

THE EARTHQUAKE INTERVENT TIME DISTRIBUTION ALONG THE HELLENIC SUBDUCTION ZONE

Papadakis G.¹, Vallianatos F.^{1,2} and Michas G.¹

¹*Institute for Risk and Disaster Reduction, University College London, Gower Street,
London, WC1E 6BT, UK (georgios.papadakis.10@ucl.ac.uk)*

²*Laboratory of Geophysics and Seismology, Technological Educational Institute of Crete,
Chania, GR 73133, Crete, Greece*

Abstract

The Hellenic Subduction Zone (HSZ) is the most seismically active region in Europe (Becker and Meier, 2010). The evolution of such an active region is characterized by complex phenomenology and is expressed through seismicity. Seismicity temporal patterns remain as one of the most important topics in earth sciences. The Weibull distribution has been used as a recurrence time model for large earthquakes (Rikitake, 1976; Rikitake, 1991). Moreover, Hasumi et al. (2009) used the Weibull-log Weibull distribution for the study of the interoccurrence times of earthquakes in Japan. The dataset formed in this study concerns the seismic belt of the HSZ during the period 1976-2009. We use the external seismic sources of shallow earthquakes in the Aegean and the surrounding area (Papaioannou and Papazachos, 2000) along with the updated and extended earthquake catalogue for Greece and adjacent areas (Makropoulos et al., 2012). The application of the Weibull distribution to the interevent times of the formed dataset is analyzed and discussed.

Key words: *Hellenic Subduction Zone, Weibull distribution, seismicity*

Περίληψη

Η ελληνική ζώνη υποβύθισης είναι η πιο σεισμική περιοχή της Ευρώπης. Η κατανομή Weibull έχει χρησιμοποιηθεί σαν μοντέλο για την περιγραφή των χρονικών διαστημάτων μεταξύ διαδοχικών σεισμών σε συγκεκριμένες ρηξιγενείς ζώνες (Rikitake, 1976; Rikitake, 1991), καθώς και για την περιγραφή της σεισμικότητας μίας ευρύτερης περιοχής (Hasumi et al., 2009). Τα δεδομένα που αναλύουμε σε αυτή την εργασία αφορούν την ελληνική ζώνη υποβύθισης και καλύπτουν την περίοδο 1976-2009. Χρησιμοποιούμε τις σεισμικές πηγές επιφανειακών σεισμών όπως αυτές ορίζονται από τους Papaioannou and Papazachos (2000), καθώς και τον κατάλογο σεισμών των Makropoulos et al. (2012) για την Ελλάδα και τις παρακείμενες περιοχές. Η εφαρμογή της κατανομής Weibull στα χρονικά διαστήματα μεταξύ διαδοχικών σεισμών αναλύεται και περιγράφεται σε αυτή την εργασία.

Λέξεις κλειδιά: *Ελληνική ζώνη υποβύθισης, κατανομή Weibull, σεισμικότητα*

1. Introduction

The eastern Mediterranean region presents a remarkable record of major earthquakes (Ambraseys and Jackson, 1998). The Hellenic Subduction Zone (HSZ) is an active seismic belt (Becker and Meier, 2010; Meier et al., 2004). Many destructive earthquakes have taken place along the HSZ (Papathanasiou et al., 2005; Papazachos and Papazachou, 2003). This high seismic activity is caused by the subduction of the Adriatic continental lithosphere in the north and the Ionian oceanic lithosphere in the south (Royden and Papanikolaou, 2011). The Kephallonia Transform Zone (KTZ) separates the northern part (N.HSZ) of the Hellenic subduction boundary from the southern one (Fig. 1). The evolution of such an active region is characterized by complex phenomenology and is expressed through seismicity.

