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Pattern recognition of the spatial distribution of earthquake epicenters in the Zagros region (Iran)

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Abstract

The Zagros fold-thrust belt of Iran, as a continental-continental collision zone, is one of the most seismically active regions of the world. In this research, statistical point pattern analysis of earthquake locations in this region during 1976-2019 and the assessment of spatial association between earthquakes and major active faults of the region were carried out. For this purpose, different measures, (e.g., Nearest Neighbor Ratio, Global Moran's I and Local Getis-Ord's Gi^* indices) were estimated and computed for the data catalog. Additionally, the directional anisotropy of the earthquake epicenters distribution and earthquake-fault association were assessed. Results obtained indicate a completely clustered pattern of epicenters for the whole region and also indicate that earthquakes with greater magnitudes show higher degrees of clustering. Also, a spatial autocorrelation of higher values of magnitudes are observed. The spatial relationships of earthquake locations and active faults pattern indicates that the trend of maximum dispersion of epicenters for the whole region is remarkably parallel with the general trend of this belt, as well as with the dominant trend of the major active faults of the region. Moreover, toward the south of the region, an obvious change in the directional anisotropy of epicenters is observed. The results of this study indicate that spatial analysis techniques reliably could be employed for revealing the seismicity pattern in tectonically active regions.

Keywords: Point pattern statistics, autocorrelation indices, seismicity, spatial statistics, seismotectonics, earthquake distribution

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1 Introduction

Study of the spatial distribution of earthquakes has long been a focus of research by seismologists and statisticians. Spatial statistical analysis of earthquake epicenters can provide us useful information regarding seismicity and seismotectonic nature of active regions. Especially when the active faults in a seismically active region are hidden and occurred earthquakes are not reliably associated with known surface ruptures, the point pattern analysis methods can be used for identification and characterization of blind active faults. Today, the availability of great amount of seismicity data on time and location of occurred earthquakes in seismically active regions enables us to quantitatively model the spatial distribution of earthquakes as point processes and find the hidden structures related to these processes. It is believed that the location of earthquake epicenters is controlled by the active faults generating these earthquakes.

During the past decades, point pattern analysis techniques widely have been used for exploring the internal structure of stochastic point processes such as earthquakes. Many works have used spatial statistical methods to evaluate earthquake data and produce predictions for the future (e.g., Gelfand et al., 1976; Briggs et al., 1977; Kagan and Knopoff, 1980; Harte, 1998; De Luca et al., 1999; Vere-Jones, 1999; Kagan, 2007, 2010; Zimeras, 2008; Stein et al., 2010; Yamada et al., 2011; van Lieshout and Stein, 2012; Bray and Schoenberg, 2013; Trofimenko and Bykov, 2017). Ouchi and Uekawa (1986) investigated the spatial distribution of earthquake foci using the Polya-Eggenberg model and the Morishita index. They found that the spatial distribution of earthquakes in Japan is characterized by clustering. Eneva and Hamburger (1989) studied the spatial and temporal patterns of earthquake distribution in Soviet Central Asia and found that the spatial clustering of earthquakes appears to characterize the overall tectonic and structural regime of this region. Ogata and Katsura (1988) and Ogata (1998, 1999, 2004) outlined different aspects of the space-time distribution of earthquakes. Amorese et al. (1999, 2009) analyzed the distribution of earthquake epicenters in different parts of France using point pattern analysis. Hashemi (2011) studied the spatial pattern of earthquake epicenters in Iran and compared these patterns for different tectonic zones of the region. Zamani and Agh-Atabai (2011) studied the spatial distribution of earthquake epicenters and the homogeneity of seismic activity in the Zagros and Alborz-Kopeh Dagh regions of Iran using multifractal analysis. Al-Ahmadi et al. (2014) employed the spatial statistical analysis techniques for the study of earthquakes occurred along the Red Sea and found that these techniques are capable of detecting clusters in earthquake data. Also, the spatial associations between earthquakes and faults have been studied by many authors (e.g., Berman, 1986; Daneshfar and Benn, 2002; Hetényi et al., 2018).

The Zagros region in Iran, as a continent-continent collision zone, is one of the most seismically active regions of the world. It is beleived that the seismic activity of this belt is related to the Arabia/Eurasia collision initiated at ~ 35 Ma (Mouthereau et al., 2012). This zone extends from eastern Turkey in the northwest to the Strait of Hormuz in the southeast, with a length of about 1200 km and a width of about 200-300 km (Agard et al., 2011). During the past decades many destructive earthquakes occurred in this region. The most recent earthquake of 12 Nov. 2017 with M_w 7.3 occurred within this region (in Ezgeleh area), resulted in huge loss of life and property.

The main aim of this study is to evaluate the efficiency, capability, and usefulness of spatial analysis methods in examining and analyzing seismicity data. For this purpose, the spatial statistical analysis of the earthquake epicenters in the Zagros region was carried out in order to reveal the characteristics of the distribution pattern of epicenters and invertigate the spatial associations between earthquakes and faults in this region.

