCUSSION

The spatial distribution analysis was carried out as follows. The "distances between" the epicenters of the i-th earthquake and the previous in time event, (t^{-1}), were calculated from the catalog. A FORTRAN program was developed, intending to calculate distances between points on the Earth's surface. For this purpose, conversion of the geographic coordinates, φ and λ, into geocentric, φ^G and λ^G, was performed, in order to take into account the ellipsoid shape of the Earth:

$$\varphi^G = \varphi + 0.00339466 \sin(2\varphi) \ , \tag{1}$$

$$\lambda^G = \lambda \ . \tag{2}$$

Then the distance Δ° (in degrees) was defined by the formula:

$$\cos(\Delta^\circ) = \sin\varphi_1^G \sin\varphi_2^G + \cos\varphi_1^G \cos\varphi_2^G \cos\left(\lambda_2^G - \lambda_1^G\right) \ , \tag{3}$$

and the indexes 1 and 2 were assigned to the coordinates of the pair of events from the seismic catalog. The results for Δ° were converted into kilometers d, one angular degree being equal to approximately 111.1 km (Christoskov and Lazarov 1981).

In this way, a list of the spatial distances d_i (jumps) between successive events is obtained. The range of change of the distances is divided into subintervals of length Δd. The number n_j of values for each subinterval is taken into account and its relative frequency is calculated:

$$p_j(d) = \frac{n_j(d)}{N} \ , \tag{4}$$

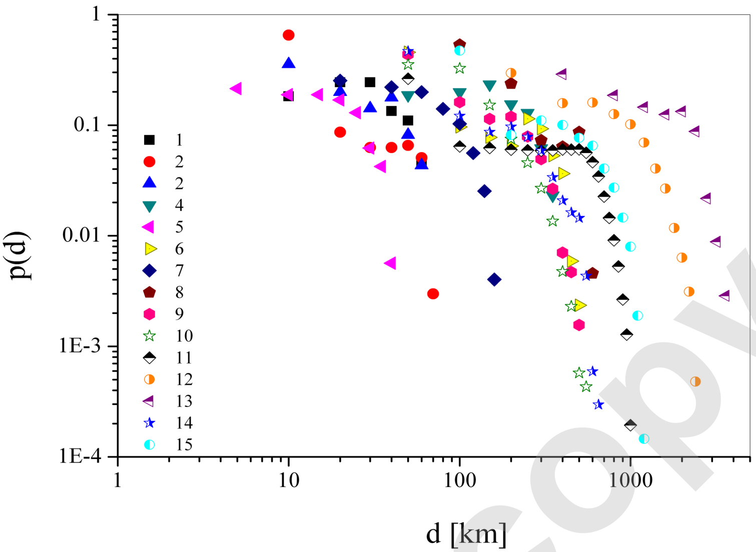


Fig. 1. Frequency distribution $p(d)$ of the spatial distances *versus* distance value d, for the epicenters of the earthquakes listed in Table 1. Colour version of this figure is available in electronic edition only.

where N is the total number of earthquakes, $j = 1, \ldots, k$ where k is the number of subintervals into which each range of change of the distances is divided.

Figure 1 shows the graphs obtained for the distribution $p(d)$, considering different regions. It can be seen from Fig. 1 that there is a similarity in the curves – however, they (the curves) are displaced from one another.

We find it more practical to describe the distribution of the inter-event distance by means of "probability density", $P(\Delta d)$, defined as

$$P(\Delta d) = \frac{\mathrm{Prob}(d < d' \le d + \Delta d)}{\Delta d} , \tag{5}$$

where Prob denotes probability, and Δd is the bins over which the probability density is calculated.

It is straightforward to estimate $P(\Delta d)$ from $p_j(d)$ as

$$P_j(\Delta d) = \frac{p_j(d)}{\Delta d} = \frac{n_j(d)}{\Delta d \; N} , \tag{6}$$

where N is the total number of earthquakes (of any size); in practice, Δd should be small, in order not to modify the continuous nature of $P(\Delta d)$, but also large enough to provide statistical significance in any interval it defines.