Seismicity temporal patterns remain as one of the most important topics in earth sciences. Over the past years, much has been written about the distribution of interevent times, which are defined as the time intervals between successive earthquakes. Various distributions have been used to fit earthquake interevent time statistics (Abaimov et al., 2008). Among them, one of the most recent is proposed by Vallianatos et al., (2012), where the spatiotemporal properties of the 1995 Aigion (Greece) earthquake aftershock sequence were investigated using the concept of Nonextensive Statistical Physics formalism (Tsallis, 1988; Tsallis, 2009). The aforementioned authors conclude that Tsallis entropic term describes very well the observed distributions and the spatiotemporal earthquake patterns. An alternative approach is based on the application of the Weibull distribution to the interevent times of an earthquake sequence as it has been performed by many authors (Hagiwara, 1974; Rikitake, 1976; Rikitake 1991). Hasumi et al. (2009) used the Weibull-log Weibull distribution for the study of the interoccurrence times of earthquakes in Japan. The latter distributions have renewed their use in geosciences, since they can be used in seismic hazard assessment (Votsi et al., 2011). It is the scope of the present work to use the Weibull distribution for the analysis of the cumulative distribution of the interevent times along the seismic zones of the HSZ.

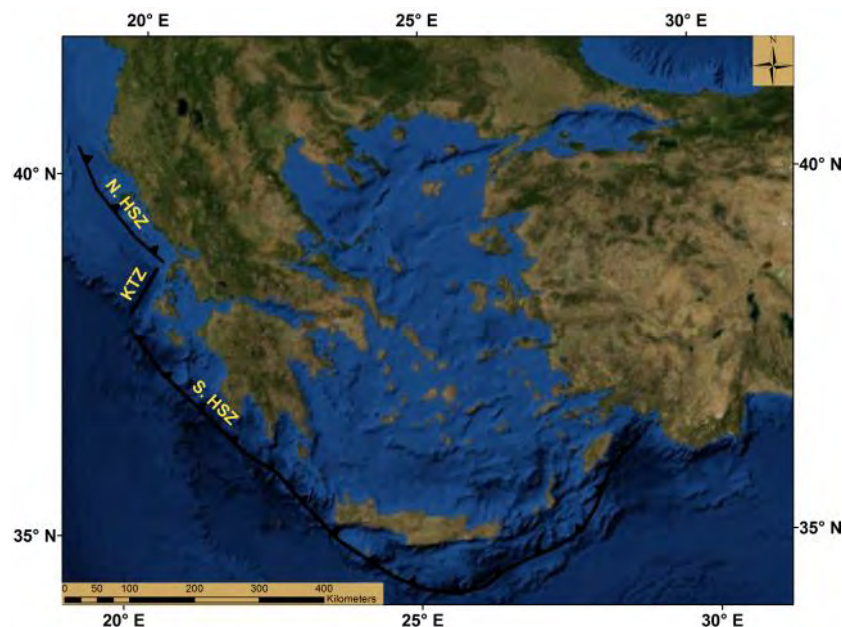


Figure 1 - The active trenches (thick dark lines with solid barbs) for the HSZ, as Royden and Papanikolaou (2011) indicate them. The Kephallonia Transform Zone (KTZ) separates the northern part (N. HSZ) of the Hellenic subduction boundary from the southern one (S. HSZ).

2. Seismic Zones and Earthquake Dataset

Papaioannou and Papazachos (2000) separated the region of the Aegean and the surrounding area in 67 seismogenic sources. This separation is based on previous work on seismic zonation, work on seismicity and active tectonics, as well as on geological and geomorphological information. In the present work, we use the external seismic sources, which are associated with the compressional stress field to define a dataset regarding the subduction zone. These sources have axes parallel to the external coast of the area, to the strikes of the seismic faults (thrust or strike-slip), and are associated with the lithospheric convergence (Papazachos, 1990). In order to create a dataset with a significant number of events that will lead us in a confidence result, we merge the external seismic sources to form larger areas of study called seismic zones, as it is proposed in Papadakis et al., (2013). It should be noticed that the latter process is in fully agreement with the zonation study originally proposed in Papaioannou and Papazachos (2000). Table 1 provides the composition of each seismic zone as regards the seismic sources forming them and the correspondent number of seismic events used in each of the zones. We note that the dataset used in this study is based on the updated and extended earthquake catalogue for Greece and the adjacent areas by Makropoulos et al. (2012). It concerns shallow earthquakes (focal depth $\leq 60\text{km}$) and covers the period 1976-2009 (Figure 2).

