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# Statistical Analysis of the Inter-Event Time, Distance, and Migrating Trend Distribution of Successive Large Earthquakes in Iran

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## ABSTRACT

*In this study, the waiting time, spatial distance, and migrating trend pattern of successive large earthquakes in Iran have been investigated. In order to carry out this work, the earthquake data of Iran with  $M \geq 4.5$  (1976-2018) have been obtained from the USGS catalog. Then, the statistical distribution of the Inter-event time, migrating distance, and directional trend of migration of successive events were studied using different lower magnitude thresholds. The statistical and probability distributions of inter-event times of earthquakes were assessed and modelled by different distribution models. Furthermore, the directional analysis of migrating trends, as well as the spatial distances of successive events with different lower magnitude, was carried out. It is observed that the inter-event time distribution of earthquakes can be quite well fitted by the Gamma distribution model. The results obtained also indicate a decreasing trend in spatial distance distribution and a meaningful correlation between the directional pattern of the migrating trends of successive events and the dominant trends of the active faults of the region. The results of this study can be considered as an effective step to better understanding the temporal-spatial pattern of seismicity in Iran and also as an attempt to achieve earthquake prediction in this country, in a regional scale.*

### Keywords:

Inter-event time distribution; Statistical distribution of earthquakes; Spatio-temporal analysis; Seismicity; Seismotectonics

## 1. Introduction

Earthquakes are the result of the release of stresses stored in the Earth's crust. Today, human knowledge of fault physics during earthquakes and the geometric structure and pattern of seismic faulting have been increasing, dramatically. However, our knowledge of the physical processes involved in earthquakes still remains incomplete [1]. Earthquake as a spatio-temporal stochastic event has always been of interest to researchers in statistics and data modeling. Finding the order in which the temporal and spatial pattern of earthquakes occur is an important and effective step in achieving earthquake prediction. Various factors control the spatio-temporal pattern of earthquakes. Therefore, understanding the pattern of earthquake occurrence

in time and space is very complex. It is expected that with the use of new data analysis methods and applied modeling, a hidden data structure can be achieved which is a useful step to better understanding processes and achieve event predictions.

The Iranian region occupies a part of the Alpine-Himalayan orogenic belt. This region is characterized by high topography, recent volcanisms and many active faults that cause the occurrence of destructive earthquakes with different mechanisms. This region is one of the most seismically active regions in the world. During the past decades, many destructive earthquakes occurred in this region, resulted in great loss of life and property, including the most recent November 12, 2017,

Ezgeleh ( $M_w = 7.3$ ) earthquake, at the Iran-Iraq border.

The generalized tectonic map of Iran, showing the main tectonic features of the region, is presented in Figure (1). As can be seen in this figure, within the Iranian region, different structural zones can be identified. At the south and west of the region, continental-continental collision zone of Zagros is one of the youngest and most active collision zones on the Earth, resulting from the continuing north-eastward drift of the Arabian plate relative to the Eurasian and Central Iranian Microcontinent. Seismicity of this zone can be characterized by the occurrence of low to moderate magnitude earthquakes most of which nucleate on blind thrust faults. The Sanandaj-Sirjan belt extends parallel to the Zagros. Contrary to the Zagros, this zone shows minor seismic activity. The highly seismogenic region of the Alborz and Kopet Dagh covering north and northeast of Iran constitutes a part of the northern limit of Alpine-Himalayan orogenic belt. This zone faces the stable Turan platform (Eurasia) to the north. The oceanic-continental subduction zone of Makran, where the consumption of oceanic crust of Arabian plate has occurred continuously along a north dipping subduction zone underneath the Eurasian-Central Iranian Microcontinent, covers

the southeast part of the region. Although at the present time this zone shows minor seismicity, the existence of mud volcanoes and uplifted young beaches indicates that this zone can probably yield major earthquakes after long period of quiescence [2]. Eastern Iran represents an intra-plate environment, which is seismically active and characterized mainly by a series of fault systems with north-south trends. During the past century, major earthquakes have occurred in this zone. Within this broad deforming region including the above-mentioned active zones, there are large areas such as northwest part of Iran, Central Iran and Lut block that appear to be almost aseismic, and therefore to behave as relatively rigid blocks surrounded by active belts [3]. However, it seems that the borders of these rigid blocks are active faults causing the occurrence of major earthquakes.

Over the past decades, the statistics of the waiting times between consecutive earthquakes (so-called inter-event times) have become the focus of research (e.g., [4-7]). Statistical analysis of inter-event times of earthquakes allows the derivation of useful information that can allow the development of earthquake forecasting strategies [6], also, inter-event time statistics for moderate to small events may be used to extrapolate inter-event