2 Seismicity and tectonic setting

The Zagros fold-and-thrust belt is known for its high seismic activity. This belt is amongst the world's most seismically active mountain ranges, and is influential in our understanding of continental collisions (Nissen et al., 2011). This mountain range is the result of the collision between the Arabian and Eurasian plates during the Cenozoic (Agard et al., 2011) and is an important element in the active tectonics of the Middle East. Seismic activity in this zone is characterized by the occurrence of low to moderate magnitude earthquakes, most of which nucleate on blind (hidden) thrust faults (Berberian, 1995). The belt hosts many small to moderate earthquakes with depths ranging from 4 to 20 km (Talebian and Jackson, 2004), and there is no evidence for a seismically active subducted slab dipping NE beneath Central Iran (Engdahl et al., 2006). The 12 November 2017 Ezgeleh earthquake occurred at the northern part of this region where large earthquakes have not been documented for several centuries (Gombert et al., 2019).

During the past decades, the study of seismicity and seismotectonics of this region has been the focus of many research (Falcon, 1974; Koyi and Hessami, 2000; Hatzfeld et al., 2003; Hashemi and Mehdizadeh, 2015; Kalaneh and Agh-Atabai, 2016; Mirhoseini et al., 2021). In Figure 1 the approximate location of the Zagros region in the general structural and tectonic frame of Iran is shown.

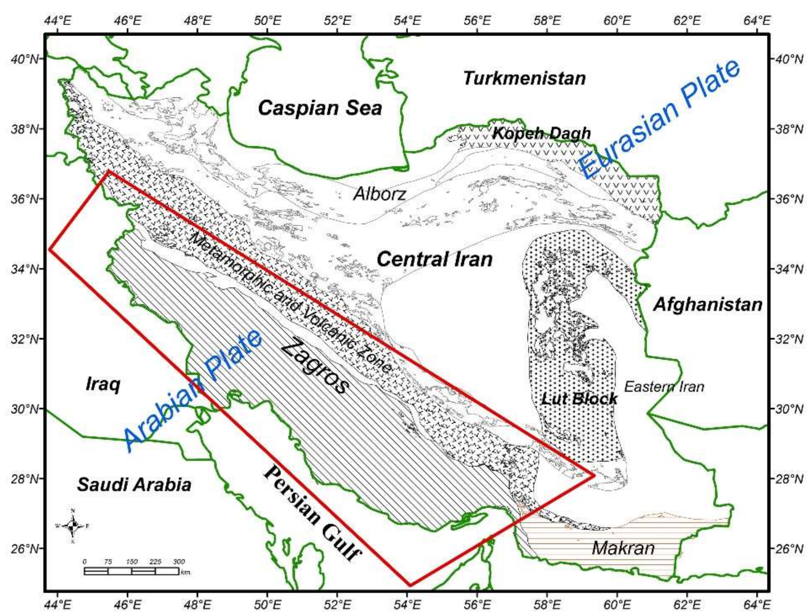


Figure 1. General structural and tectonic map of Iran [modified and adapted from Stöcklin (1968) and Berberian (1981)]. The approximate location of the examined region is shown in this map.

Due to the geological characteristics of the Zagros region, many earthquakes in this region are not associated with noticeable surface rupture. Many blind thrust faults and hidden seismogenic active folds have been reported by authors in this region (e.g., Berberian, 1995; Sepehr and Cosgrove, 2005).

Accordingly, the study of the spatial pattern of seismicity could be very useful for revealing underlying active seismogenic structures in this region. In general, processes that show mostly spatial heterogeneity such as earthquakes are sometimes modelled as stationary in time, so by assuming that the seismic activity in a region is stationary through time, the spatial pattern of this process can be studied using point pattern analysis methods. Therefore, it is expected that point pattern analysis, as a pattern recognition and modelling technique, can be reliably used for revealing the general pattern of seismic activity in a seismically active region.

As Tavakoli et al. (2008) stated, the belt of Zagros is composed of two distinct structural domains. The narrower is North Zagros domain oriented obliquely to the direction of regional shortening which is associated with orogen-parallel thrust faults and truncated by large strike-slip faults suggesting partitioning of this oblique motion. The wider structural domain is Central Zagros oriented perpendicular to the direction of Arabia–Eurasia shortening which is also associated with thrust faults experiencing pure shortening, and the presence of the Hormuz salt detachment layer at depth (Talebian and Jackson, 2004), confirmed by the presence of the SW and SE domains (Hashemi and Baizidi, 2018). Major active faults of the Zagros region are shown in Figure 2-a. Also, the spatial distribution of the epicentres of earthquakes that occurred in Zagros during 1976-2019 with M ≥ 4.5 is shown in Figure 2-b.