Table 1 – The composition of the seismic zones used in this study and the correspondent number of seismic events.

Seismic Zones	Seismic Sources	Seismic Events
1	4,5	111
2	6,7,8,11	265
3	9,10,12,13	248
4	14,15,16,17	327
5	18,19,20	179

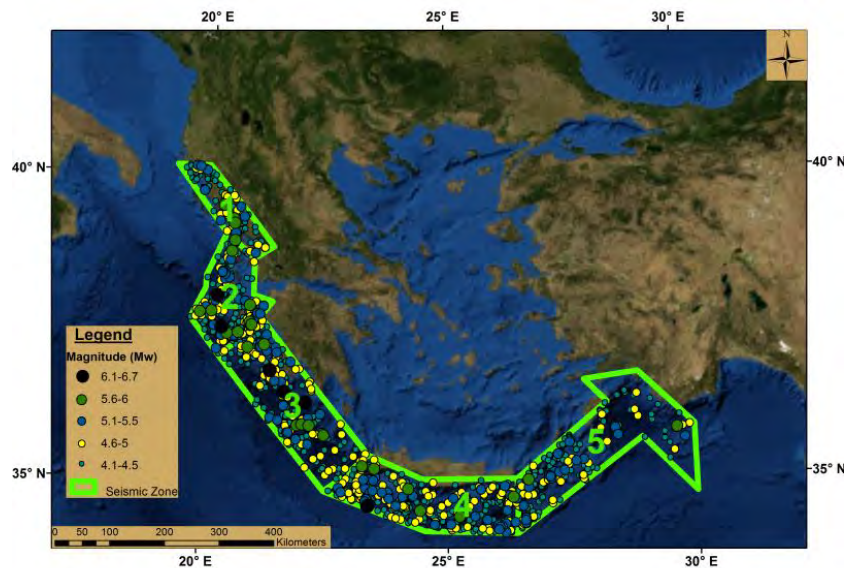


Figure 2 - The seismic zones (polygons 1-5) (Papaioannou and Papazachos, 2000) of the HSZ, and the seismic events (colored circles) (Makropoulos et al., 2012) of shallow earthquakes (focal depth $\leq 60\text{km}$) covering the period 1976-2009.

Moreover, Makropoulos et al. (2012) have computed the magnitude of completeness (M_c) of their updated catalogue for the period 1976-2009 to be as $M_c = 4.1$. The final dataset used in this study, is extracted using the application of the window method, introduced by Gardner and Knopoff (1974) and modified by Uhrhammer (1986) for the declustering of the original earthquake catalogue.

3. The Weibull Distribution

The probability density function (pdf) for a Weibull distribution is given as:

Equation 1–The probability density function (pdf)

$$p(t) = \frac{\beta}{\tau} \left(\frac{t}{\tau}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\tau}\right)^\beta\right],$$

where β is the shape parameter or the Weibull modulus and τ is the scale parameter.

The cumulative distribution (cdf) of the Weibull distribution is given as:

Equation 2–The cumulative distribution function (cdf)

$$P(t) = 1 - \exp\left[-\left(\frac{t}{\tau}\right)^\beta\right],$$

where $P(t)$ is the fraction of the recurrence times that are shorter than t .

The survival function $R(t)$ is given as:

Equation 3–The survival function

$$R(t) = 1 - P(t).$$

The hazard function $h(t_0)$ is the pdf that an event will occur at a time t_0 after the occurrence of the last event (Abaimov et al., 2008). The hazard function exhibits a power-law behavior and it is given as:

Equation 4–The hazard function

$$h(t_0) = \frac{pdf}{1 - cdf} = \frac{\beta}{\tau} \left(\frac{t_0}{\tau}\right)^{\beta-1}.$$

If $\beta > 1$ the probability that an earthquake will occur increases as a power of the time t_0 since the last earthquake. For $\beta = 1$ the Weibull distribution reduces to the exponential distribution. That means that earthquakes occur randomly. For $\beta < 1$ the Weibull distribution is known as the stretched exponential distribution (Yakovlev et al., 2006).