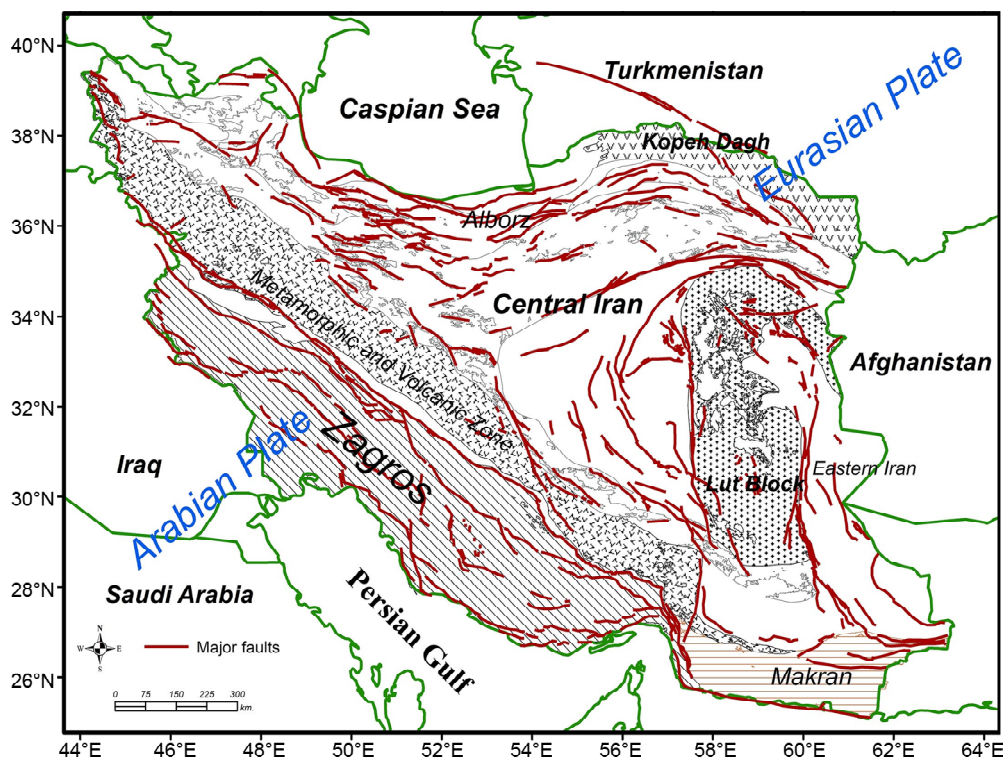


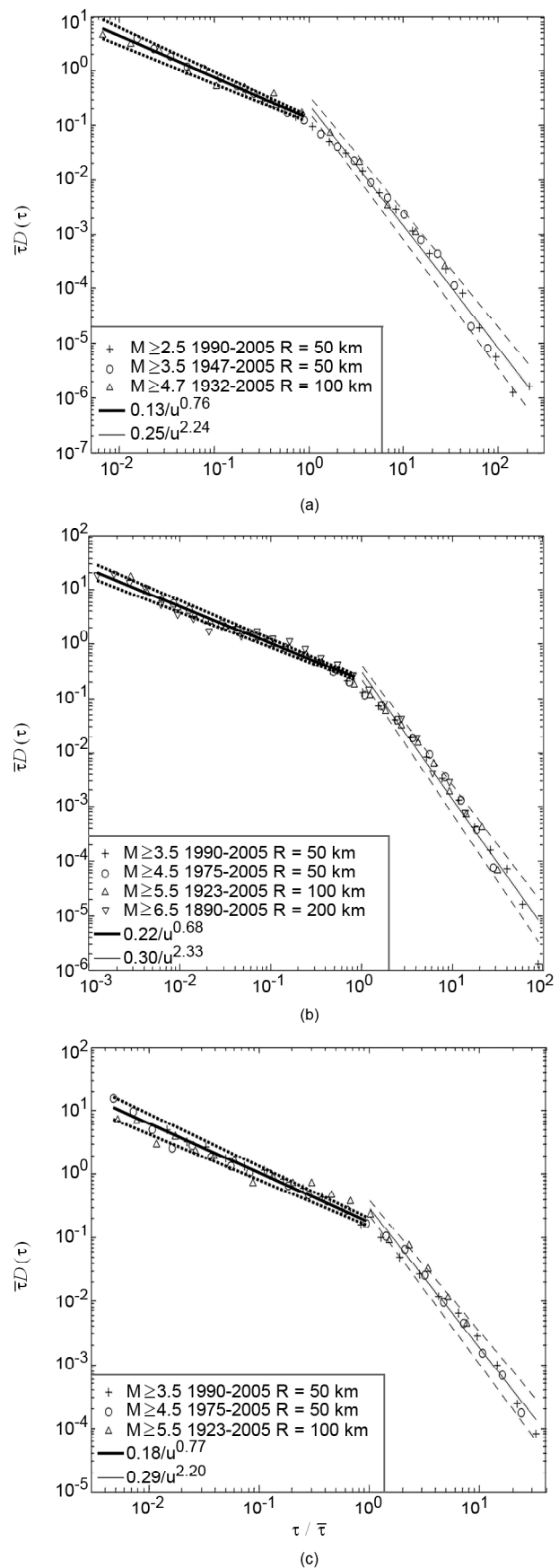
Figure 1. Tectonic and structural map of Iran including major active faults of the region.

time behaviour at larger scales [8-9]. A number of different distribution models have been proposed to account for inter-event time variability of large earthquakes, including exponential, lognormal, Gamma, and Weibull distributions. Utsu [10] used four renewal probability distributions (Weibull, Gamma, lognormal, and exponential) to estimate earthquake recurrence in Japan and surrounding areas. Later, several researchers (e.g., [7-8]) applied similar methodologies for their respective geographic regions of study. On the other hand, the study of the spatial distance distribution of subsequent earthquakes statistically helps us to determine how far away the next earthquake in a region will be. Furthermore, statistically analyzing the migrating trends of successive events should be helpful to assess the segmentation behavior of active fault systems of the region under consideration. The statistical analysis of the spatial distance and migrating trend of subsequent earthquakes has been studied by some authors (e.g., [11-12]).

In Iran, Ref. [13] evaluated the statistical distribution of the time distribution between earthquakes occurring in different tectonic zones of Iran and for different magnitude intervals, and analyzed the statistical parameters of some important statistical distributions for these data. Also, Ref. [14] investigated the seismic pattern in the Zagros region using time series analysis method. In addition to the aforementioned, investigating the temporal pattern of earthquake events and examining the statistical distribution of time between events in large earthquakes occurring in different parts of the world has been the subject of much research in recent decades [15-17].

As a case study, Talbi and Yamazaki [18] studied the robustness of earthquake recurrence time distribution scaling in details, using earthquake catalogs from different parts of the world (Southern California, Japan and Turkey) (Figure 2). They showed that, big events occurring after seismically quiescent periods and foreshocks preceding large events are linked in a single quantified cause-effect structure.

In addition, Chen et al. [19] studied the earthquake inter-occurrence time distribution models in Taiwan, and based on the goodness-of-fit testing of different models, they suggested the use of the Gamma distribution for modeling earthquake inter-occurrence



**Figure 2.** Scaled distributions of interevent times with different magnitudes and different sampling radiuses, for (a) Southern California, (b) Japan and (c) Turkey. Solid lines are the linear regressions whereas dashed lines are 95% confidence limits [18].

periods in the Taiwan region (Figure 3).