In any case, the probability density removes the dependence of the size distribution on Δd, as well as on the seismic activity and extension of the spatial region under analysis.

The result, given in Fig. 1, shows that the curves can be transformed into coordinates, rescaled as follows:

The x-axis is divided by L and the y-axis is multiplied by L, *i.e.*,

$$x = \frac{\Delta d}{L}, \tag{7}$$

$$y = L \times P(\Delta d), \tag{8}$$

where L is the maximum distance obtained for the investigated region.

The process of rescaling causes a change in the curves of Fig. 1, presented in Fig. 2. The data given in Fig. 2 are divided into two parts. Figure 2a shows all the data described in Table 1. Figure 2b gives only the results from the regional catalogs. It can be seen that considering the inter-event distances distribution, the data collapses when rescaled.

Distributions of the inter-event distances are successfully approximated by the beta-distribution:

$$f(x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha,\beta)} \tag{9}$$

with shape parameters $\alpha > 0$ and $\beta > 0$ and $0 < x < 1$. $B(\alpha,\beta)$ representing the beta function, appears as a normalization constant.

The data shown in Fig. 2 was approximated in Eq. 9. The fit of the rescaled by the beta function distributions is good for intermediate and large values x ($= \Delta d/L$) > 0.20.

When fitting the data separately for each of the regions in Table 1, the values of the parameters α and β vary as it follows:

- α changes from 0.80 to 5.34,
- β – from 2.18 to 6.06.

When mixing the data, shown in Fig. 2a, parameter α is 0.76 with standard error of 0.15 ($\alpha = 0.76 \pm 0.15$), and parameter β is 2.15 with standard error of 0.30 ($\beta = 2.15 \pm 0.30$).

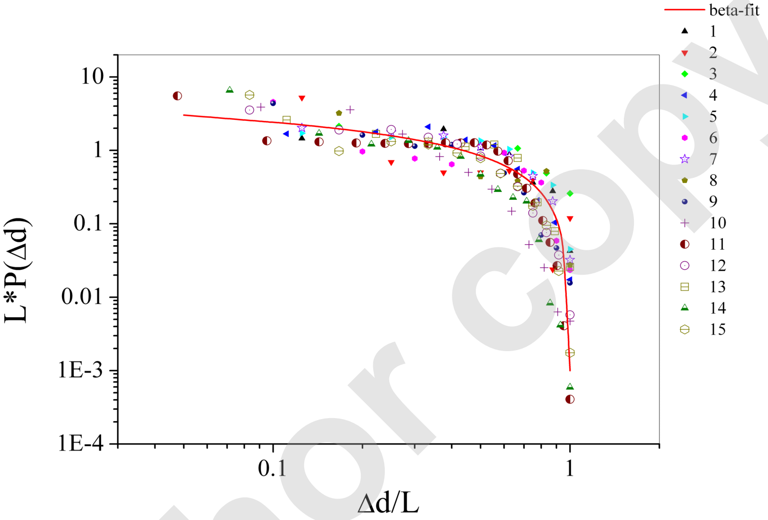
When considering only the regional catalogs (Greece, Japan, Alaska, SHLK, NCEDC) and fitting separately, the values of the parameters α and β change within the following boundaries:

- α – from 0.65 to 4.00,
- β – from 1.84 to 6.06.

When mixing the data, shown in Fig. 2b, the parameters are as follows: $\alpha = 1.12 \pm 0.16$, $\beta = 2.61 \pm 0.32$.

For some regions there is a clear tendency for the distribution to exceed the value given by the used model function; there is an excess of (rescaled) short inter-event distances (Fig. 2a). When only these points are selected (from the mixed probability density) the distribution is characterized by a decreasing power-law regime ($\sim x^{-\delta}$) up to $x \sim 0.60$ with an exponent $\delta \approx 0.86 \pm 0.06$. For $x > 0.60$, it decays extremely rapidly.