4. Interevent Time Cumulative Distribution

The cumulative distribution of the interevent times for each seismic zone and for the HSZ as a unified system is given in Figure 3. The best fit of the Weibull distribution using the maximum likelihood estimation is also presented.

The calculated Weibull parameters are presented in Table 2. An inspection to the obtained values of the shape parameter β suggests its increase as we move from seismic zone 1 to seismic zone 5. The β value is equal to 0.92 for the HSZ as a unified system. It becomes equal to 0.77 in seismic zone 1. Moving southward it increases and becomes equal to 0.88 and 0.89 in seismic zones 2 and 3, respectively. This trend continues to appear along the northeast portion of the Hellenic arc

presenting values equal to 0.95 and 1.08 in seismic zones 4 and 5 respectively. On the other hand the scale parameter τ shows variations that do not follow the trend of the shape parameter and has a value equal to 9.15×10^5 (sec) for the HSZ as a unified system.

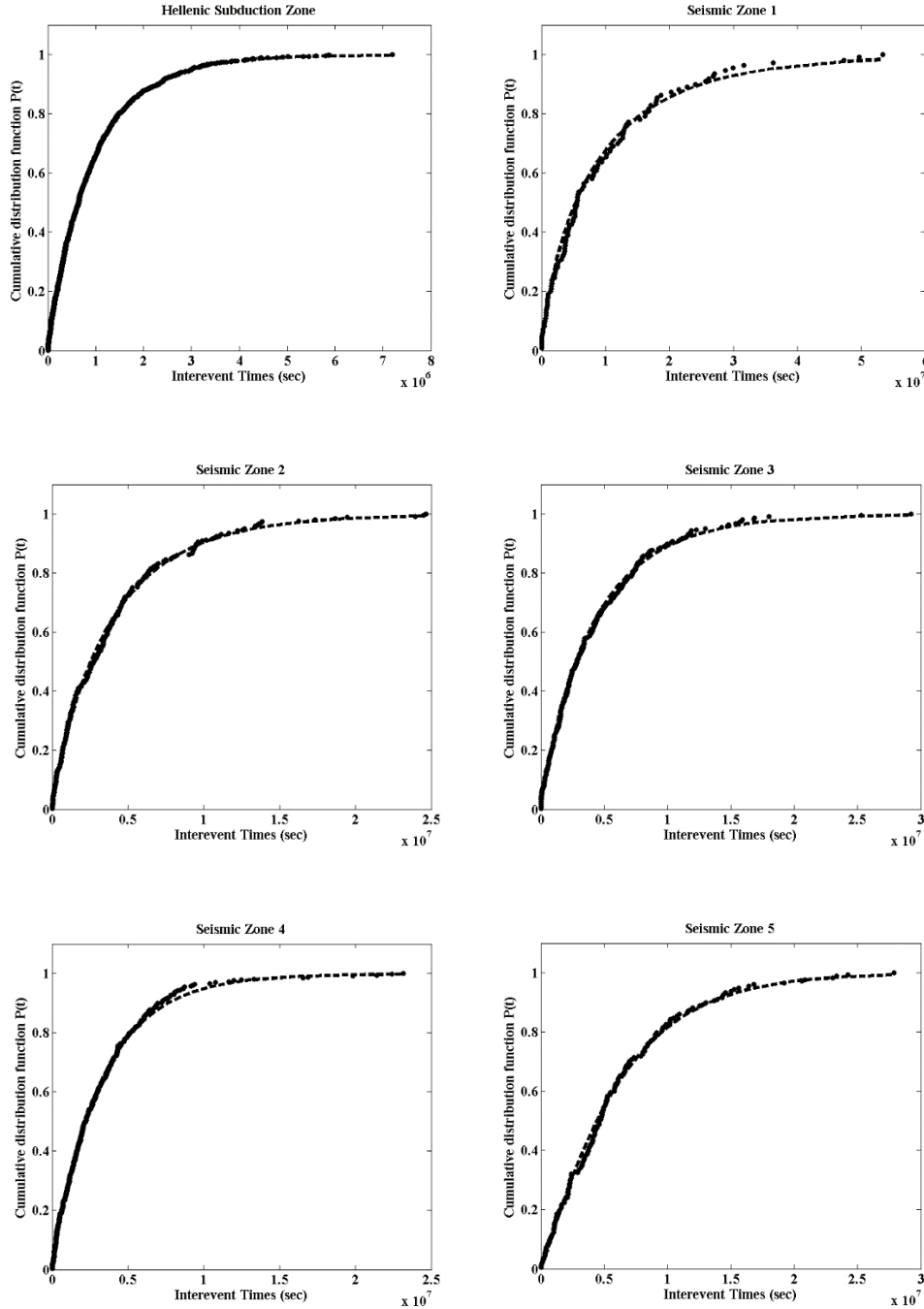


Figure 3 - The cumulative distribution ofintervent times for each seismic zone and for the HSZ as a unified system. The black discontinuous line is the best-fit Weibull distribution. The estimation of the Weibull parameters has been performed using the maximum likelihood estimation.

Table 2 - The Weibull parameters β and τ and their 95% confidence intervals $[\beta_1, \beta_2]$ and $[\tau_1, \tau_2]$ for each seismic zone and for the HSZ as a unified system.

Seismic Zones	β	$\tau(\text{sec})$	$[\beta_1, \beta_2]$	$[\tau_1, \tau_2]$
HSZ	0.92	$9.15 \cdot 10^5$	[0.88, 0.96]	$[8.56 \cdot 10^5, 9.77 \cdot 10^5]$
1	0.77	$8.50 \cdot 10^6$	[0.66, 0.90]	$[6.61 \cdot 10^6, 1.09 \cdot 10^7]$