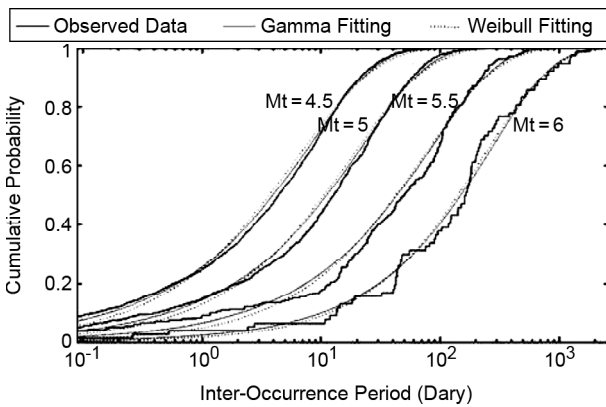
Also, Pasari [20] considered 12 time-dependent probability distribution models for the analysis of earthquakes in northwest Himalaya and adjoining regions. He suggested that the best fit arises from exponential Weibull, exponentiated exponential, Weibull, and Gamma distributions (Figure 4).

The basics of the statistical distribution of the time distribution between earthquakes under static conditions are fully described by Ref. [21]. Also, it should be noted that according to previous research

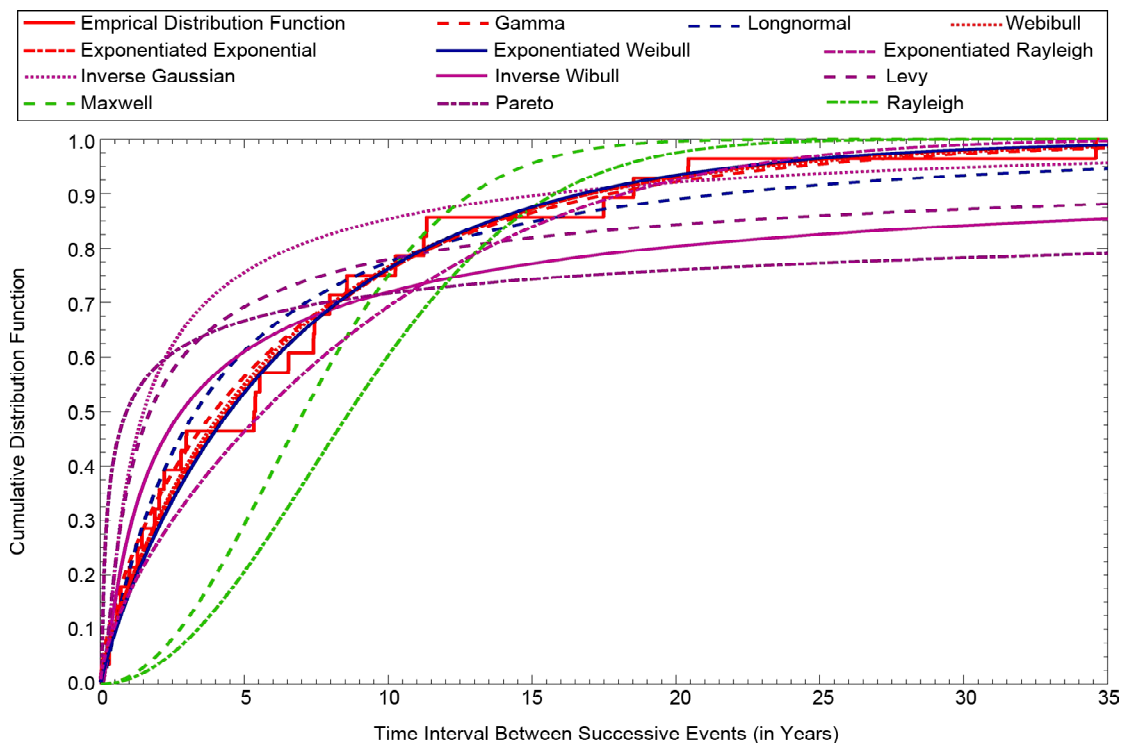
ers' findings, that the pattern of time distribution between earthquakes appears to depend on factors such as the extent of the study area or area, seismic characteristics of the areas, and the magnitude of the earthquakes under study [22]. Assuming that the release of seismic energy (by occurring earthquakes) is stationary in the whole region of Iran, in this research, the spatio-temporal relationships of the occurrences of large earthquakes in this region have been studied. This paper attempts to present a time, distance, and migration pattern of successive large earthquakes occurred in Iran during 1976-2018.

## 2. Methods

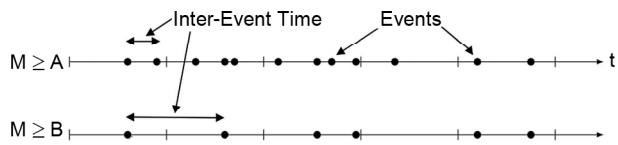
From the statistical point of view, the waiting times between successive events can be considered as continuous data, which can be modelled by continuous distribution statistical models to fit and evaluate their consistency. These data depend on the magnitude of the earthquakes. Larger earthquakes are expected to occur at longer intervals. The pattern of occurrences of successive earthquakes in a region can be characterized by inter-event time, migrating distance (jumps), and migrating trend of these events. The inter-event time is defined as the time interval between consecutive events for a given



**Figure 3.** Comparison between observation, Gamma and Weibull models in Taiwan. The Weibull distribution forecasts a lower probability in the shortest and longest part of inter-occurrence periods and higher in the middle part in relation to the Gamma distribution [19].



**Figure 4.** Cumulative distribution of interevent times of earthquakes that occurred in northeast Himalaya and adjoining regions, modelled by 12 distribution functions [20].



**Figure 5.** Diagram showing the time-distribution pattern of earthquakes and the inter-event times for earthquakes with different lower magnitude thresholds.

lower magnitude threshold,  $M_t$ . In Figure (5), the concept of inter-event time for different lower magnitude thresholds is shown.