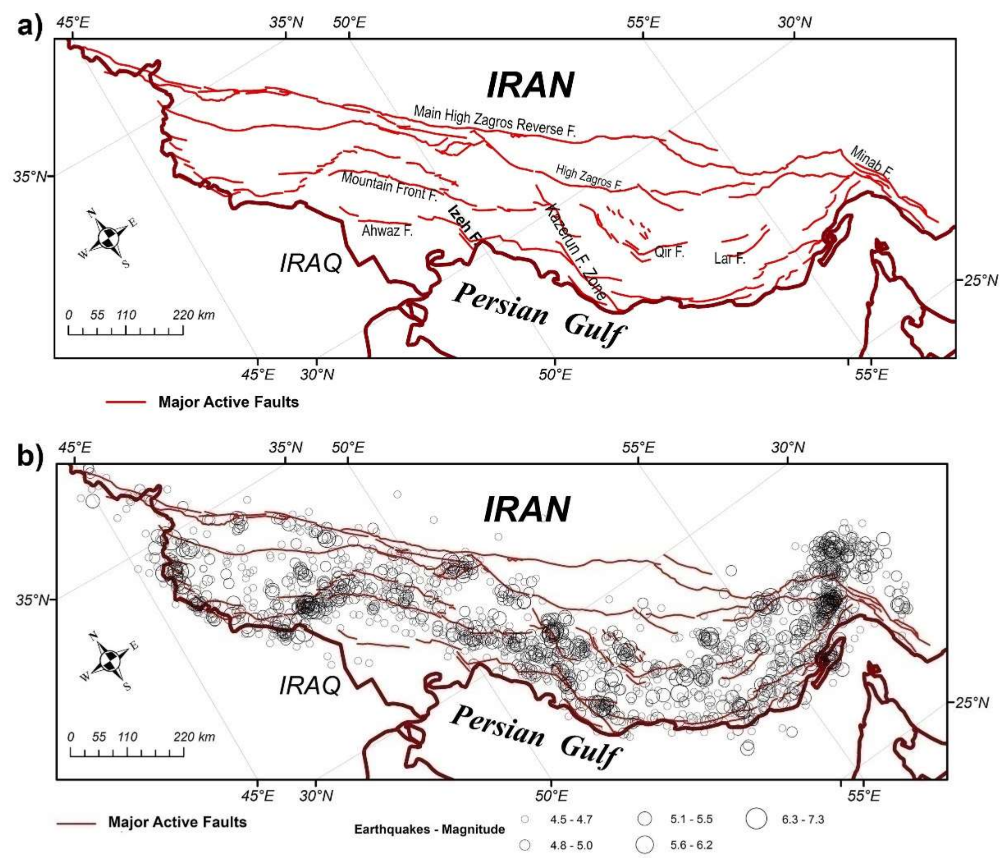


Figure 2. (a) Major active faults of the Zagros region adapted from Hessami et al. (2003). (b) Epicentral distribution of M ≥ 4.5 earthquakes that occurred in the Zagros region during the period 1976-2019.

3 Methodology

Spatial point pattern analysis is a powerful technique to find the relationships in a spatial data distribution. Theory of this technique has rapidly grown in recent decades and its background has been described in many texts (e.g., Baddeley, 2007; Fotheringham et al., 2007; Daley and vere-Jones, 2008; Illian et al., 2008; Diggle, 2014). In general, point pattern analysis can be used for modeling and describing the location of some point events (earthquake epicenters) of interest within a given region. The locations of these point events (epicenters) in the area of study will be called a point pattern. Sometimes additional attributes (such as magnitude or focal depth in case of earthquakes) may be recorded and they will be attached to the locations of the observed events. Diggle (2014) gives a detailed description of different types of point process and their main properties. Generally, the analysis of point patterns is mainly focused on the spatial distribution of the observed events and making inferences about the controlling processes that generated them. In a descriptive analysis, we usually represent the points (here in this paper, earthquake epicenters) in the examined region as a point pattern map. This map will give us an idea of the spatial distribution of the points, and it can also lead to possible hypothesis about the processes generated the events.

Point pattern analysis is a popular method in many fields of research and among them, in Earth sciences. During the past decades, a number of studies have dealt with the detection of spatial patterns within earthquake epicenters in different seismically active regions of the world (Briggs et al., 1977; Gelfand et al., 1977; Ouchi and Uekawa, 1986; Amorese et al., 1999; Koyi and Hessami, 2000; Zimeras, 2008; Shi et al., 2009; Stein et al., 2010; Al-Ahmadi et al., 2014; Djenaliev et al., 2018).

Point pattern analyses typically begin with a test for complete spatial randomness where the null hypothesis states that the pattern is random. This test enables one to differentiate between patterns which are of no further interest (i.e., random) and those which may be of interest. Regularly spaced patterns or those exhibiting aggregated patterns or clusters (Diggle, 2014), when we apply quadrant count analysis and the average nearest neighbor index, are of interest. Other statistical methods can be used to summarize the pattern and/or trend over the extent of the study area. In this study, different measures of spatial statistics, (e.g., Nearest Neighbor Ratio, Global Moran's I and Local Getis-Ord's Gi^* indices) were estimated and computed for the data catalog of the Zagros region. Additionally, the directional anisotropy of the earthquake epicenters distribution and earthquake-fault association were assessed. A brief discussion of some spatial analysis methods used in this research is presented as follows.

3-1 Density analysis

Assessing the spatial variation of point densities across the study area is one way to study point patterns. Different methods such as kernel density function (KD) can be used to assess the intensity of events in 2- or 3-dimensional space. Generally, maps showing the spatial variation of point densities can be very useful for revealing the point pattern structure. In this research, the point density technique was simply employed for providing density maps showing spatial variation of earthquake epicenters concentration across the study region by calculating the total number of events situated within a given net of quadrangle cells.