(a) All data



(b) Regional catalogs

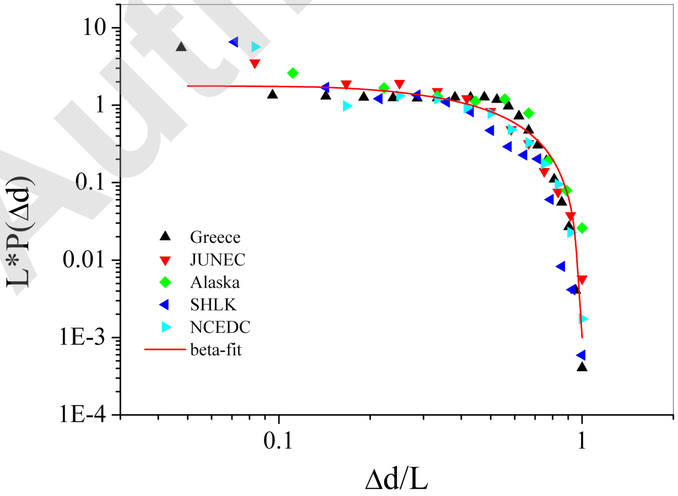


Fig. 2. Probability density for the rescaled data: $x = \Delta d/L$, $y = L \times P(\Delta d)$ from catalogs, listed in Table 1. The continuous line is a beta distribution fit. Colour version of this figure is available in electronic edition only.

Note that the similar power-law regime was obtained in Davidsen and Paczuski (2005), mixing many areas in Southern California and including non-stationary periods. The difference between our value $\delta \approx 0.86$ and the value given by Davidsen and Paczuski (2005) is due to the way in which the rescaled distribution is obtained. In Davidsen and Paczuski (2005) the data from the same region (Southern California) is mixed, after the area is pre-divisioned into cells with dimensions $L_s \times L_s$, with values of L_s varying. For each L_s different threshold values of the magnitude are chosen. In the present study, as shown in Fig. 2, the mixing of data is carried out for different seismic regions.

Besides, there is some difference in the analysis of the obtained rescaled distribution. The distribution up to $x \leq 0.5$ is used by Davidsen and Paczuski (2005). An approximating power law is obtained for them with $\delta = 0.6$.

The function used in the present paper is different – a beta distribution; it proves to be appropriate at $x \geq 0.20$. Since there remain points from the rescaled distribution, not lying on the model curve, a power law of fitting is appropriate for them. The negative power law in this case has a parameter $\delta = 0.86$. The studied regions where these points exist are relatively large in area. Since during data selection aftershock series have not been removed, it is possible that the availability of an increased number of short distances between the earthquakes is due to them. In smaller sized regions, such increased numbers of small distances are not observed, as the distances between the aftershocks in them and the distances between the independent events will be comparable.

Stationary periods of seismicity in the studied regions have not been selected in the present paper, unlike in the investigations of Corral (2006a). Stationarity means that time periods are described by the seismic rate, R (defined as the number of earthquakes per unit time) and in such a case, a linear increase of the cumulative number of earthquakes *versus* time must be observed. Notice that stationarity does not mean that aftershocks are not present in the data, but periods of time were considered for which no aftershock sequence dominates in the spatial region.

The results for Greece, Japan, Alaska, and SHLK catalogs are shown in Fig. 3, using events with magnitude M above different thresholds M_{th} (*i.e.*, $M \geq M_{\text{th}}$). An important conclusion drawn from the figure is the independence of the inter-event distance distributions on the magnitude threshold, as in Davidsen and Paczuski (2005), implying that the spatial occurrence of large earthquakes is not different from the occurrence of small ones, in contrast to what was described in Molchan and Kronrod (2005). The data is also fitted in these cases by beta distribution for values of $x > 0.20$, as well as an excess of (rescaled) short inter-event distances (excluding the data about Alaska).