This study simply used three statistical distribution models for assessing the distribution of inter-event time data of earthquakes in this study (i.e., the exponential, the Gamma, and the Weibull distributions). The respective probability density functions of these distributions are expressed as follows:

$$f_{(x)} = \lambda e^{-\lambda x}, \text{ for the exponential distribution} \quad (1)$$

$\lambda = \text{rate}$

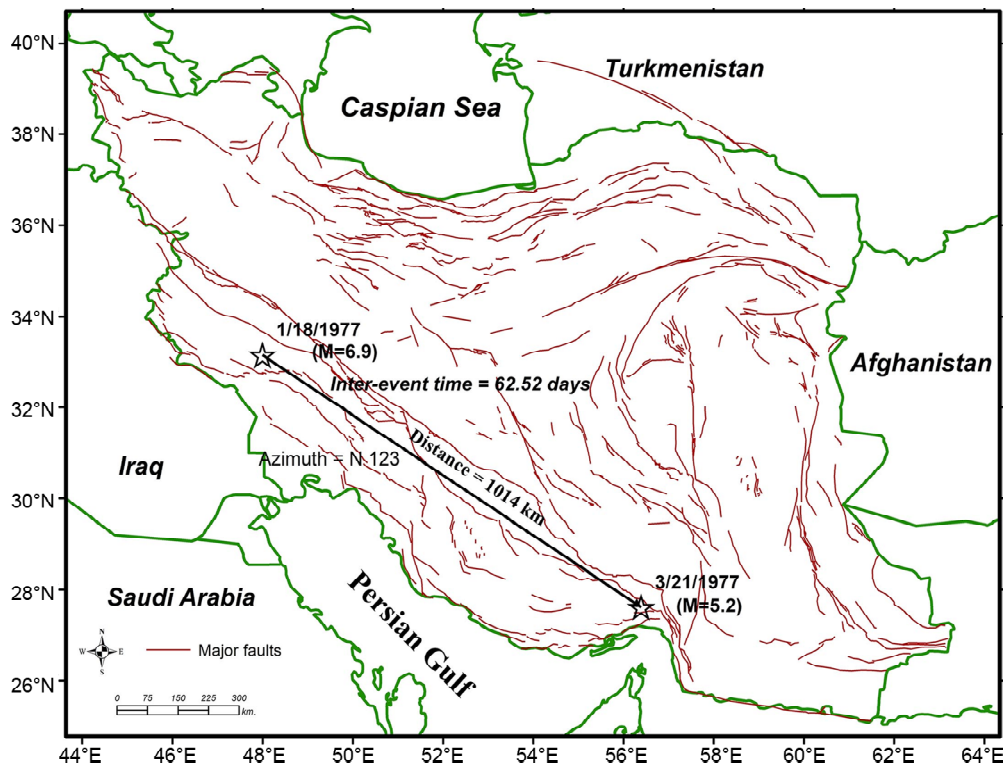
$$f_{(x)} = x^{k-1} \frac{\exp\left(\frac{-x}{\theta}\right)}{\Gamma(k)\theta^k}$$

$\theta = \text{scale}$ , for the Gamma distribution (2)  
 $k = \text{shape}$

$$f_{(x)} = \left(\frac{k}{\lambda}\right) \left(\frac{x}{\lambda}\right)^{(k-1)} e^{-\left[\frac{x}{\lambda}\right]^k}$$

$\lambda = \text{scale}$ , for the Weibull distribution (3)  
 $k = \text{shape}$

By comparing the fitness of models and empirical probabilities for these three models, the best distribution model for the cumulative probability of inter-occurrence periods of earthquakes for Iran is proposed. Additionally, in this study, the statistical distribution of the migrating distance and trend of successive events has been assessed. In Figure (6) the map showing the spatial distance (or jump) and migrating trend of two successive earthquakes that occurred in Iran is presented. It is suggested that a systematic pattern should be existed in data concerning with these distances and trends of events. The migration distances (jumps) of successive earthquakes are also continuous data that can be interpreted and analyzed statistically by examining their statistical distribution charts. In addition, the directions of migration of successive earthquakes are also considered as directional data, which can be studied through directional statistics methods in order to determine dominant trends.