3-2 Nearest neighbor analysis

Nearest neighbor analysis examines the distances between each point and the closest point to it, and then compares these to the expected values for a random sample of points from a CSR (complete spatial randomness) pattern. The Average Nearest Neighbor ratio (ANN) is defined as the ratio of the observed mean distance between point events to the expected mean distance. The expected distance is the average distance between neighbors in a hypothetical random distribution. Then, ANN is calculated as:

$$ANN = \frac{d_{obs}}{d_{\exp}} \tag{1}$$

where

$$d_{obs} = \frac{\sum d_i}{n} \tag{2}$$

$$d_{\exp} = \frac{1}{2\sqrt{n/A}} \tag{3}$$

In above equations, d_i is the distance between points, n is the number of points in the distribution, and A is the area of the study region.

As a rule, if ANN is less than 1, the pattern exhibits clustering and if ANN is more than 1, the trend is toward dispersion or competition. This index is scale-dependent and is very sensitive to the area value under study (small changes in the area values can result in significant changes in the results). Therefore, this method is more effective for comparing different point features in a fixed region. In this paper, ANN index was employed for revealing the distribution pattern of earthquake epicenters.

3-3 Global Moran's I and Getis-Ord Gi* analysis

In order to assess the spatial autocorrelation of point patterns, two indices of Global Moran's I and Getis-Ord Gi* could be very helpful. Spatial autocorrelation measures the correlation based on both point (epicenter) locations and the feature attributes, simultaneously. For a set of point features and an associated attribute, this tool evaluates whether the point pattern is clustered, dispersed, or random.

Moran's I index is calculated as:

$$I = \frac{n}{S_o} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{4}$$

where z_i is the deviation of an attribute for point i from its mean, $w_{i,j}$ is the spatial weight between point i and j, n is the total number of points and S_o is the aggregate of all the spatial weights. Getis-Ord Gi* statistic identifies significant hot and cold spots statistically. This statistic is calculated as:

$$Gi^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{s\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{5}$$

where x_j is the attribute value for point j, $w_{i,j}$ is the spatial weight between points i and j, and n is the total number of points. A Gi* value near zero indicates the absence of clustering of either high or low values surrounding the target point. The larger positive Z score, the more intense the clustering of high values (a hot spot) and the smaller negative Z score, the more intense the clustering of low values (a cold spot) (Mitchell, 2005).

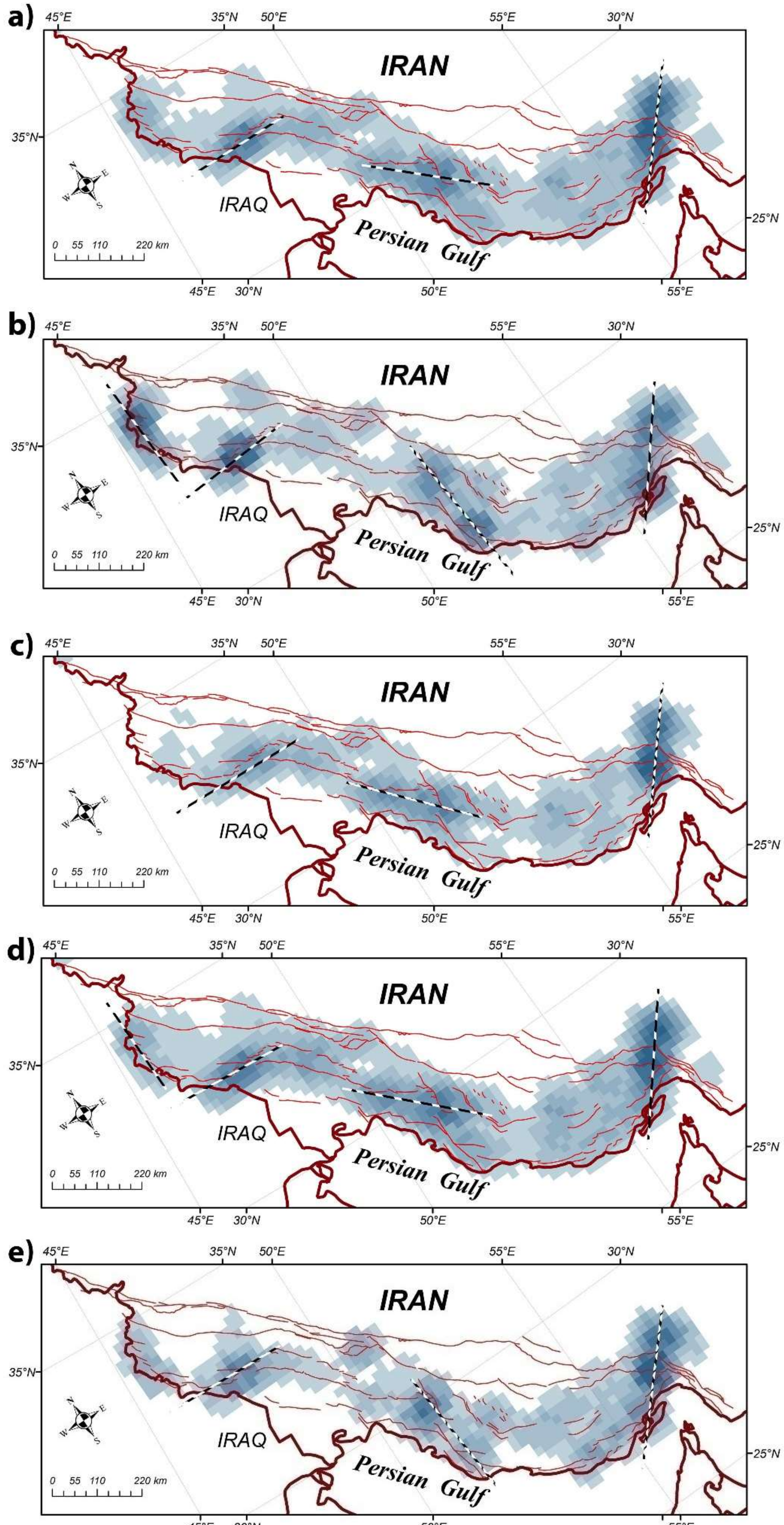
3-4 Anisotropy and earthquake-to-fault distance analysis