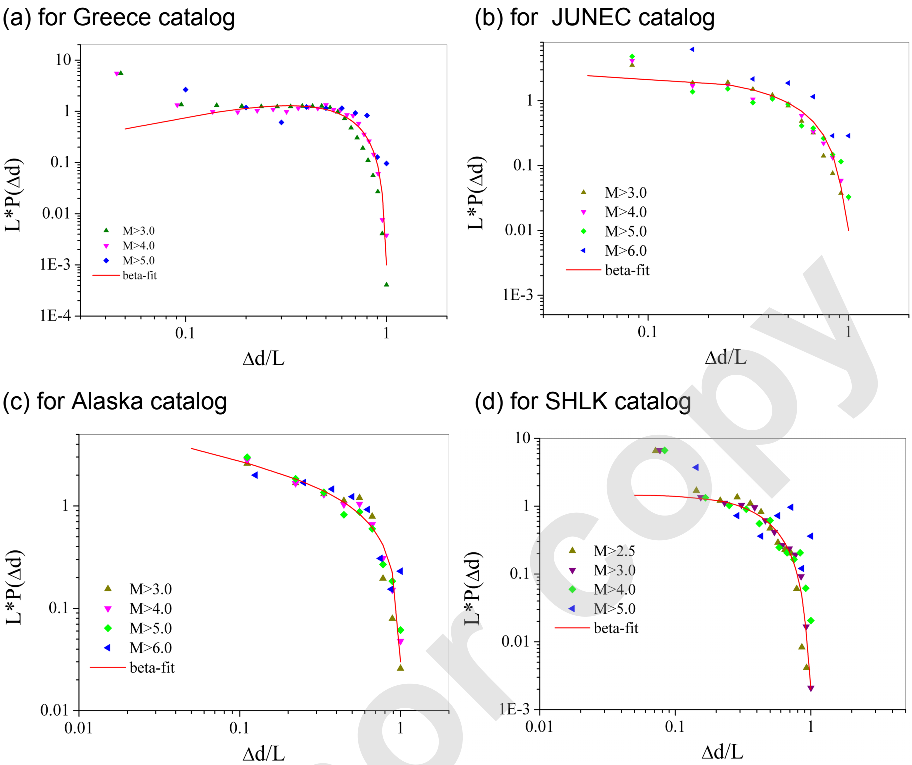


Fig. 3. Probability density for the rescaled data: $x = \Delta d / L$, $y = L \times P(\Delta d)$ for different magnitude thresholds. The continuous line is a beta distribution fit. Colour version of this figure is available in electronic edition only.

The collapse of the data for distances as a result of rescaling of the respective values is an indication of a critical phenomenon. It is known that in cases exactly like this a phenomenon of collapse of data (scaling) is observed. This analysis confirms once again that the earthquakes belong to the class of the self-organized criticality (SOC) (Kanamori and Brodsky 2004).

The next step in the current investigation was to perform the declusterization to the initial catalogs for the zones listed in Table 1. The preliminary removal of the aftershock events here was carried out according to “Reasenberg’s spatial-time window”, included in the ZMAP program (Wiemer 2001). The time intervals, and the number of the earthquakes, after declustering, are listed in Table 2.