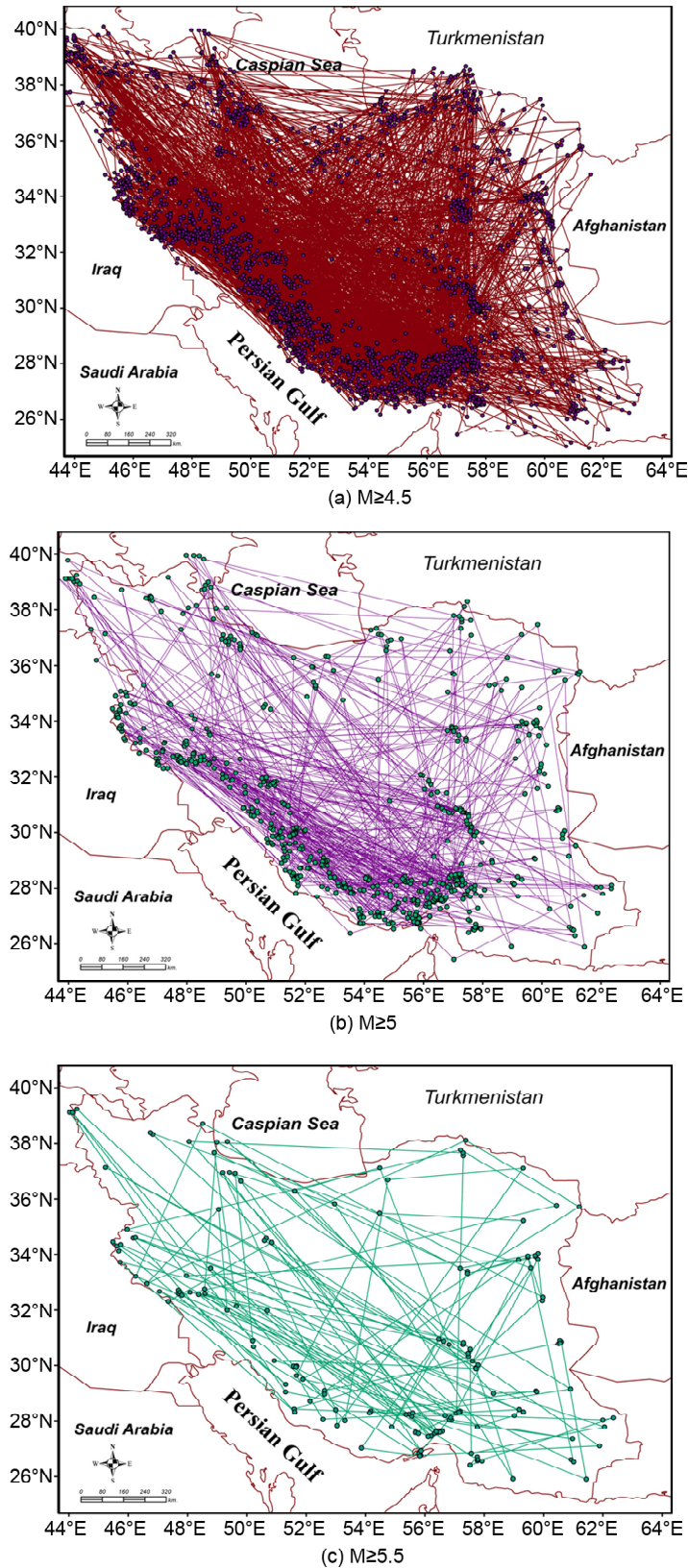


**Figure 6.** Map showing the concept of inter-event time, distance, and migrating direction of two successive earthquakes that occurred in the region.

### 3. Data Analysis and Discussion

In this research, the inter-event time distribution, migration distance (jump), and directional trend pattern of the occurrence of successive earthquakes in Iran, with different lower magnitude thresholds

( $M \geq 4.5$ ,  $M \geq 5.0$ , and  $M \geq 5.5$ ), have been investigated. Data catalog used in this analysis spans the years 1976-2018, containing 2781 earthquakes with  $M \geq 4.5$ , extracted from USGS database. Figure (7) simply shows maps indicating the migration pattern

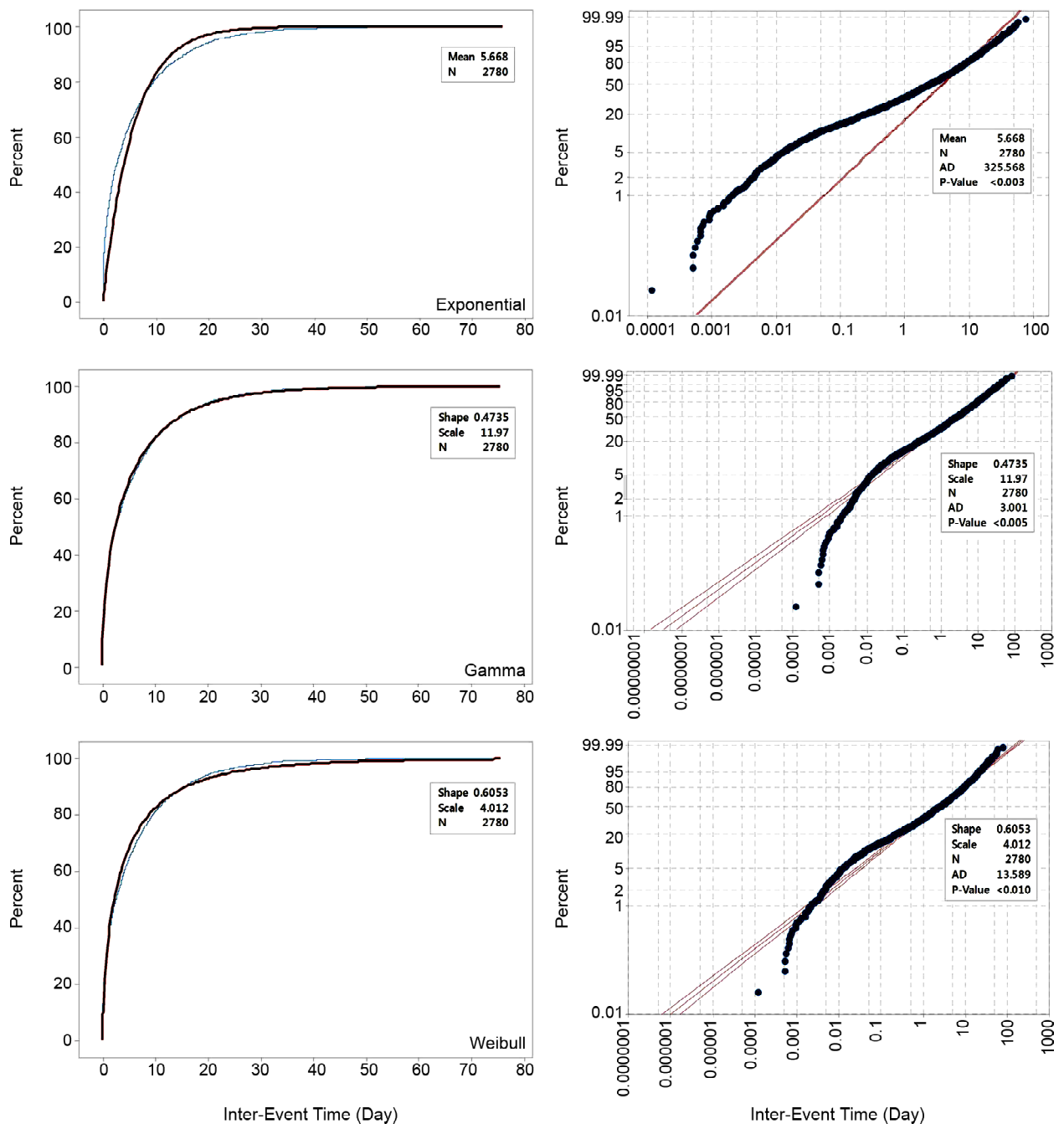


**Figure 7.** Maps showing the migration pattern of successive large earthquakes with different lower magnitude thresholds.

of successive large earthquakes with magnitudes equal to and greater than 4.5, 5.0, and 5.5. In these maps, tie lines showing the directional and distance pattern of the occurrences of these successive earthquakes are illustrated.