In this work, the standard deviational ellipse as a proper visualization tool is used to show the spatial spread of epicenters. This tool simply provides valuable information about the point dispersion and orientation. Generally, geological structures such as active faults control earthquake epicenters, thereby producing a directional bias in their spatial distribution. Standard deviational ellipse well illustrates this spatial anisotropy. Accordingly, the major axis of this ellipse will be the direction of maximum spread of the points (epicenters) and the minor axis will be the direction of the minimum spread (Wong and Lee, 2005). Furthermore, the more dispersed a set of point features (epicenters) around the center, the larger the ellipse. Furthermore, in this research earthquake-to-fault distance analysis was carried out by calculating the distance of each earthquake to the nearest mapped major active fault. This distance was computed horizontally as the dip information of the faults is not available.

4 Data analysis and discussion

For this study, earthquake data for the study region during the period of the beginning of 1976 to the end of February 2019 were extracted from the USGS catalog. In order to obtain a more homogenized data catalog, and to be sure that all recorded events analyzed in this research are natural earthquakes, events with magnitude less than 4.5 were excluded. To avoid edge effects, earthquake epicenters in neighboring regions with a distance of 0.5 geographical degrees are also taken into account. An overall view on the spatial pattern of earthquake epicenters in the Zagros region (Figure 2-b) indicates that in the northwestern part of the region, where the salt layer (Hormuz formation) is thin or missing (Ni and Barazangi, 1986), the epicenters of earthquakes are restricted to narrower zones surrounding major active faults. In general, the spatial distribution of earthquake epicenters is characterized by the clustering in the whole region.

In order to investigate the spatial variation of epicenters density, maps showing point density pattern were prepared for whole data as well as for different focal depth and magnitude ranges (Figure 3). As it is obvious in Figure 3-a, areas with high values of intensities correlate well with the central parts of the belt, mainly in agreement with the general trend of the major active faults of the region such as Main Front Fault. Additionally, around the major active faults of the region (e.g., Kazerun Fault), higher densities of earthquake epicenters are observed. In general, the dominant trend of the high-density linear trends (presented in Figure 3 as dashed lines) shows a good agreement with the general trend of the belt as well as the trends of main NW-SE and N-S trending faults of the region. Figs. 3-b and 3-c show density maps for shallow (less than 30 km depth) and deep (more than 30 km depth) earthquakes, respectively. As shown in Figure 3-b, shallow earthquakes better correlate with transversal active faults of the region. In addition, Figs. 3-d to 3-f present the epicentral density maps of earthquakes with different magnitude ranges. Earthquakes with larger magnitudes (Figure 3-f) concentrate mainly with known active faults of the region and high-density linear trends of these earthquakes correlate well with the trends of active faults. The high seismic activity of some transversal active faults of the region (e.g., Kazerun Fault Zone and Izeh Fault Zone) is confirmed by the pattern of high-density linear trends. In general, the linear trends presented in Figure 3 indicate the trends of higher density or concentration of earthquake epicenters that can be considered as surfaces or zones of weaknesses which have higher seismic activity potential than the surrounding areas. However, many of these high-density linear trends don't show any associations with the known mapped active faults. These trends may be related to the hidden active faults of the region and need to be studied in more details in future. In the contrary, some parts of the Main Zagros Reverse Fault and High Zagros Fault don't show any spatial associations with epicentral high-density locations, which means these parts of the mentioned faults are not seismically active during this period. As a whole, the clustering pattern maps of earthquake epicenters, presented here in this study (Figure 3), are acceptably consistent with the results made by Karasözen et al. (2019). As they stated, the overall diffuse pattern of seismicity and also the large concentration and high density of larger events in this region imply that seismogenic structures of the region are mostly broken up into short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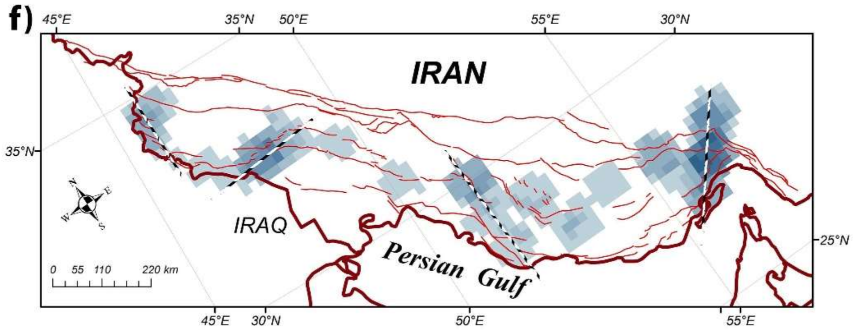