2	0.88	$3.81 \cdot 10^6$	[0.80, 0.97]	$[3.30 \cdot 10^6, 4.40 \cdot 10^6]$
3	0.89	$4.12 \cdot 10^6$	[0.81, 0.99]	$[3.56 \cdot 10^6, 4.76 \cdot 10^6]$
4	0.95	$3.17 \cdot 10^6$	[0.87, 1.03]	$[2.81 \cdot 10^6, 3.57 \cdot 10^6]$
5	1.08	$6.15 \cdot 10^6$	[0.96, 1.22]	$[5.34 \cdot 10^6, 7.09 \cdot 10^6]$

5. Conclusions

In the present work the analysis of the interevent time distribution using the Weibull distribution is being investigated. The studied area is the Hellenic subduction belt divided in 5 seismic zones as it is recently used in Papadakis et al., (2013) and as it is originally proposed in Papaioannou and Papazachos (2000) for the separation of the Aegean and the surrounding area in 67 seismogenic sources. The declustered earthquake dataset concerns earthquakes with $M_c = 4.1$ and covers the period 1976-2009. The Weibull distribution used in this study fits rather well to the observed distributions simplifying its usefulness in the investigation of the interevent time distribution along the HSZ. The shape parameter β presents increasing values as we move from the northwestern (seismic zone 1) to the southeastern part (seismic zone 5) of the Hellenic subduction boundary. On the other hand the scale parameter τ presents variations that do not follow the trend of the shape parameter along the seismic zones of the HSZ.

6. Acknowledgments

This work was supported by the THALES Program of the Ministry of Education of Greece and the European Union in the framework of the project entitled “Integrated understanding of Seismicity, using innovative Methodologies of Fracture mechanics along with Earthquake and non-extensive statistical physics – Application to the geodynamic system of the Hellenic Arc. SEISMO FEAR HELLARC”.