The investigations carried out for the declusterized catalogs are analogous. The calculation of the set of spatial distances d obtained for each

Table 2

Zones used in this study

No.	Region	M_C	Time period	N_{ZMAP}
1	Charlevoix, Canada	3.0	1910-1993	65
2	Imperial Valley, California	3.5	1932-1975	109
3	Calaveras fault, California	3.0	1941-1975	151
4	West Quebec, Canada	3.0	1903-1995	218
5	Morgan Hill, California	3.0	1941-1974	66
6	Lower St. Lawrence, Canada	3.0	1941-1992	73
7	Garm, Asia	3.0	1962-1989	567
8	Cascadia, Canada	3.9	1964-1999	155
9	Offshore region, Canada	3.0	1960-1991	662
10	Toktogul, Asia	3.3	1929-1991	1215
11	Greece catalog (NOA)	3.1	1964-2008	30230
12	Japan catalog (JUNEC)	3.0	1985-1998	34422
13	Alaska catalog (AIEC)	3.0	1970-2008	18735
14	SHLK catalog	2.5	1984-2002	11061
15	NCDEC catalog	3.0	1982-2008	7396

Explanations: M_C is the chosen magnitude threshold, $\boldsymbol{N}$ is the number of remaning events after declusterization by Reasenberg's method (N_{ZMAP}).

investigated region by Eqs. 1-3 determines the frequency distribution of distances $p(d)$. Figure 4a shows the graphs of the distribution $p(d)$ for all studied regions. After that, rescaling of the data was performed, in accordance with Eqs. 5-8. This causes a change in the curves of Fig. 4a, presented in Fig. 4b. It can be seen that the data collapses when rescaled. The collapse of the data is indicative of scaling. The data is well fitted with the model of beta distribution (Eq. 9).

When fitting the data separately for each of the regions in Table 2, the values of the parameters α and β vary as follows:

- α changes from 0.92 to 2.54,
- β – from 1.57 to 3.84.

When mixing the data shown in Fig. 4b, the parameters are, respectively: $\alpha = 1.34 \pm 0.07$, $\beta = 2.56 \pm 0.16$.

For some regions in the previous cases (Figs. 2 and 3) there is a clear tendency for the distribution to exceed the values given by the model curve; there is an excess of short inter-event distances. In this case, however, such tendency is not observed.