In Figures (8), (9), and (10), Graphs showing Cumulative Density Function (CFD) and probability plots, provided for the Exponential, Gamma, and Weibull distributions, and fitted to the empirical data on inter-event times of successive earthquakes with  $M \geq 4.5$ ,  $M \geq 5.0$ , and  $M \geq 5.5$ , are presented.

A comparison of these plots indicates that the inter-event time distribution is well described by Gamma distribution model, and also, by increasing the lower magnitude threshold, the degree of goodness-of-fit decreases. Additionally, significant deviations from employed distribution models, especially for Gamma distribution, are observed at greater inter-event times, as previously reported by other researchers (e.g., [23]). The deviations from distribution models at small waiting times could be acceptably attributed to the aftershock activities.

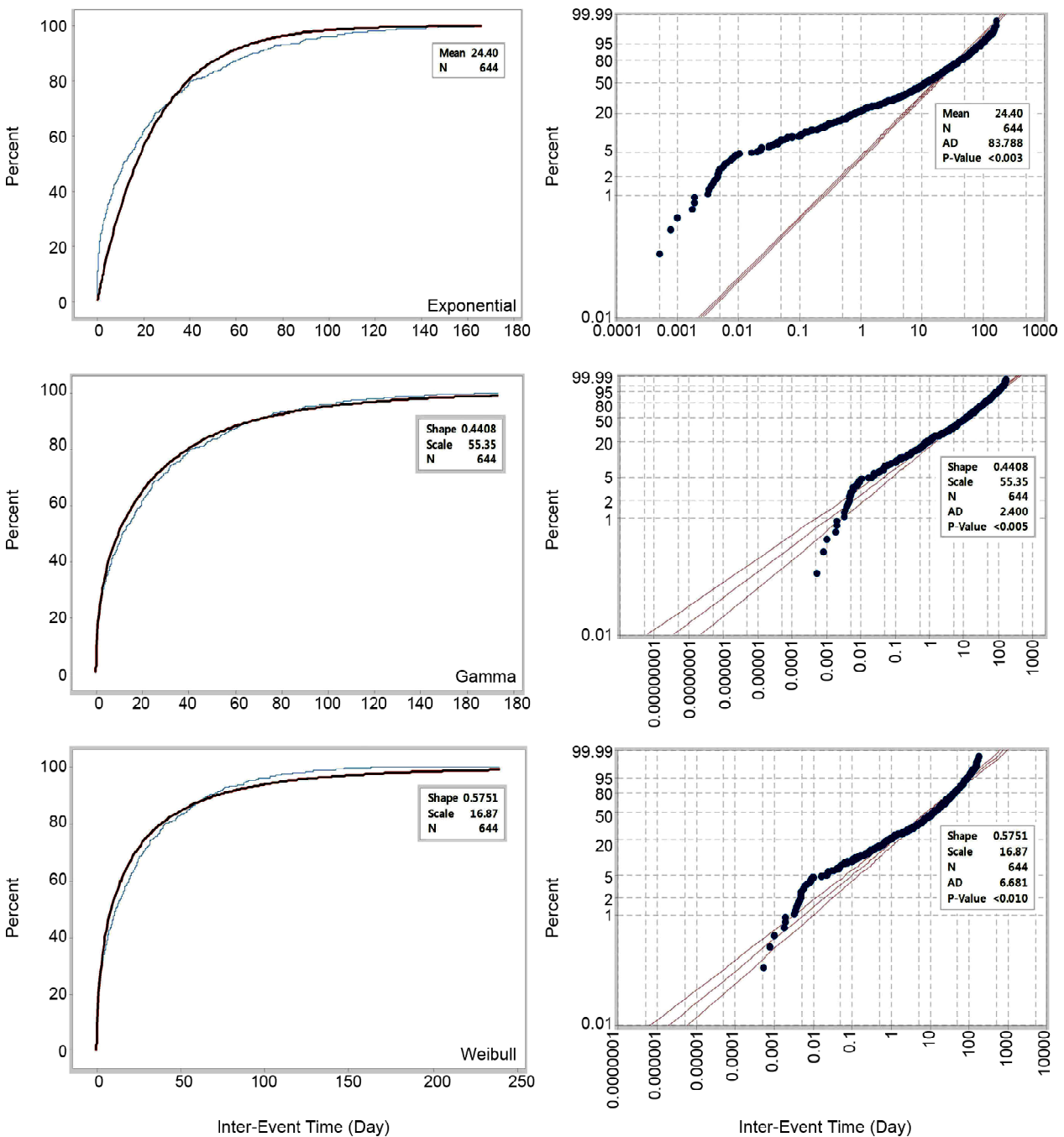


**Figure 8.** Graphs showing cumulative density function (CFD) (left) and probability plots (right) of Exponential, Gamma, and Weibull distributions fitted to inter-event times (day) of successive earthquakes with  $M \geq 4.5$ , that occurred in Iran during 1976-2018.

Therefore, it is expected that by removing dependent events (mostly aftershocks) using reliable de-clustering techniques, the resulting empirical curves be better fitted with these distribution models.