Figure 3. Density maps showing the earthquake spatial concentration over the Zagros region. (a) Whole earthquake data analyzed in this research ($M \geq 4.5$). (b) Earthquakes with $D \leq 30.0$ km. (c) Earthquakes with $D > 30.0$ km. (d) Earthquakes with $4.5 \leq M < 5.0$. (e) earthquakes with $5.0 \leq M < 5.5$. (f) earthquakes with $M \geq 5.5$ [D is focal depth (km) and M is magnitude (Richter)]. Dashed lines shown in these maps indicate high-density linear trends.

fault segments. In this research, to quantify certain aspects of the spatial pattern of seismicity, ANN ratios were calculated through Nearest Neighbor analysis, for the whole seismic data catalog of the Zagros region as well as for different parts of the region. Additionally, the General Moran's I index was carried out for the earthquake epicenters of the region based on two attributes of magnitude and focal depth. The final outputs of these analyses are listed in Table 1. As can be seen in this table, the values of ANN ratio calculated for the distribution of earthquake epicenters and the related z-values indicate that from the northern part to southern part of the region, ANN ratio increases, which means the degree of clustering is decreasing.

High/Low clustering of epicenters was analyzed by calculating Local Getis-Ord Gi^* statistic and considering magnitude as weighting attribute. Positive and signify cant values of this statistic suggest a cluster of high values, whereas negative and significant values suggest a cluster of low values. This statistic returns a Z-score and p-value for each point in the data set. The higher the value of the Z-score (significant positive values), the more intense the clustering of high values (hot spots). In contrast, the smaller the value of the Z-score (significant negative values), the more intense the clustering of low values (cold spots). A Z-score value near zero indicates no apparent spatial clustering. Through this analysis, the clusters of high-magnitude spatially auto-correlated epicenters (hot spots) and low-magnitude spatially auto-correlated epicenters (cold spots) can be identified. Map shown in Figure 4 clearly presents hot and cold spot patterns of earthquake occurrence in this region. According to this map, it is observed that hot spots represent earthquakes with high magnitudes, which are surrounded by high-magnitude neighboring earthquakes.

Table 1. Spatial statistics parameters computed for the whole Zagros region as well as for the southern, central, and northern Zagros based on the analysis of 1831 earthquakes with $M \geq 4.5$ that occurred during 1976-2019 (data derived from USGS data catalog).

Spatial pattern statistics	Zagros (whole region)	Southern Zagros	Central Zagros	Northern Zagros
Average Nearest Neighbor index (ANN)	0.606 * -32.22	0.715 * -15.32	0.679 * -13.81	0.616 * -16.31
Global Moran's I (attribute: magnitude)	0.036 * 6.90	0.087 * 5.49	0.039 * 2.51	0.023 * 2.16
Global Moran's I (attribute: focal depth)	0.122 * 22.83	0.287 * 17.41	0.051 * 3.18	0.155 * 13.18

These areas could be considered as higher strength behavior of the crust, and in contrast, cold spots may be evidence of crustal weakness areas of the region. Hot spot areas presented in this figure (Figure 4) spatially correlate well with the trends of major active faults of the region. Especially, hot spots located near to the Makran region are very clear. As a result, this map provides greater certainty in terms of where hot spots are located, i.e., the most risky areas of the region from the viewpoint of seismic hazards.

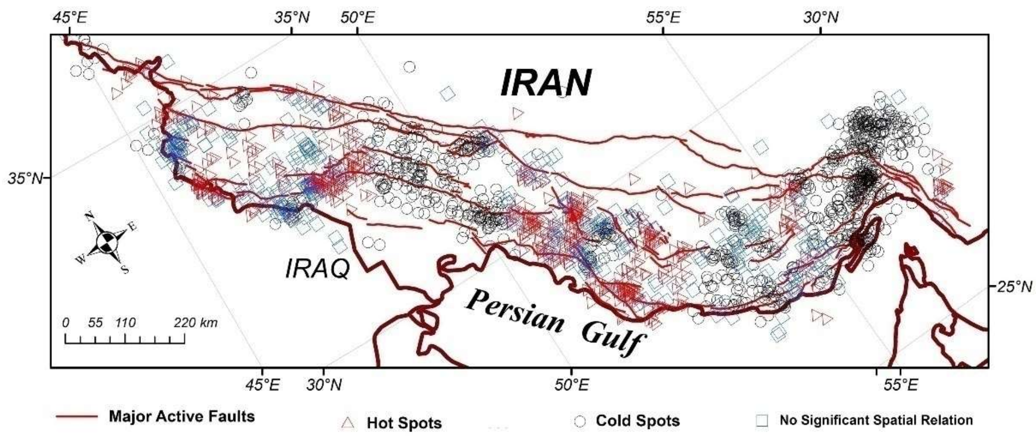

Figure 4. Map showing the spatial pattern of hot and cold spots resulted from spatial autocorrelation of earthquake data over the examined region.