7. References

- Abaimov S.G., Turcotte D.L., Shcherbakov R., Rundle J.B., Yakovlev G., Goltz C. and Newman W.I. 2008. Earthquakes: Recurrence and Interoccurrence Times, *Pure Appl. Geophys.*, 165, 777-795.
- Ambraseys N.N. and Jackson J.A. 1998. Faulting associated with historical and recent earthquakes in the eastern Mediterranean area, *Tectonophysics*, 60, 1-42.
- Becker D. and Meier T. 2010. Seismic Slip Deficit in the Southwestern Forearc of the Hellenic Subduction Zone, *Bull. Seismol. Soc. Am.*, 100, 325-342.
- Gardner J.K. and Knopoff L. 1974. Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?, *Bull. Seismol. Soc. Am.*, 64, 1363-1367.
- Hagiwara Y. 1974. Probability of earthquake occurrence as obtained from a Weibull distribution

- analysis of crustal strain, *Tectonophysics*, 23, 313-318.
- Hasumi T., Akimoto T. and Aizawa Y. 2009. The Weibull-log Weibull distribution for interoccurrence times of earthquakes, *Phys. Stat. Mech. Appl.*, 388, 491-498.
- Makropoulos K., Kaviris G. and Kouskouna V. 2012. An updated and extended earthquake catalogue for Greece and adjacent areas since 1900, *Nat. Hazards Earth Syst. Sci.*, 12, 1425-1430.
- Meier T., Rische M., Endrun B., Vafidis A. and Harjes H.P. 2004. Seismicity of the Hellenic subduction zone in the area of western and central Crete observed by temporary local seismic networks, *Tectonophysics*, 383, 149-169.
- Papadakis G., Vallianatos F. and Sammonds P. 2013. Evidence of Non Extensive Statistical Physics behaviour of the Hellenic Subduction Zone seismicity, *Tectonophysics*, DOI: 10.1016/j.tecto.2013.07.009. (In press)
- Papathanassiou G., Pavlides S. and Ganas A. 2005. The 2003 Lefkada earthquake: Field observations and preliminary microzonation map based on liquefaction potential index for the town of Lefkada, *Eng. Geol.*, 82, 12-31.
- Papaioannou C.A. and Papazachos B.C. 2000. Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources, *Bull. Seismol. Soc. Am.*, 90, 22-33.
- Papazachos B.C. 1990. Seismicity of the Aegean and surrounding area, *Tectonophysics*, 178, 287-308.
- Papazachos B.C. and Papazachou C.B. 2003. *The earthquakes of Greece*, Thessaloniki, Ziti Publications.
- Rikitake T. 1976. Recurrence of great earthquakes at subduction zones, *Tectonophysics*, 35, 335-362.
- Rikitake T. 1991. Assessment of earthquake hazard in the Tokyo area, Japan, *Tectonophysics*, 199, 121-131.
- Royden L.H. and Papanikolaou D.J. 2011. Slab segmentation and late Cenozoic disruption of the Hellenic arc, *Geochem. Geophys. Geosyst.*, 12, Q03010.
- Tsallis C. 1988. Possible generalization of Boltzmann-Gibbs Statistics, *J. Stat. Phys.*, 52, 479-487.
- Tsallis C. 2009. *Introduction to Nonextensive Statistical Mechanics: Approaching a Complex World*, New York, Springer.
- Uhrhammer R. 1986. Characteristics of northern and central California seismicity, *Earthquake Notes*, 57, 21.
- Vallianatos F., Michas G., Papadakis G. and Sammonds P. 2012. A non-extensive statistical physics view to the spatiotemporal properties of the June 1995, Aigion earthquake (M6.2) aftershock sequence (West Corinth rift, Greece), *Acta Geophys.*, 60, 758-768.
- Votsi I., Tsaklidis G.M. and Papadimitriou E.E. 2011. Seismic hazard assessment in central Ionian Islands area (Greece) based on stress release models, *Acta Geophys.*, 59, 701-727.
- Yakovlev G., Turcotte D.L., Rundle J.B. and Rundle P.B. 2006. Simulation-based distributions of earthquake recurrence times on the San Andreas Fault System, *Bull. Seismol. Soc. Am.*, 96, 1995-2007.