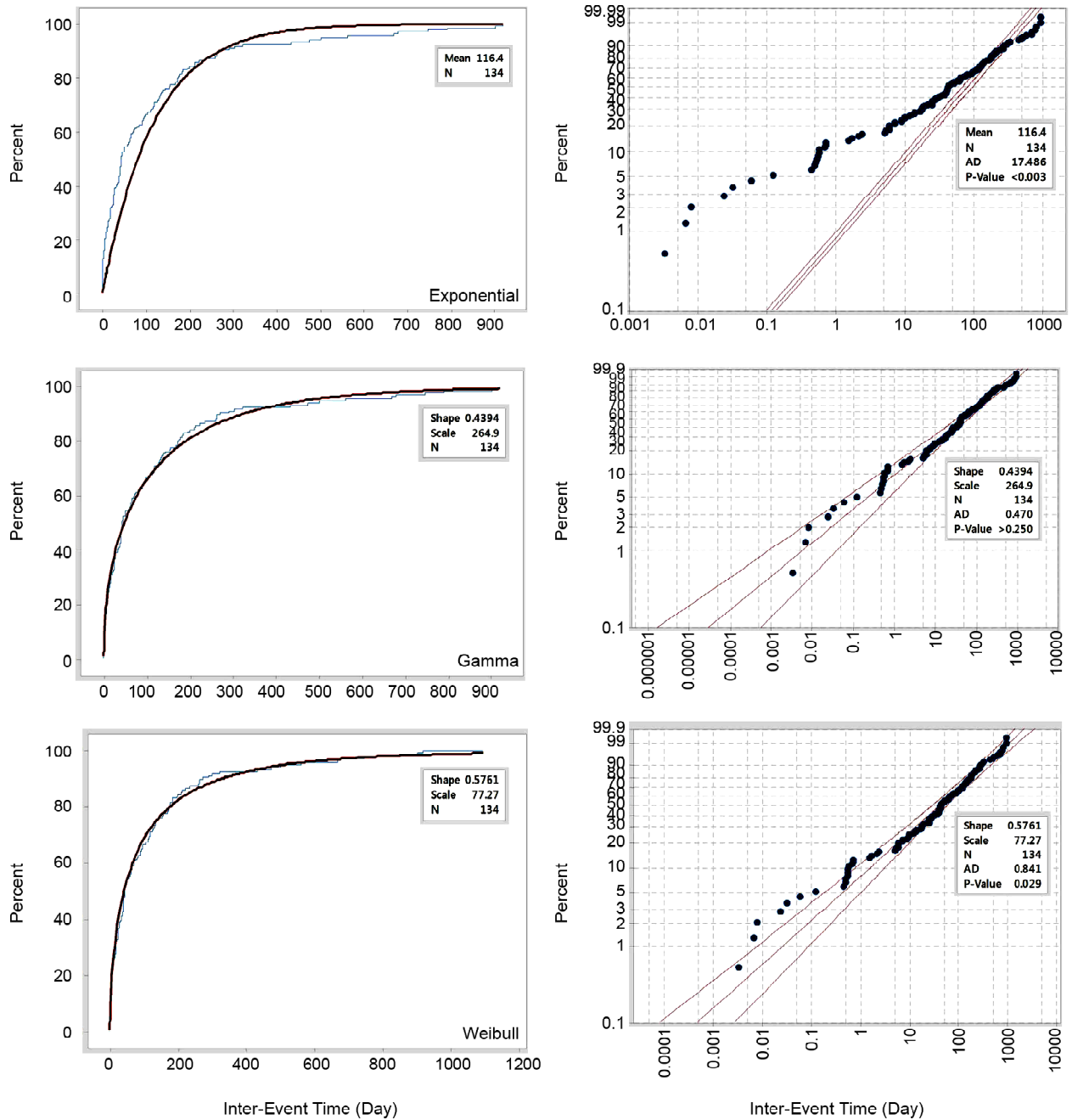
To analyze the distribution of spatial distances between successive earthquakes or "jumps", these distances are computed using ArcGIS software for different lower magnitude thresholds. As shown in Figures (11)-(13a), the distribution shows a generally decreasing trend, similar to inter-event time values. An overall look at the histograms represent-

ing the statistical distribution of spatial distances of successive earthquakes, prepared for different lower magnitude thresholds ( $M_t$ ), indicates that the first part of the diagrams shows a decreasing trend, while in the second part the diagrams show a nearly normal distribution. It seems that a more reliable and stable pattern may be achieved by analyzing de-clustering data. As stated by Ref. [12], the spatial distances between successive earthquakes in a region show a nearly power-law behavior with no significant dependence on the threshold magnitude.

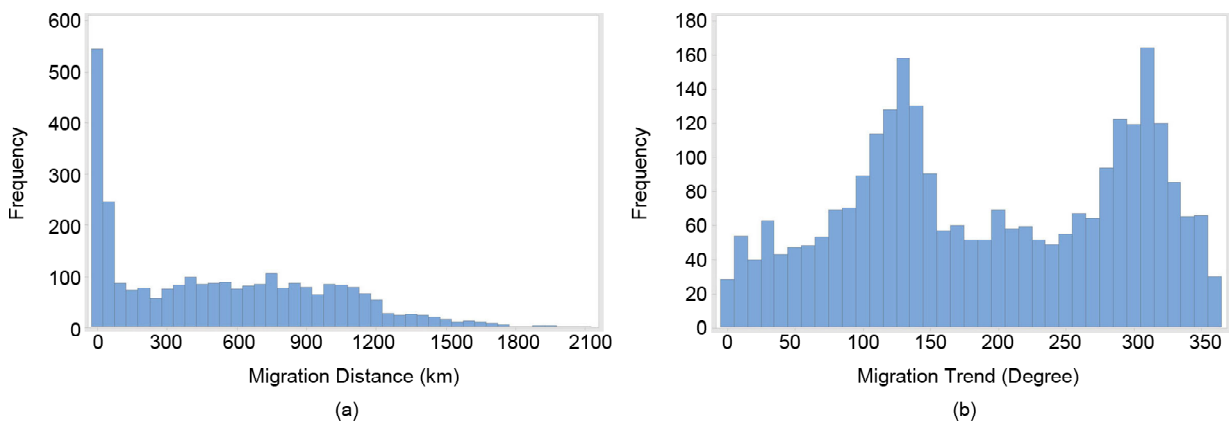


**Figure 9.** Graphs showing cumulative density function (CFD) (left) and probability plots (right) of Exponential, Gamma, and Weibull distributions fitted to inter-event times (day) of successive earthquakes with  $M \geq 5.0$ , that occurred in Iran during 1976-2018.