To detect the directional anisotropy of earthquake epicenters in the Zagros region, and to find how concentrated the epicenters are around the geographic mean position of epicenters, and whether or not they exhibit a directional trend, the standard deviational ellipses, showing the directional anisotropy of earthquake epicenters, were provided for northern, central, and southern parts of the region (Figure 5). As can be seen in Figure 5, the major axis of the standard deviational ellipse obtained in this analysis, as the axis of maximum spread of epicenters, correlates well with the overall trend of the Zagros fold-and-thrust belt. Furthermore, the standard deviational ellipses indicate that from the northwest to the southeast of the region a change in the major axis trend of the ellipses can be observed. The rotation of the ellipses and their correlations with the general trend of major faults is meaningful.

The spatial association between earthquake epicenters and supposedly-active mapped faults was carried out. For each earthquake, the distance to the nearest active fault was calculated. Earthquake-to-fault distance distribution analysis was carried out in this work. Histogram showing this distribution is shown in Figure 6-a.

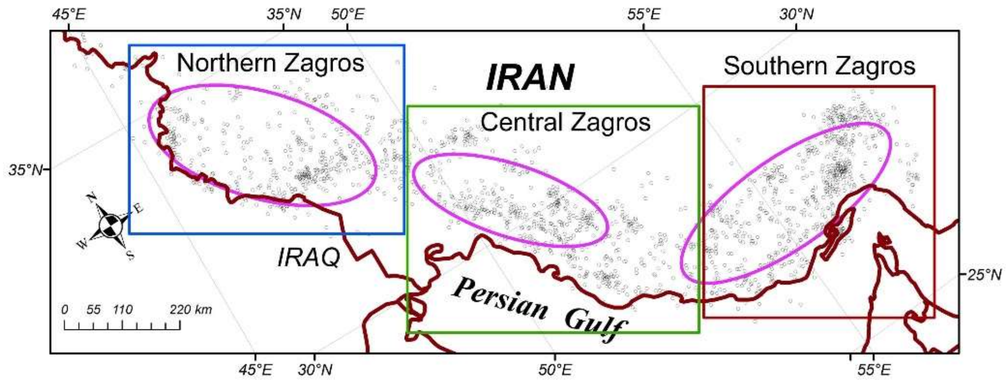

Figure 5. Map showing the directional deviational ellipses of earthquake epicenters pattern, for the northern, central, and southern parts of the Zagros region.

From this graph, it is clear that most of the earthquakes occur at 5 to 10 km distance from active faults. Earthquake-to-fault distance values were computed for different magnitude and focal depth ranges. The results are given in Table 2. Data listed in this table indicate that in general about 70% of the earthquakes can be considered as being close to the active faults (with distances less than 20 km), and about 30% are far. Data listed in Table 2 simply indicate that earthquakes with higher magnitudes as well as those with smaller focal depths occur more closely near to the major active faults. According to the dip structure of the major active faults of the region, these earthquake-fault relationships are acceptable. Figure 6-b illustrates the scatter plot of magnitude versus earthquake-to-fault distance of earthquakes with a meaningful negative relation of these two variables. It is observed that by increasing magnitude, earthquake-to-fault distance simply decreases, which means most of the high-magnitude earthquakes occur near to the major known active faults of the region.

Table 2. Results of the earthquake-to-fault distance analysis (for the whole data and for different focal depth and magnitude intervals) presented as percent of earthquake epicentres located in different distances to the active faults of the region based on the analysis of 1831 earthquakes with M ≥ 4.5 that occurred during 1976-2019 (data derived from USGS data catalog).

Data	No.	% of earthquakes located in different fault-buffer zones			
		10 km	**20 km**	**30 km**	**40 km**
Total data with M ≥ 4.5	1831	43.7	69.3	82.6	90.4
***D ≤ 30.0**	763	46.8	71.6	83.2	92.5
D > 30.0	1068	41.5	67.7	82.1	89.0
4.5 ≤ **M < 5.0	1425	41.9	68.5	83.0	91.0
5.0 ≤ M < 5.5	326	51.5	72.1	81.3	88.3
M ≥ 5.5	80	48.8	72.5	81.2	90.0

***D: focal depth (km)** ****M: magnitude (Richter)**

5 Conclusions

In this paper, the spatial distribution of earthquake epicenters in the Zagros region was studied. The most recent release of ArcGIS package (version 10.7) has been employed for this analysis and for providing maps. The results of this analysis are summarized as follows:

(1) The density maps representing epicentral concentration of earthquakes with different magnitude and focal depth ranges indicate high-density linear trends approximately parallel to the general trend of the whole mountain belt. The direction of highest lateral variation of earthquake density is nearly SW-NE. This direction shows a considerable change towards the southern parts of the region, indicating an increase in seismic activity towards the southeast of the region. Additionally, in this spatial pattern analysis, the role of