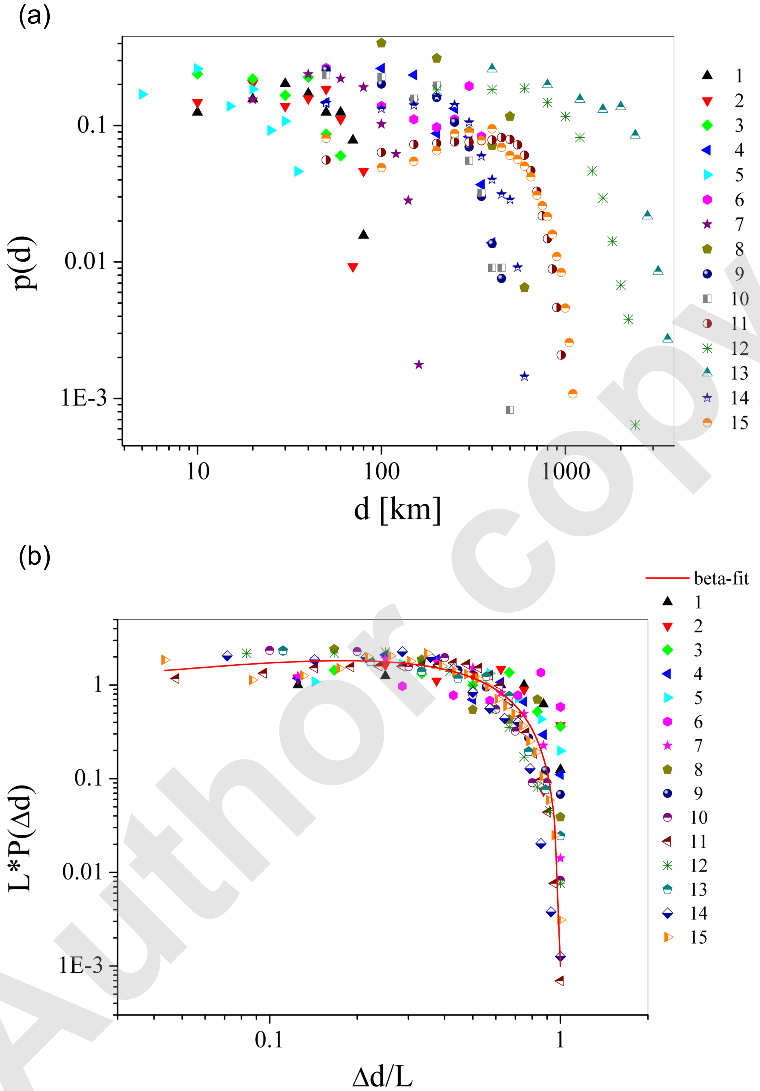


Fig. 4. Data for declustered catalogs listed in Table 2: (a) Frequency distribution $p(d)$ of the spatial distances d between earthquake epicenters; (b) Probability density for the rescaled data: $x = \Delta d\,/\mathrm{L}$, $y = L \times P(\Delta d)$. The continuous line is a beta distribution fit. Colour version of this figure is available in electronic edition only.

4. CONCLUSIONS

The paper presents an investigation of the distribution of distances between consecutive earthquakes from different seismic regions. It has been established that when these distributions are rescaled, all curves converge in one.

The rescaled data is well fitted by beta distribution for $x\ (= \Delta d/L) > 20$. The obtained results do not confirm the availability of two scaling modes, as described by Corral (2006a). Nevertheless, the contention that the investigated distribution of distances between consecutive earthquakes indicates the availability of correlation between the events at small values of the distances can be supported.

Earthquakes occurring close together in space are more likely generated by the same aftershock sequence and are therefore correlated. However, after the value of $x\ (= \Delta d/L) \approx 60$, the shape of the distribution decays extremely rapidly. This can be attributed to the fact that earthquake events happening at very large distances away from each other are less likely to be correlated, and are thus generated by random, independent processes.

When considering the regional (numbered from 11 to 15 in Table 1) and local catalogs, the distribution of distances between consecutive events is similar, though they comprise different ranges of change (Fig. 1). It can be expected that the distribution for smaller regions is just a section from the distribution, related to big regions, but Fig. 2 categorically denies this fact. It provides a clear illustration of earthquake-occurrence self-similarity in space.

The availability of a power law, approximating the distribution of distances in the range of the small values of x is the evidence for clusterization of the earthquakes. It is impossible, however, on basis of the conducted investigations, to say whether the clusterization is a typical aftershock or it is a grouping of some other type. Therefore, additional removal of the dependent events by Reasenberg's method has been carried out. In the process of obtaining the analogous distribution with the help of the declusterized catalogs, such a mode, described by a power law, is not observed (Fig. 4b).

It is important that considering the distance distribution, the data collapse in Figs. 2, 3, and 4b, which is a proof for critical process, since only these exhibit this type of collapse, known as scaling in critical phenomena. This analysis shows that earthquakes are a phenomenon of SOC (Bak *et al.* 1987, Bak 1996, Kanamori and Brodsky 2004).

The separate analysis of both the inter-event distances and times (Marekova 2012) between successive earthquakes from several regional datasets allows marking important properties of seismicity. We can understand seismic activity as a random walk over the Earth surface, where one event comes after another at a distance that follows $P(\Delta d)$ and after a waiting time Δt given by the waiting-time probability density, $P(\Delta t)$. Events happening at close proximity to each other are shown to be more likely to happen after shorter waiting times, demonstrating the clustering behavior of correlated earthquakes simultaneously in space and time. In this line of thought, it can be expected that events happening at long separation distances are more likely to also be separated by long waiting times, which hints at independent mechanisms generating these events. However, an important ingredient is missing in this picture, as we need to take into account the correlations between distances and waiting times.

Therefore, it is necessary to carry out joint research on space-time properties of seismic activity, similar to that in Batac and Kantz (2013), which will be the subject of future work.

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