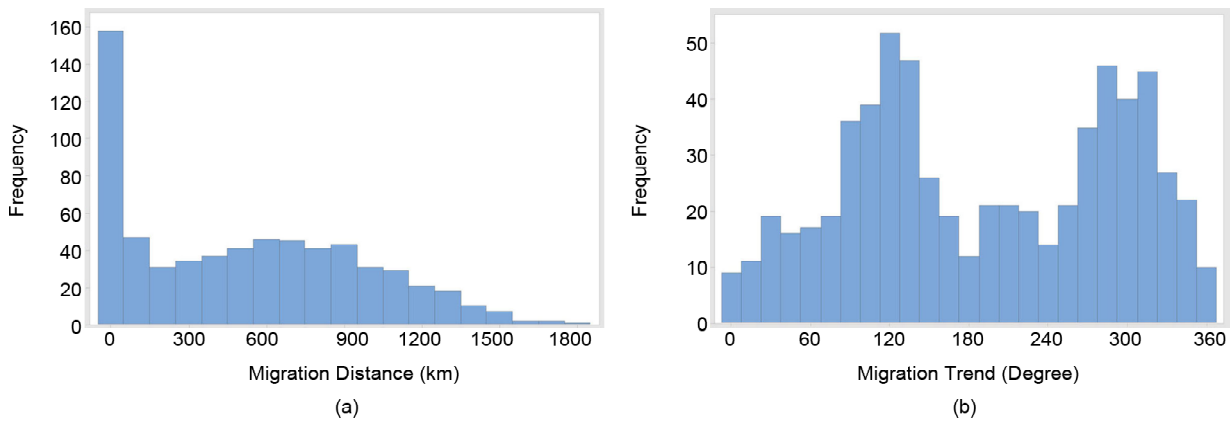




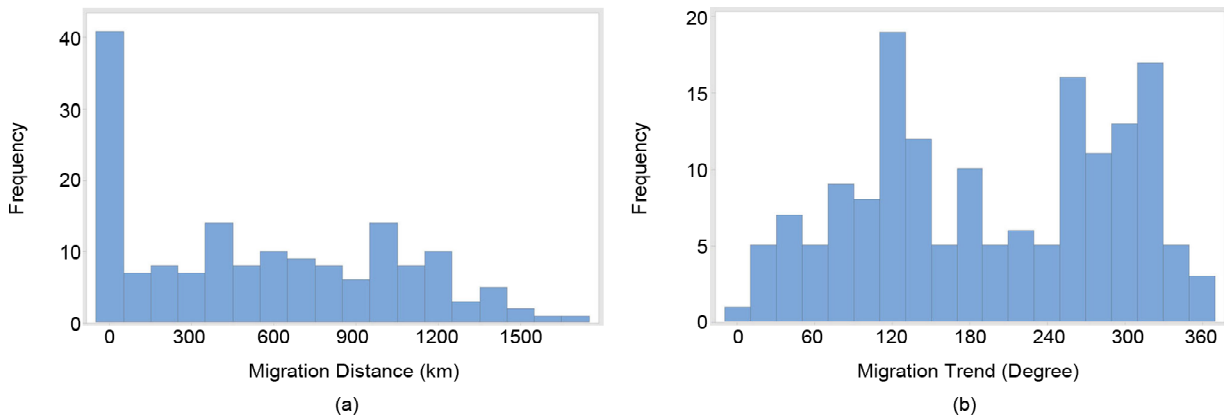
**Figure 10.** Graphs showing cumulative density function (CFD) (left) and probability plots (right) of Exponential, Gamma, and Weibull distributions fitted to inter-event times (day) of successive earthquakes with  $M \geq 5.5$ , that occurred in Iran during 1976-2018.



**Figure 11.** Histograms showing the frequency distribution of a) migration distance, and b) directional trend of successive earthquakes with  $M \geq 4.5$ , that occurred in Iran during 1976-2018.



**Figure 12.** Histograms showing the frequency distribution of a) migration distance, and b) directional trend of successive earthquakes with  $M \geq 5.0$ , that occurred in Iran during 1976-2018.



**Figure 13.** Histograms showing the frequency distribution of a) migration distance, and b) directional trend of successive earthquakes with  $M \geq 5.5$ , that occurred in Iran during 1976-2018.

In Figures (11b), (12b), and (13b), histograms showing the frequency distribution of migrating trend of successive earthquakes with  $M \geq 4.5$ ,  $M \geq 5.0$ , and  $M \geq 5.5$ , are presented. Assessing the directional distribution of migrating trend of successive earthquakes with different magnitude ranges shows that the dominant migration trend is mainly in N130 and N310 (by azimuth), which is almost in agreement with the dominant trend of active faults in Iran and especially large active faults of the Zagros region. This migration trend nearly parallel to the fault trends can be a reason for the segmentation behavior of the active faults in the study region.

#### 4. Conclusions

Results obtained in this study demonstrate that the inter-event time distribution of successive earthquakes with different lower magnitude thresholds shows a clearly decreasing trend. Comparing graphs showing the statistical distribution of inter-event times of successive earthquake, provided for

different lower magnitude thresholds ( $M_t$ ), fitted to three probability models (e.g., exponential, Gamma, and Weibull) shows earthquakes with  $M_t$  of 4.5 best fit with the Gamma statistical model and also the Weibull model shows acceptable fitting. For larger earthquakes ( $M_t$  of 5.0 and 5.5), the best fit with the Weibull model is seen. Furthermore, with the increase in  $M_t$ , fitting with the statistical models decreases.

Similarly, the first part of the histograms provided for migrating distance of these earthquakes shows decreasing trends, although, the second part of this distribution shows a nearly normal pattern. The dominant migration trend of successive large earthquakes is in good agreement with the general trend of major active faults across the Iranian region and may indicate that most of these migrations occur along the different segments of these large active faults. Results obtained also indicate that the inter-event time distribution of earthquakes in Iran can be fitted quite well by the Gamma distribution,

although, significant deviations from this distribution model, are observed at larger inter-event times.

Investigating the statistical pattern of inter-event time, migrating distance and trends of successive earthquakes, with different magnitude ranges, can improve our understanding of the spatial and temporal pattern of active faults in the study region and especially of the alternating pattern of quiescent and active stages of seismic activity of active fault interactions in regions. It is expected that in future by better access to more accurate data and also by using new methods such as neural network modeling and artificial intelligence will help to better understand the temporal and spatial pattern of earthquake events. Therefore, such a study should be an important and effective step in achieving earthquake prediction.

### Acknowledgments

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