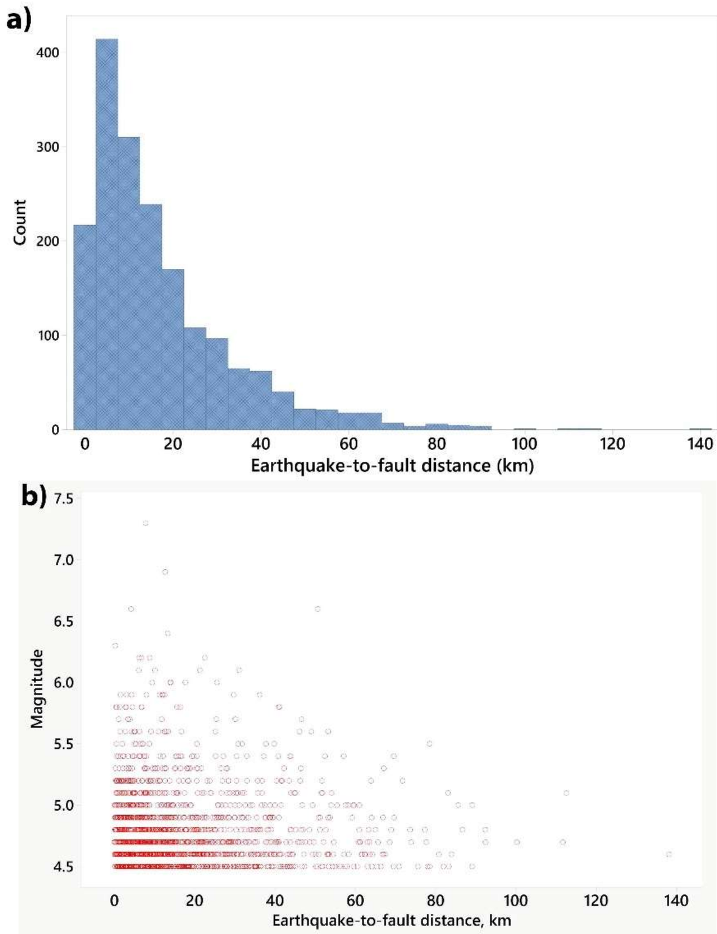

Figure 6. (a) Histogram showing the statistical distribution of earthquake-to-fault distance data. (b) Scatter plot showing the magnitude versus earthquake-to-fault distance values calculated for 1831 earthquakes with $M \geq 4.5$.

major transversal strike-slip faults of the region such as the Kazerun fault zone and Izeh fault zone was revealed. High concentration of earthquake epicenters indicates the higher degree of seismic activity of these structures in relation to the adjacent areas. These findings are acceptably in agreement with the GPS data analysis presented by the previous researchers (e.g., Walpersdorf et al., 2006). Furthermore, the low concentrations of epicenters in the Dezful Embayment area (Figure 3) and the flexure of isodensity areas near to this part of the region well indicate the nature of the northern promontory of the Arabian plate that presently converges with the Eurasian plate (Allen et al., 2013). Consequently, results obtained indicate that areas with higher fault densities show more epicentral concentrations. The epicentral density maps produced in this study could acceptably be employed for assessing the degree of concentration of active faults and evaluating seismic activity of the study area.

(2) The Nearest Neighbor Analysis results indicate a completely clustered pattern of earthquake epicenters for the whole region of Zagros and also indicate that earthquakes with greater magnitudes and focal depths show higher clustering intensities. This fact that earthquakes with greater magnitudes and focal depths show higher degree of clustering can be explained by the fact that large and deep earthquakes nucleate on major active faults often with a remarkable spacing, while the smaller and shallower earthquakes occur on minor faults showing less

localizations. Additionally, it is observed that from the northern part of the Zagros towards the southern part, an obvious increase in the degree of spatial clustering of earthquakes is seen. This complexity of seismicity pattern, especially the heterogeneities in density of earthquake epicenters is in good agreement with the seismicity maps of the region presented by Kalaneh and Agh-Atabai (2016).

(3) The Global Moran's I analysis indicates that both for magnitude and focal depth a spatial autocorrelation is observed. This spatial autocorrelation degree is higher for focal depth (as an attribute) than for magnitude. Among different parts of the Zagros region, the southern Zagros shows highest level in spatial autocorrelation.

(4) The Local Getis-Ord Gi^* analysis indicates clear hot and cold spots showing areas with spatial autocorrelation of high- and low-magnitude earthquakes, respectively. Hot spot areas can be interpreted as areas with higher crustal strength and in contrast, cold spot areas may be considered as areas with crustal weakness.

(5) The anisotropy analysis results indicate that the trend of maximum dispersion of epicenters for the whole region of Zagros (major axis of the standard deviational ellipse) is remarkably parallel with the general trend of this belt, as well as with the major faults of the region (e.g., Mountain Front Fault). Moreover, toward the south of the region, a change in the pattern of the ellipses can be observed.

(6) Earthquake-to-fault distance analysis results indicate that most of the earthquakes occurred in this region located close to nearby active faults and high-magnitude and shallow earthquakes show better associations spatially with the adjacent active faults.

As a result, in regions such as Zagros which surface fault ruptures associated with earthquakes is extremely rare and most information about the active faulting comes from earthquakes, the spatial point pattern analysis can be a very powerful tool to discriminate the seismicity linked to a particular fault and to easily reveal the trend of major hidden (blind) active faults.

Finally, this research simply presents the usefulness and reliability of different spatial statistics methods for revealing the seismicity characteristics of the Zagors region, as a case study. The techniques used in this research are data driven and the reliability of the results obtained depends on the quality of the input datasets. It is expected that in future, the analysis of more accurate and reliable data catalogs will lead to better results. Furthermore, the choice of the study area and the scale of study, as an important component of a point pattern analysis, can remarkably change the pattern observed, so it is suggested testing and verifying the results of this study by applying the methods for studying the other seismically active regions and also by running the technique in other scales.

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